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*A Technically Useful History*  
of the Critical Mass Laboratory  
at Rocky Flats

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Robert E. Rothe

\*Retired, Rocky Flats.



The World's Greatest Science Protecting America

***Dedication***

*This book is respectfully dedicated  
to the memory of*

***Clarence Lee Schuske***

*whose imaginative vision  
solidified into structural reality  
in 1964  
and who faithfully served  
a still-young industry  
during it's formative years.*

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## ***Foreword***

Critical mass data underpin all operations with significant quantities of fissile material. Knowledge of the critical state for both idealized as well as prototypic configurations is essential for direct application to setting subcritical operating limits as well as for benchmarking analytic tools.

As the totality of critical mass measurements grew, the need for additional measurements lessened. This led to a dramatic decrease in the number of facilities capable of performing such measurements in the US. It is important that practical, operational knowledge of this work, which was born in the 1940s, flourished for a few brief decades, and is nearly extinct less

than 60 years later, be preserved for the benefit of future experimenters.

Also of significant value is the technical detail necessary to enable the accurate documentation of unreported experiments lying in dusty logbooks or in electronic files. Finally, as experimental uncertainties associated with previously reported experiments are deemed too large for current benchmark applications, the technical detail reported herein may prove invaluable in reducing these uncertainties.

Thomas P. McLaughlin  
Los Alamos, NM  
April, 2005

## ***Preface***

The Critical Mass Laboratory at the nuclear facility commonly known as “Rocky Flats” and located northwest of Denver, Colorado, was built in 1964. It served a very productive life until what later proved to be its final experiment in October of 1987. Throughout intervening years, about 1700 experiments were performed with a common goal of enhancing nuclear criticality safety at that plant as well as the rest of the world-wide nuclear industry. Experiments were performed with high-enriched uranium, weapons-grade plutonium, as well as low-enriched uranium such as that used in some nuclear reactors. The physical form of these materials included solid metal in various shapes, solution at various concentrations, and powdered compound. Both single fissile units and arrays of identical components were studied. Experiments were conducted both unreflected and reflected by a variety of materials; and a number of different neutron absorbers and/or neutron moderators were employed in different programs.

Many of these studies have been reported in the open literature at one time or another. Some were documented by the lead experimenter, called the Senior Experimenter, immediately following the study. This was, of course, the preferred procedure. Other studies which, for one reason or another, were not documented at that time have since been published by this author during the 1990s. This latter work was accomplished through a government contract administered by Mr. J. Blair Briggs of the Idaho National Engineering Laboratory (INEL)—later the Idaho

National Engineering and Environment Laboratory (INEEL).

Several important justifications for writing this historical document exist. It embellishes any and all papers ever published reporting early experimental programs at this laboratory because the earliest papers may have suffered from insufficient detail. That oversight was not so much a failure of early authors as it reflects the inability of anyone to foresee the high level of detail needed in modern times. Other valuable information related to safety is also contained in this book. Off-normal events, including spills and accidents are detailed; and this information was helpful to those demolishing the building. An important discussion of certain physical properties of Raschig rings is included. One chapter even addresses specific cautions relevant in the new millennium. This book is an historical overview of the facility, describing the evolution of procedures and documentation. Persons affiliated with the laboratory throughout its lifetime are also identified for credit due them.



## Introduction

An understanding of history, according to a time-honored cliché, enables one to avoid repeating mistakes. That platitude is only partially true with respect to the Critical Mass Laboratory<sup>1</sup> at Rocky Flats.<sup>2</sup> Accidents such as spills, leaks, contamination incidents, and similar “problems” might never be avoided; but they need not lead to a criticality. The CML did serve as an effective tool in preventing nuclear criticality during normal operations as well as consequences of such accidents throughout the plant site during its entire lifetime—which spanned most of the last half of the twentieth century. The existence of quality experimental data is largely responsible for this enviable record. Therefore, given the evolution of the nuclear industry as it actually happened during the century’s middle decades, the construction of a CML at Rocky Flats was the right thing to do.

Still, the history revealed in this volume is unmistakably multifaceted. Parts of it will appeal to a significant variety of readers with a wide range of specific interests and for an equally diverse collection of reasons. Some will find only certain chapters of great interest while other chapters bore to tears. Isolated paragraphs may prove intensely useful to some while the remainder of the text has little interest.

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<sup>1</sup>The acronym, CML, will be used throughout this book to refer to the Critical Mass Laboratory.

<sup>2</sup>Rocky Flats plantsite was given the acronym RFP for many years; but the national move toward “political correctness” prompted the later adoption of Rocky Flats Environmental Technology Site (RFETS). That acronym is occasionally used in this book.

In truth, few will plod through the entire document—this laborious chore is reserved for the book’s courageous but masochistic Peer-Reviewer.

The multiple purposes behind this writing prompted its unusual title. The document is, indeed, much more than merely “A History of the Critical Mass Laboratory at Rocky Flats.” Details, physical properties of apparatus, problems encountered and eventually solved, and a realm of unrelated facts will prove useful to different people in different ways. Consequently, this book is much more appropriately viewed as: “A *Technically-Useful* History of the Critical Mass Laboratory at Rocky Flats.”

The Critical Mass Laboratory was built in 1964 at a site northwest of Denver, Colorado. That overall site, known as Rocky Flats, had housed a nuclear facility for well over a decade before that. This CML served a very productive life until what later proved to be its final experiment in October of 1987. Between, about 1700 experiments were performed with a common goal of enhancing nuclear criticality safety at that plant as well as the rest of the world’s nuclear industry. Experiments were performed with high-enriched uranium, weapons-grade plutonium, as well as low-enriched uranium such as that used in some nuclear reactors. Their physical form included solid metal in simple geometries, fissile solution at various concentrations, and powdered compounds. Both single units and arrays of interacting fissile components were studied. Experiments were both unreflected and reflected

by a variety of non-fissile materials; and a number of different neutron absorbers and/or moderators were employed at different times.

Many of these studies have been reported in the open literature at one time or another. Some were documented by the lead experimenter, called the “Senior Experimenter,” immediately following the work; and this was definitely the preferred procedure. However, other programs, for one reason or another, were not documented at that time but have since been published by this author. This delayed publication work was accomplished during the 1990s through a government contract administered by J. Blair Briggs of the Idaho National Engineering Laboratory (INEL)—later the Idaho National Engineering and Environment Laboratory (INEEL). By the year 2000, every experimental program ever undertaken at the RFETS CML had been described in the open literature.

Several considerations justify writing this present historical document. First, it embellishes any and all papers ever published which reported early studies at this laboratory. Many early papers lacked sufficient detail. That oversight was not so much a failure of early authors as it reflects the inability of anyone to foresee the high level of detail needed in modern times. Other valuable information related to safety is also contained in this book. Off-normal events, including spills and accidents are detailed; and this information has already aided those demolishing the building. An important discussion on the stability of certain physical properties of Raschig rings is included; and this may prove helpful in writing future national standards. One chapter even addresses specific cautions relevant in the new millennium. Persons affiliated with the

laboratory throughout its lifetime are also identified for credit due them. This book is an historical overview about one building. It describes the evolution of procedures and documentation. It reflects the coming of age of one laboratory serving an industry little more than six decades old itself.

## **Potential Readers of This History Document**

The true historian—the one who seeks merely to put the Rocky Flats CML and its progress and problems into perspective with respect to the evolution of the nuclear industry—may choose only to skim the entire document. That reader is not interested in boring physical details. The first sentence or two of each paragraph may sufficiently convey the sought-for historic unfolding. Details buried deeper may prove an unnecessary deterrent. That reader, unlike others, may not find the document “Technically Useful.”

That same frivolous detail, so extraneous to the historian, may prove quite useful to Criticality Safety Engineers. This includes those helping to shut down the bevy of production buildings at Rocky Flats as well as other safety experts in the nuclear industry around the world. The universal need to validate computer codes against quality experimental data spans nations; and this important task will continue far into the foreseeable future. For improved safety, computer calculations must be compared against extremely well-defined experimental conditions for physical systems which have attained criticality. This book—coupled with previously published papers—provides that detail.

Many published articles resulting from data obtained at Rocky Flats from the 1950s through the mid-1970s do not contain adequate description of peripheral

apparatus to permit a complete physical description of the environment surrounding an experimentally critical system. The importance of that detailed descriptions of geometry and composition to the computational validation was not clearly recognized in early years. Authors typically described materials up to a couple of meters from the critical assembly and ignored features further away. Room walls and other neutron moderating and reflecting materials were often omitted.

This defect probably also exists relative to publications from other facilities; but, sadly, those who labored there have not seen the merit of supplying this much-needed missing detail. Fortunately, this is not the case for Rocky Flats because this author was employed during the entire life span of the Rocky Flats CML. He was an active participant in almost every experiment ever performed there. He is both able and willing to describe in this book the detail of peripheral equipment omitted from earlier publications.

Another significant defect of earlier publications was a too-generic description of certain materials. For example, a room's walls might have been described as "concrete" with no elaboration. Concrete composition is known to vary widely. A limestone aggregate, as one illustration, contains carbon in the form of metallic carbonates; and carbon is a good neutron moderator. As another example, a "metal" component may have been referenced with no further specifics provided. For example,

was that object mild steel or stainless steel?<sup>3</sup> If the latter, was it type 304, 304L, 316, or one of the myriad of other, less common, types? These differences can have significant impact on today's improved computational capabilities. This book presents that added detail.

This book also provides a chronology for the evolution of the facility. Its growth, improvements, additions, and modifications can be pin-pointed in time. This information is important because it can then be used to reconstruct the actual physical condition of the facility at any time a particular experiment of interest was being performed. For example, a computer evaluation of Rocky Flats data from an earlier date would benefit from knowing, through this book, whether or not the large elevated concrete platform in the southeast corner of the Assembly Room had been installed yet.

Details buried in this paper—of little interest to the historian—will provide that missing additional information and, therefore, will almost certainly prove most valuable to improved validations. In particular, the code validation efforts spearheaded by J. Blair Briggs of the Idaho National Engineering and Environment Laboratories (INEEL) may readily welcome this additional detail about ancillary equipment and nearby objects as they attempt to validate modern computer codes against experimental data generated at Rocky Flats. This assembly of many talented experts and their efforts are called

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<sup>3</sup>This author has long contended that well-defined *nominal* standard compositions of certain very common alloys, such as different types of stainless steel, are a better estimate of that material's true composition than publishing the result of a single (or even a few) laboratory analyzes of selected samples from the piece actually used. Standard compositions are well-controlled under tight limits; but too many anomalies can be introduced into any sampling procedure. This can be traced to slight inhomogeneities within the manufactured material or analytical biases in laboratory measurements. Conversely, the best estimate of the composition of materials like concrete, whose composition varies widely depending on the source of aggregate, impurities in the sand, and the type cement used, is to analyze multiple samples. No standard composition is available for such materials.

the International Criticality Safety Benchmark Evaluation Project (ICSBEP).

Another group of potential readers *have already* found early drafts of this document most useful. They are those persons responsible for the safe and orderly deactivation, decontamination, decommissioning, disassembly, and demolition of Building 886. Their task began in the mid-1990s and concluded in the spring of 2002 with the complete razing of the entire building.

Their efforts were so concurrent with the writing of this book that, on a number of occasions, requests for advance copies of as-yet unfinished chapters and detailed verbal discussions about the building's past have occurred. Many at Rocky Flats are aware of this book and have already benefitted from it as indicated by the following quotations. Radiological Engineer, Rock Neveau, wrote:

Engineers, waste disposal technicians, and other support personnel have used this information throughout the history of decontamination and demolition activities in Building 886. The task of removing solutions began in the early 1990s, and concluded with the demolition of a radiologically clean structure in the spring of 2002. Throughout the years, project personnel have found Dr. Rothe to be an invaluable resource when planning work activities in areas of Building 886. Information on the uranium and plutonium that remained within glove boxes, ventilation ducts, and other systems after the Rocky Flats Plant was officially closed proved to be very useful when engineering the safe removal of these areas of concern. Often, a pipe run, ventilation duct system, or tank needed clarification as to what material had been used in the system or the expected type and quantities of material remaining within the system. Having this information readily available allowed the demolition project to attack each area with knowledge and foresight not often afforded to the workers in other similar projects. The information provided was valuable, even in draft form, for the Building 886 Demolition; and it will undoubtedly prove its worth for other D & D projects in similar uranium laboratories and facilities.

A Criticality Safety Engineer, Paul Felsher, wrote:

As the primary Criticality Safety Engineer supporting the project to shutdown, close, and eventually demolish building 886, I frequently encountered situations where access to detailed operational history of the facility greatly helped in tailoring criticality safety controls to true—rather than perceived—hazards. Similar to many of the older facilities at Rocky Flats, a documented history detailing the normal operation of building 886 as well as the various operational mishaps which could have resulted in depositions of holdup in unexpected places, simply did not exist at the beginning of this project. On many occasions, I relied on telephone conversations with this book's author to help fill in details of how particular pieces of equipment were built, operated, and used in the normal course of conducting experiments. Later on in the project, as the planning stages for dismantling some equipment were entered, simply quoting from a telephone conversation with him was not sufficient to dispel the rampant rumors and myths regarding the location and quantity of holdup that could potentially be encountered. Luckily at about this time, he was starting to document the complete, unabridged history of the Critical Mass Laboratory. Shortly thereafter, he shared early drafts of some of the

chapters with me. Although only in draft form, the information permitted us to tailor the criticality safety controls to match the true hazards and helped block the external imposition of overly conservative and costly controls. Work package planners as well as Radiation Safety and Safeguards and Accountability personnel also expressed sincere gratitude for having access to written details of specific events that occurred within the facility. While this report has already proved to be an invaluable resource at Rocky Flats, it will surely be just as valuable to the Criticality Safety community as a whole because it provides a unique and entertaining narrative of the complete life-cycle of the Rocky Flats Critical Mass Laboratory.

Finally, a criticality expert at another DOE facility in Tennessee, Karla Elam, was validating computer codes against Rocky Flats experimental data for enhanced nation-wide criticality safety. She wrote:

Critical experiment facilities are becoming increasingly rare, not only in this country but worldwide, and Nuclear Criticality Safety Engineers must depend more and more on the results of computer calculations to determine margins of safety. These computer codes and their associated cross-section data sets are now—and will continue to be—validated against critical experiments that were performed many years earlier. (It has become very difficult and expensive to perform new experiments.) When constructing a computer model of an experiment, it is important to consider both the configuration as well as its surroundings, and not all of peripheral information had been documented in previously published reports from any laboratory. Therefore, the detail and unique information contained in the document concerning the history of the Rocky Flats CML has been—and will continue to be—most valuable. This description is especially instructive to Nuclear Criticality Safety Engineers who have not had the advantage of having seen a working critical-experiments laboratory.

Some of this important information included the description of hidden—and previously unpublished—sources of contamination sites and other potential problems. This book contains a lengthy chapter titled “Anomalous Events” which discusses a large number of unplanned and unwelcome events. Some are more significant than others. A few are even humorous. A couple are trivial, enlightening none, but included for completeness. Many, if not all, of these unplanned occurrences have been openly discussed by this author during the closure phase. Few have ever been published until now. Publishing them in the

open literature is the best this author can do to make the information readily available to any who might benefit from owning it.

For example, information about the Vent Overflow Problem of 1967 has already been used by Safety Engineers who prepared the disassembly of the Assembly Room’s Hot Exhaust System. Another Criticality Safety Engineer has asked for information about the uranium solution leaks that once partially filled the cable trenches in the floor of the Assembly Room. That information has already benefitted crews that sawed the concrete floor of the Assembly Room into rectangular pieces.

Quite possibly, another group of interested readers may be those at other nuclear facilities responsible for documentation. They might like to compare the nature and depth of governing documents which served the CML for over three decades against their own. A comparison with the evolution of this documentation at Rocky Flats might also prove beneficial as well as interesting. Certainly, the magnitude of regulatory documents has increased significantly over the years.

The performance of critical experiments form one illustration of the evolution of controls and oversight over nuclear operations. When the first experimental programs were performed, the lead scientist just naturally discussed his intentions with colleagues; and, together, they mapped out a reasonable approach to the study. After that discussion, however, he and one other person were allowed to perform the experiments with no further requirements being met. That second person was often just any other science-oriented person associated with the Nuclear Safety Group. Even Criticality Engineers helped with experiments under the leadership of a staff person from the CML. This was not considered unsafe because anyone working in Building 886 was assumed to understand nuclear fission in general and criticality in particular. Their knowledge about the subject was assumed because they had been specifically hired for that knowledge. Concern for their own personal safety naturally presumed that experiments would be performed safely. Self-recognition of their own physical limitations caused them to add reactivity slowly enough to permit a rapid response lest some unplanned event occur.

Policies governing experiments became increasingly regulated as decades passed. By the end of the 1970s, only personnel

designated as an “Experimenter” could perform a critical-approach experiment; Criticality Engineers, however knowledgeable, were not allowed. Two levels were defined: “Senior Experimenters” were assumed more knowledgeable than “Experimenters.” Both were screened, trained, and given special examinations designed to prove qualifications. Both designations were reviewed and approved by the United States Government and certifications maintained on file.

Documents related to experiments also became more structured. Carefully written and detailed “Experimental Plans” replaced the informal discussions. These Plans were scrutinized by a variety of safety experts spanning many fields long before that program could even begin. Each Experimental Plan included clearly defined operational limits. These were designed to protect less-conservative (closer to accident conditions) “Safety Limits” which were spelled out in the CML’s “Technical Specifications” document. This last was a DOE-approved document against which all critical experiments were measured. Even a minor violation of this document was taken seriously and treated harshly. Policies and procedures had, indeed, changed markedly over a couple of decades.

Still another audience will benefit from this writing. Although small in number, they are the Working Group of the American National Standard, ANSI/ANS-8.5. They are charged with the required periodic review and update of such an important safety document. The last version (1996) of this Standard, “Use of Borosilicate-Glass Raschig Rings as a Neutron Absorber in Solutions of Fissile Material”, is currently due for that review; and it must be re-approved or revised within the first few years of the new millennium. This author was the Secretary of the previous

Working Group which produced ANSI/ANS-8.5-1996. Even though that Working Group worked diligently for many years, the 1996 edition had to be published with two extremely conservative limitations because peer-reviewed evidence to safely relax either of them had not yet been published. One chapter of this book addresses both limitations specifically and intentionally.

The two properties of Raschig rings which need to be brought into clearer perspective include the mechanical strength of the glass and the ability of this glass to retain its boron content under any conceivable commercial applications. The strength issue falls into two related camps: static strength and dynamic strength. Experiments performed at Rocky Flats in the early-1990s on several sets of never-used rings showed that the weakest rings in the weakest ring-to-ring configuration broke under a static loading equivalent to 200 stories tall. Dynamic strength is almost as impressive. The weakest rings in, again, the weakest configuration broke when a 7 kg weight was dropped from one-third of a meter height. Similar tests were repeated at Los Alamos National Laboratory on well-used Raschig rings removed from the Rocky Flats CML in the late 1990s; and those results were very similar. Rings immersed for over three decades in an acidic solution of concentrated fissile material retained the same mechanical strength after that long exposure.

The second parameter studied was chemical stability. The boron content of these three-decade-old well-used rings revealed that the boron content had not changed at all in that length of time. In fact, a few cases appeared to gain boron content; but that difference fell well within the uncertainties of the measurement method. These later tests on well-used rings were also performed at LANL.

These results were documented in a lengthy paper<sup>4</sup> written by this author at the request of DOE. That work was completed late in 1998 and submitted to DOE for peer review and eventual publication. Unfortunately, funds to publish this completed work never became available; and the paper has resided with DOE, receiving no action, ever since. This is unfortunate because the document contains much useful information about the true properties of Raschig rings and dispels some false notions. The unpublished document could justify significant relaxation in both existing limitations within the current national standard. One chapter in this book summarizes those same findings.

## How to Locate Information

The preceding portion of this Introduction addressed *who* might have an interest in this book. The rest of it deals with *where*—other than this book itself—those same readers might find additional information about the Rocky Flats CML. This might include supporting evidence for points made in this book, an even increased depth of descriptive detail of features surrounding an experiment, the raw experimental data for all past experimental programs, the original evidence associated with nuclear incidents at the CML, and, quite possibly, many other kinds of information not anticipated as of this writing.

Raw experimental data may ultimately prove to be the most fundamentally significant component of stored records. As hard as any scientist attempts to publish experimental results free of personal biases and interpretations, some “bending” or

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<sup>4</sup>“Parameter Testing of Borosilicate-Glass Raschig Rings for Nuclear Criticality Safety,” Dr. Robert E Rothe, *et al.* 1998.

“slanting” of the raw data is bound to occur. This author’s philosophy has always been that raw experimental data should be preserved *in perpetuity* as a means of future—and totally independent—interpretation by unbiased researchers. That is a cardinal rule, in his opinion, of good science. The staff at the Rocky Flats CML always strove toward that noble goal. Whether or not it was always met remains speculative.

### ***The LANL Archives***

The bulk of all historic records from the Rocky Flats CML were donated to the national scientific Archives maintained at the Los Alamos National Laboratory (LANL). This donation took place in 1996. Twenty-one boxes (over 2.4 cubic meters) of records were shipped from Rocky Flats to LANL at that time. There, they have been cataloged and stored in acid-free boxes and file folders.

This donation was made at the urging of Dr. E. Dwayne Clayton, longtime Director of the Critical Mass Laboratory near Hanford, Washington. His dedication to the historic preservation of these kinds of records in the face of nation-wide closures of such facilities is gratefully acknowledged. Dr. Clayton lobbied long and hard for some centralized storage of such documents from the handful of laboratories across the nation once performing these unique kinds of delicate measurements. This author happily and willingly concurred with his suggestion. Facilities at Hanford, Washington, and the Brookhaven National Laboratory on Long Island, New York, have, likewise, already contributed to the Archive. Sadly, those at Oak Ridge National Laboratory in Tennessee and the laboratory at Livermore, California, have not.

The contents of the twenty-one boxes had been organized into loosely-related categories prior to shipping. These categories, scribbled on the outside of each box, were:

*Experimenter Training at Rocky Flats*  
*R. E. Rothe’s Course Notes*  
*Initial Construction Records*  
*Early Letters if Interest*  
*Procedure Documents of All Kinds*  
*Leak Test Files*  
*R. E. Rothe Correspondence*  
*Regarding Rocky Flats*  
*Daily Log Books and Calendars*  
*All Maintenance Work Orders*  
*Archive Rocky Flats Records*  
*History of Uranium Solution and Tank Farm*  
*Selected Stripcharts*  
*Accidents/Incidents/Problems*  
*CRAC Data*  
*Laboratory Analyses*  
*Reflected Slab Experiment*  
*Misc. Files and records*  
*Pu Metal Cylinder Experiments*  
*Uranium Solution with Boron-Stainless Steel Plates*  
*Uranium Solution Coupled With Uranium Metal Shells*  
*4.5% Uranium Oxide Studies—Box 1/3*  
*4.5% Uranium Oxide Studies—Box 2/3*  
*4.5% Uranium Oxide Studies—Box 3/3*  
*Misc. Unsorted Records for*  
*Rocky Flats CML—Box 1/3*  
*Misc. Unsorted Records for*  
*Rocky Flats CML—Box 2/3*  
*Misc. Unsorted Records for*  
*Rocky Flats CML—Box 3/3*  
*Tank Records for Tanks #441—#447*  
*Tank Records for Tanks #451 and #452 and*  
*Other Misc. Tanks*  
*Annular Tanks: Nested and Shielded Annular Tanks*  
*R. E. Rothe’s Papers*  
*Nuclear Material Forecasts*  
*Crit Tab. (the meaning of this abbreviation is*  
*unclear now)*  
*ICNC*  
*Slides and Movies*  
*Raschig Rings at Rocky Flats*  
*ANSI/ANS-8.5*

A four-page-long instruction, “How to Use This Archival Record of the Rocky Flats Critical Mass Laboratory” was written to accompany the shipment. All this effort was intended to facilitate assembling a better-organized collection once the truck-load of material arrived at LANL.



The contents of ten “map drawers” also accompanied the boxes. These were mostly “D-sized” drawings (0.86 m x 0.56 m) of Building 886 in general, the CML in particular including details, building equipment, as well as some of the laboratory’s experimental apparatus. They included the oft-used set of pre-construction drawing marked “For Information Only;” they were not truly an “as-built” set of drawings. Some repetition of drawings existed.

All this material was received at the LANL Archives, ably managed by Archivist Roger Meade, in 1996; and it was assigned Accession Number: A-1996-051. The LANL Archive is located right in the city of Los Alamos, several miles from the Pajarito Site where critical mass experiments are still being performed. This collection may be found in the A-Bay in locations 02-H, 03-J, 03-L, 09-05, 09-06, and 11-41. As of 2000, the documents were divided into 59 “boxes;” and each box contained between a few and many “folders”. Thus, to use the archive, one must select information by “Box/File” and then read through its contents until the needed information is found. A compilation of all these boxes and folders is listed on a 19-page-long listing “Inventory Detail Report” which can be obtained free of charge from the LANL Archives. In that listing, each folder carries a somewhat terse “description.” This distribution of documents and their corresponding descriptions were done by Linda Sandoval, Assistant Archivist, during 1996. Either Archivist may be reached by telephone at (505) 667-3809 or by electronic mail at: <rxzm@lanl.gov>. Her descriptions are often quite adequate to help a researcher find sought for information. Sometimes, however, they are helplessly vague. Occasionally, they offer no information at all such as Box/File 18/4: “Miscellaneous Reports.”

The consequence of this quandary is that future researchers may have a more difficult time tracking down information. Perhaps more Folders than necessary would have to be examined to find the needed ones; and some with seemingly applicable headings would prove not useful. Still, looking through Folders is not an onerous chore for the researcher physically present at the Archives. Little effort is involved. Labeling shortcomings, however, become more worrisome for the researcher attempting to use Archive services from afar. Quite possibly, extraneous copies of entire Folders might needlessly be mailed to a distant location to ensure the needed information was received. A better organization of these records would facilitate matters.

A possible resolution of this dilemma has already been suggested. This author proposes to travel to LANL for, possibly, a week’s visit sometime in the early 2000s. He would reexamine all 614 Folders, one at a time, and create a “cross correlation” index. This could be used by any future researcher to locate his/her needs. The index would contain numerous “Topics”—perhaps a few dozen—in which someone might reasonably be interested. Then, the applicable contents of relevant Folders within any Box (and, possibly, individual documents within a Folder) would be listed under the Topic. Under this scheme, the researcher would be told what Boxes and Folders were most likely to contain the sought-for information.

Topics are easily identified. Certainly, each individual experimental program ever conducted at Rocky Flats would be a separate Topic. There were at least 26 individual experimental programs over the CML’s three decades. Other than experiments, many aspects of CML life would become Topics. These could be specific to rooms within the building,

building equipment, operational procedures, governing documents, and a host of other Topics. A very incomplete initial list of other possible Topics is given below:

*Initial Building Construction*  
*The Assembly Room*  
*The Mixing Room*  
*The Storage Vault*  
*The Cold Area of the Building*  
*Horizontal Split Table*  
*Solution Base*  
*Liquid Reflector Apparatus*  
*The Control Console*  
*Raschig Rings*  
*Raschig Ring Standard (ANS-8.5)*  
*Raschig Ring Routine Measurements*  
*Assembly Room Leak Rate*  
*....and many more about hardware*

*Experiments with Plutonium*  
*Experiments with Uranium Solution*  
*Experiments with Uranium Metal*  
*Experiments with Low-Enriched Uranium*  
*Radioactive Sources*  
*Governing Documents Related to Experiments*  
*Documents Related to Material Handling*  
*Emergency Response Plans*  
*Nuclear Material Accountability*  
*Laboratory Purchase Requisitions*  
*Work Orders in General*  
*Experimental Log Books*  
*Experimenter's Proficiency*  
*Examinations*  
*....and many more about experiments*

As just one illustrative example of how this cross correlation, a Topic headed "Raschig Ring Standard (ANS-8.5)" would show the following locations by Box/Folder number and Ms. Sandoval's terse descriptions:

10/2	(ANS-8.5 N-16 votes and schedule)
10/3	(ANSI/ANS-8.5 (1996)
	<i>Development Chronology, 1995–1996)</i>
10/4	(ANSI/ANS-8.5 (1996)
	<i>Development Chronology, 1993–1995)</i>
10/5	(ANSI/ANS-8.5 (1996)
	<i>Development Chronology, 1992–1993)</i>
11/4	(Normal Ketzlach re/ ANSI/ANS-8.5)
11/11	(NS 8.5 Ballots and Comments)
12/4	(ANS-8.5 disk)
12/5	(Resolution of each of 123 comments from N-16, 1995–1996)

Only the Box/Folder numbers would be shown under the Topic heading. Titles of those Folders are included here only because the entire 19-page-long index is not appended to this book.

In anticipation of eventual closure, this author made four lengthy, but not professionally scripted, video tape recordings of himself simply talking about the facility. He wanted to record for posterity the essence of working in a critical mass laboratory<sup>5</sup> because this kind of research may someday fade from the face of the earth altogether. These annotated recordings were made in the Control Room (Room 112) of Building 886. Each tape was about 90 minutes long. One photographically pans the entire Control Console and is accompanied by a verbal description of the purpose and functioning of each instrument. A second reveals some of the unplanned incidents and accidental events that have also been described in better detail elsewhere in this document. These four video tapes reside in the LANL Archives.

The disastrous fire of the summer of 2000 which threatened the city of Los Alamos was also a potential worry with respect to the Archives. After the more important concern of human safety was abated, concern focused on whether or not the fire would engulf the Archives. If it had, not only would Rocky Flats documents have been lost but countless other irreplaceable documents from many locations would have been consumed or badly damaged. Fingers of the fire approached to within a mile of the Archives; but, happily, no holdings were lost.

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<sup>5</sup>The CML had been his only source of employment throughout his entire professional career; and a certain amount of nostalgia might be forgiven.

### ***Another Location***

This author purposefully held back a sizeable number of documents when the large collection was sent to the LANL Archives in 1996. Retained documents amounted to, perhaps, 10% of the initial shipment. These are maintained in an office area within his private home. They were retained for the purpose of aiding his contractual writing of several papers pertaining to past experiments at Rocky Flats. This contract, administered by Mr. J. Blair Briggs of the Idaho National Engineering and Environment Laboratories (INEEL) at Idaho Falls, Idaho, was to write papers concerning previously unpublished (or inadequately published) experiments. Many documents retained at his home were original raw data related to a number of unpublished experiments. Two other boxes contained a complete collection of photographs—accumulated over the lifetime of the laboratory—of the building, the CML, its equipment, and close-up details. These photographs have been used often in the preparation of those INEEL papers and this book. Photographs are cataloged for easy retrieval.

All of these still-retained documents are readily acknowledged to belong to the United States Government; and every one of them will eventually be contributed to the existing collection at LANL—expanding it significantly. This author plans to keep none of the original documents. He plans to keep only one copy of each published journal article published by himself or his colleagues at Rocky Flats. His copies are labeled “Author’s Copy” and contain corrections and comments offered from time to time by others long after publication.

The seven papers published between 1993 and 1998 under the INEEL contract reported either original experimental results not previously published or, in a couple of cases, expanded significantly on incompletely published results. Periodically, as these papers were completed and published by INEEL, the corresponding Rocky Flats documents no longer needed were delivered personally to the Archives. One of these deliveries was made as part of a business trip to Los Alamos wherein many people from several facilities nationwide met to discuss archiving. Another delivery was made in the fall of 1997 enroute to a holiday vacation. As late as 2004, a small number of documents await shipment to the LANL Archives.

After the seven were finished in 1998, one more book-length report was written under the same contract. This book, mentioned earlier, pertained to the physical properties of new as well as well-used borosilicate glass Raschig rings. The book was commissioned by DOE; but the contract was, again, administered by INEEL. This contractual arrangement was an expedient because the subject matter did not strictly fall under the *benchmarking* purview of that contract. The finished manuscript was sent off to DOE, presumably to be published, by late 1998. As stated elsewhere, however, this book, has yet to be published. The current thought is that it may someday be published as an electronic document on the Internet; but even that remains uncertain.

Once work on this Raschig ring document was finished, the INEEL contract lapsed into closure. All experimental work ever performed at the Rocky Flats CML had been published in peer-reviewed open literature. Nothing associated with the laboratory at Rocky Flats remained unpublished. This was a happy conclusion to the building’s eventual demise.

Late in 1998, LANL negotiated a different contract with this author. He was to serve whenever needed as an information source concerning any aspect of the Rocky Flats CML. This technically-useful history of the facility is a product of that contract. Hopefully, the contract can include the cross-correlation index of the archived collection.

Sometime following the initial donation, this author required some documents—already donated to LANL—for other work. This proved no problem at all; and Mr. Meade’s gracious cooperation is gratefully acknowledged. These documents, too, are retained in the author’s home office and will be returned to LANL shortly after the publication of this history.

One other important document should be acknowledged. In 1972 (still early in the history of the facility), a very terse and factual chronology of experiments performed to date at the Rocky Flats CML was outlined. The short paper was titled: “*A Summary of Experiments at the Nuclear Safety Facility.*” It proved to be more a *catalog* of experimental topics than any useful reporting of data. In fact, it contained no data whatsoever. Its purpose was to keep track of who had led what experiment, when it had been performed, where the raw data could be found, and where the results were published. The simple document was updated in 1977, 1990, and, finally, in 1993. The last version was expanded to include the initial shutdown activities written in the same terse format. Written by this author, this summary has never been published although informal copies of it have been distributed to a few persons. The only known copy of the final version of this paper is in the hands of this author. This history document is, in part, a direct expansion of that simple paper.

## ***History of the Rocky Flats Site***

Rocky Flats was conceived in the tension between the Soviet Union and the United States as an aftermath of World War II. The nuclear industry was still new. Nations were not certain what to do with this new-found capability nor was that capability fully understood. Uncertainty led to distrust which, in turn, led to secrecy and suspicion. Relations between nations deteriorated and each adopted a posture of a very uncertain “peace.” Rocky Flats was born out of that “Cold War” which escalated quickly and only recently (1989) entered remission among the nations of the world.

Nuclear fission had been first discovered—actually quite by accident<sup>6</sup>—in the late 1930s. Months later, Enrico Fermi and Niels Bohr observed that several neutrons were released at the expense of the one causing a fission; and this prompted speculation that a self-sustained nuclear “chain reaction” might, indeed, be a possibility. Albert Einstein recognized implications of this finding and advised the President of the United States that a quite powerful weapon of destruction could be fabricated using this new phenomenon. He further

advised the United States to proceed with caution and adopt a measure of secrecy because of certain activities undertaken by Nazi Germany. The fear was that Adolph Hitler was racing toward development of the same kind of weapon. The text of this historic letter is presented on the next page.

This hypothesized “chain reaction” might perpetuate itself indefinitely; and the accumulated energy derived from successive fissions might well be put to some use. Fermi and his collaborators verified this conjecture at the University of Chicago in 1942. The first nuclear reactor, called Chicago Pile Number 1 (CP-1), was a huge assembly of uranium oxide and graphite. The entire nuclear criticality industry was born one Friday afternoon at 3:25 PM on December 2<sup>nd</sup>, 1942.

The wisdom of Einstein’s letter coupled with the success of CP-1 and the growing world-wide tensions which had caused the United States to enter World War II prompted the development of the secretive “Manhattan Project.” Much of the development of this new weapon, called an atomic bomb, took place at the present-day Los Alamos National Laboratory in northern New Mexico. The entire situation was exacerbated by the discovery, in 1941, of the transuranic element plutonium which was destined to become the primary fissionable material used in weapons. Interestingly, the two German scientists mentioned in a footnote would have discovered plutonium<sup>7</sup> during their experiment except

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<sup>6</sup>Two German scientists named Hahn and Strassman were determined to win a Nobel Prize. They planned to bombard the natural element with the highest then-known atomic number (uranium) with neutrons expecting the beta decay process to produce the first-ever man-made element—surely, an event worthy of that distinction! Instead, they observed lighter elements from the middle of the Periodic Chart which had not been present previously. A short time later, the great Enrico Fermi correctly recognized that they had discovered nuclear fission.

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<sup>7</sup>The decay process following neutron bombardment of uranium actually leads to two successive beta decays producing first Neptunium, then Plutonium.

Albert Einstein  
Old Grove Rd.  
Nassau Point  
Peconic, Long Island

August 2nd, 1939

F. D. Roosevelt,  
President of the United States,  
White House  
Washington, D.C.

Sir:

Some recent work by E. Fermi and L. Szilard, which has been communicated to me in manuscript, leads me to expect that the element uranium may be turned into a new and important source of energy in the immediate future. Certain aspects of the situation which has arisen seem to call for watchfulness and, if necessary, quick action on the part of the Administration. I believe therefore that it is my duty to bring to your attention the following facts and recommendations:

In the course of the last four months it has been made probable—through the work of Joliot in France as well as Fermi and Szilard in America—that it may become possible to set up a nuclear chain reaction in a large mass of uranium, by which vast amounts of power and large quantities of new radium-like elements would be generated. Now it appears almost certain that this could be achieved in the immediate future.

This new phenomenon would also lead to the construction of bombs, and it is conceivable—through much less certain—that extremely powerful bombs of a new type may thus be constructed. A single bomb of this type, carried by boat and exploded in a port, might very well destroy the whole port together with some of the surrounding territory. However, such bombs might very well prove to be too heavy for transportation by air.

The United States has only very poor ores of uranium in moderate quantities. There is some good ore in Canada and the former Czechoslovakia, while the most important source of uranium is Belgian Congo.

In view of this situation you may think it desirable to have some permanent contact maintained between the Administration and the group of physicists working on chain reactions in America. One possible way of achieving this might be for you to entrust with this task a person who has your confidence and who could perhaps serve in an unofficial capacity. His task might comprise the following:

a) to approach Government Departments, keep them informed of the further development, and put forward recommendations for Government action, giving particular attention to the problem of securing a supply of uranium ore for the United States;

b) to speed up the experimental work, which is at present being carried on within the limits of the budgets of University laboratories, by providing funds, if such funds be required, through his contacts with private persons who are willing to make contributions for this cause, and perhaps also by obtaining the co-operation of industrial laboratories which have the necessary equipment.

I understand that Germany has actually stopped the sale of uranium from the Czechoslovakian mines which she has taken over. That she should have taken such early action might perhaps be understood on the ground that the son of the German Under-Secretary of State, von Weizsäcker, is attached to the Kaiser-Wilhelm-Institut in Berlin where some of the American work on uranium is now being repeated.

Yours very truly,  
(Albert Einstein)

for the confusing interspersing of other radioactive nuclides from the nuclear fission process.

The result of all this intrigue was the development of an atomic bomb by the United States. Two such devices were dropped in hostile action on the country of Japan in the summer of 1945. These were the first—and, fortunately, only—uses of such weapons in the history of mankind. Debate continues even today as to the morality of such an action taken by the United States. Many lives were saved; but the cost to the Japanese people was enormous. Use of these weapons clearly signaled the closure of World War II; but the stage was set for tension, mistrust, and suspicion among world powers at that time.

In response to this political stature, the United States Atomic Energy Commission (AEC) initiated construction of facilities around the country to contribute to the production of such weapons. These facilities joined Los Alamos in that united national front. Nuclear reactors at Hanford, Washington, went on-line to produce plutonium while others at the new Savannah River site in South Carolina produced tritium—another important component of nuclear devices. Oak Ridge National Laboratory (ORNL) in Tennessee expanded by three new facilities including one for the enrichment of the fissile isotope of uranium from the abundance found in nature. Natural uranium contains only 0.7% of the fissile isotope,  $^{235}\text{U}$ ; and ORNL enriched this to a little over 93%. This enriched uranium became known as “Oralloy” which stood for “Oak Ridge alloy.” The Commission also constructed auxiliary facilities at a number of locations throughout the United States to support these operations. By 1952, about 150,000 workers were engaged in nuclear weapons-related activities nation wide.

One of these new facilities was the Rocky Flats Plant near Denver, Colorado. It was warmly welcomed by the press and public alike. The March 23, 1951, issue of the Denver Post, a popular Denver newspaper, boasted a proud headline:

*“There’s Good News Today. U.S. to build \$45 million A-Plant Near Denver.”*

The article went on to explain that 1,000 people would be employed on a permanent basis.

Rocky Flats is situated several miles northwest of Denver, Colorado, and about equidistant between Golden and Boulder, two other Colorado cities. The picturesque site selected is shown in an aerial view taken in 1969 in Fig. 1. The plant was built within a portion of a few thousand acres of tall native grasslands, a naturally occurring wildlife habitat found rarely throughout the United States. Fortunately, the plant’s existence, including its buffer zone, for half a century has preserved that rare habitat against the onslaught of growth and development. Construction of the new site began in 1951 and lasted two years. Although owned by the government and administered at that time by the Atomic Energy Commission, it was operated by the Dow Chemical Company from the private sector. The first Plant Manager was F. H. “Heinie” Langell.

Governmental administration changed from time to time during the next half century. The Atomic Energy Commission (AEC) gave way to the Energy Research and Development Administration (ERDA) in 1975. That administration was short lived because the Department of Energy (DOE) assumed this role October 1, 1977. Their oversight continues to this day.



*Fig. 1. An aerial view of the Rocky Flats Plant Site taken in June of 1969 shows the 5-year-old Building 86, now called Building 886, within the circle.*

Not only did the government's administration of the plant change; but so did the prime contractor operating the plant. The Dow Chemical Company released control to Rockwell International on July 1, 1975. They, in turn, yielded to EG&G the first day of 1990. Kaiser-Hill assumed control of Rocky Flats on July 1, 1995; and they still operate the plant to this day. Interestingly, Kaiser-Hill introduced a new format of plant management. Four satellite companies were brought in to operate specific aspects of the plant under the Kaiser-Hill umbrella. About 100 "Third Tier" companies function at the site beneath these four.

This author finds ironic the fact that he worked three decades at the same job and

in the same building while the company he worked for changed four times and three different government agencies oversaw operations. More commonly in society, workers move from job to job every few years in order to attain professional growth.

The name of the facility, itself, suffered only one change during that half century. In the 1990s, when the company's role in the nuclear weapons industry was clearly seen to transition away from production toward deactivation and decommissioning, the name was changed from the Rocky Flats Plant (RFP) to the Rocky Flats Environmental Technology Site (RFETS). This new name reflected the new direction and was more politically palatable. Throughout the nuclear criticality safety arena of



professionals, however, the site was usually referred to simply as “Rocky.”

A 29-page-long summary of the manufacturing history of the Rocky Flats Plant was written by Ms. Jayne Aaron in the 1990s as part of an “Historic American Engineering Record” effort sponsored by the United States Government. The document had not been reviewed for factual accuracy before it was published. Understandably, it contains a few minor inaccuracies; but it does provide a good general background of activities undertaken at the Rocky Flats site over its entire lifetime. The text (only) of this interesting report is included as an Appendix to this chapter. Several dozen thumbnail pictures and some other pages of ancillary material have been omitted. The remaining text contains a few references to an “HAER” document; and this is part of what has been omitted.

One other significant change occurred at Rocky Flats during that illustrious lifetime. Upon completion of initial construction (1953), the site began routine operations on *two* fissile materials. Some buildings dealt with plutonium components while others were involved in processing enriched uranium. This included production of new components as well as the reclamation of used weapons for recycle. Sometime in the mid-1960s, the AEC decided to separate functions. Uranium capabilities were transferred to the Oak Ridge National Laboratory while plutonium processing was retained at Rocky Flats.

Public popularity of Rocky Flats varied significantly during the facility’s lifetime. Denver area newspapers happily welcomed the new plant in 1953 as cited above. The state had captured a highly sought-after “plum” funded by the federal government. The fact that the new industrial site would bring many jobs to the Mile-High city was lauded. No hint of any public animosity

was contained in these welcoming tributes. The site was considered to be so far removed from the still-small city of Denver, Colorado, that its presence hardly mattered. After all, the road from Boulder, where many workers lived, was little more than a rock-strewn mountain dirt road. Even the amenities of human habitation were rustic at the plant. A steam-powered locomotive, obtained from some railroad, provided steam heat to warm this fledgling workplace.

Public opinion about the plant began to change in the late 1960s. A major fire<sup>8</sup> occurred on Sunday, May 11, 1969. Some say this was the nation’s worst industrial fire in its history. This fire in Buildings 776/777 aggravated public fears and rattled sensitivities of a public still of a mind set to demonstrate against the Vietnam War. This, coupled with public siding with the union in a bitter strike in 1970, began to turn the tide against the plant. People wondered if all that secrecy was really necessary or merely a means to keep a curious public at bay. Possibly as a ploy to assuage those fears, an open house was held for the first time in the plant’s (then) 19-year history. Families were invited to see the facilities during “Rocky Flats Family Day” in May of 1970. A similar open house occurred again in August of 1972. Anti-nuclear and pro-environmental demonstrations began to happen in spite of these positive efforts by management. One group even constructed a Native American style teepee over the railroad tracks leading into the plant. Two Catholic nuns attempted, in 1982, to expose security weaknesses by gaining unauthorized access to the plant using fake “badges” they had constructed.

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<sup>8</sup>An aspect of this fire of personal significance to this author is reported in another section of this paper.

<sup>4</sup>Humorously, one plant representative was given a bottle of *Blue Nun*, a popular table wine, at a Christmas party later that year as a joking reminder of this event.

They hoped to be waved past the outermost security perimeter;<sup>4</sup> but they did not get very far. One year later (1983), a public demonstration against Rocky Flats set a goal of surrounding the entire plant—including its buffer zone—with concerned citizens linking hands. Although the goal was not met, newspapers gleefully reported the event. Namecalling fueled the controversy as politicians in high places referred to workers at Rocky Flats as “murderers.” This ugly mood became routine press.

More public dissent grew in the 1970s. The Director of the Jefferson County Health Department published claims linking plutonium soil contamination at the plant to cancer and infant mortality. Some blamed the plant for an albino deer seen within the buffer zone. A nearby rancher claimed one of his livestock was born deformed because of proximity to Rocky Flats. Well-known activists such as Allen Ginsberg and Daniel Ellsberg often entered into the ongoing debate. Peace activists were as certain of the immorality of Rocky Flats as its workers were convinced of their role in preventing nuclear war. The 1970s and 1980s were rough decades for the plant politically.

Attacks against the plant grew more formal and political. This increased greatly when new laws placed government facilities under the same regulations as the private sector. The United States Environmental Protection Agency (EPA) entered the fray as they administered the Resource, Conservation, and Recovery Act (RCRA) of 1976. The public was concerned over the plant’s disposal and handling of hazardous wastes. The EPA brought in the Federal Bureau of Investigation (FBI) to determine whether or not the plant had broken any environmental laws. The plant was also falsely accused of illegally using its incinerator, designed for the reduction

of contaminated combustible waste, during a mandated shutdown in 1988. That “problem,” detected by thermal imaging, proved to be merely the plant’s laundry in operation.

Plutonium operations at the Rocky Flats Plant were “curtailed” in 1989. A report to Congress in January of that year acknowledged three significant areas of concern: (1) The plant was aging. (2) Public discontent was prevalent. (3) Waste storage and other operations were increasing problems. In spite of some last-ditch efforts aimed at “resumption” and the adoption of a rigorous “Conduct of Operations” policy (which relied heavily on following written procedures), most people recognized that the plant was doomed.

A few world wide events exacerbated the situation. Both the Soviet and United States governments were moving toward major reductions in nuclear arms; and Congress was greatly reducing its budget for a nuclear arsenal. Nuclear weapons are very expensive. The fall of the Berlin Wall (1989), the breakup of the old Soviet Union (1991), and joint Russian/American ventures in space seemed to lessen the threat of hostilities between these two powers. A spirit of “friendly cooperation” pervaded international relations. President Bush canceled several nuclear programs in 1991 and 1992; and the Secretary of Energy officially announced that the mission of Rocky Flats would change from weapons production to decommissioning, decontamination, and demolition. The land would eventually be opened up for new uses.

An optimistic timetable for this conversion has been set for the year 2006. A more realistic view may extend that date a little; but the end result is a committed certainty. The plantsite *will* be cleaned up. The final degree of decontamination of the earth, however, still remains a question. One way to express that question is to ask “How clean is clean?” Others have asserted

“One will never be able to build a children’s preschool on this land.” Ultimately, the exact final condition of these lands must remain for future generations to witness.

Interestingly, the Rocky Flats nuclear weapons facility was not the first man-made industrial venture to span the plantsite. About a century earlier, a Colorado railroad entrepreneur named David Haliday Moffat envisaged a transcontinental railroad whose route would pass through the heart of the site. Grandiose dreams coupled the Atlantic and Pacific Oceans via Moffat’s lofty conception: the Denver, Utah and Pacific Railroad Company. The grade was carved out of earth northwest from Denver and threaded the present site in a westerly direction before turning, again, to a northwest line. It would climb Eldorado Springs Canyon, hoping to pierce the Continental Divide some 25 miles west of Denver. A long tunnel, difficult to construct during short seasons at these elevations, would be required. Four routes were proposed but no tunnel ever built. His transcontinental dream died in infancy with never a length of rail laid on the completed roadbed crossing the Rocky Flats site. Still, even today, aerial photographs show the abandoned grade both east and west of the present plant quite clearly. A cut through a hilly knoll to the east is a clearly visible reminder of the tenacity of man’s ability to dream.

A few years later (beginning in 1904), David Moffat did succeed in building his transcontinental railroad. The Denver and Salt Lake Railroad followed a slightly different path northwest from Denver and up the same canyon; but it bypassed the Rocky Flats site. The D&SL suffered winter conditions at high elevations before the still-in-service Moffat Tunnel was built between 1923 and 1927.

## **APPENDIX**

### **MANUFACTURING HISTORY**

**by Jayne Aaron**

#### ***Plutonium Operations***

Plutonium is a man-made transuranic metallic chemical element, it is not known to exist in nature. Plutonium, first discovered in 1941, is created from naturally occurring uranium that has been bombarded by neutrons in a production reactor. A complex chemical process is required to separate the newly created plutonium from the remaining uranium. The importance of plutonium to atomic weaponry is its highly fissile nature; it can undergo a fission reaction (which provides the force in a nuclear bomb) much more easily than uranium. However, due to its highly fissile nature, plutonium also has a higher potential of undergoing a spontaneous, uncontrolled fission reaction, also referred to as a criticality event. Plutonium occurs in two isotopes, plutonium-238 and plutonium-239. The plutonium-239 isotope is more highly fissile than the plutonium-238 isotope (Colliers Encyclopedia CD ROM, 1996).

The key to an atomic weapon is the use of fissile material. Plutonium was used to create the first-stage fission reaction (the trigger) which set off the second-stage reaction (the nuclear explosion). Plutonium is made in plutonium production reactors at Hanford and the Savannah River sites. The fissile product from the reactors was processed through chemical separation plants to segregate the plutonium and uranium from other radioactive isotopes. Most of the plutonium from these plants went to Rocky Flats to be manufactured into weapons components. It was usually in the form of metal, but liquid and powdered plutonium was also produced. One of the reasons for the mystique of Rocky Flats was the use and alteration of raw materials to finished material. Unlike other areas, all of the manufacturing, technology, people, and skills needed to convert the raw materials into completed products was conducted at the Plant.

#### ***Recovery***

The original plutonium recovery process was adapted from Los Alamos National Laboratory processes (Crissler, 1998 interview). The process was put into operation in May 1953 with the first shipment of plutonium nitrate solution from the Hanford Plant in Richland, Washington. Several years later, the Rocky Flats Plant also started receiving plutonium nitrate feed from the Oak Ridge Reservation. All of these shipments were discontinued in 1959. Since that time, internally generated plutonium residues from Plant operations were the primary feed for the recovery/metal production. Residues normally were solid materials varying in plutonium content from a few percent to almost pure plutonium metal.

The primary objective of the plutonium recovery process was the recovery of plutonium from all residues generated during plutonium-related fabrication, assembly, and research operations. The overall recovery process consisted of fifteen major operational

unit processes including incineration, cation exchange, dissolution, anion exchange, batching and evaporation, precipitation, calcination, hydrofluorination, thermal reduction, leaching, or alloy leaching, chloride dissolution/chloride anion exchange/dicesium hexachloroplutonate production, molten salt extraction, salt scrub, and electrorefining.

All incoming plutonium (either foundry-generated oxide or associated with production wastes) was dissolved in nitric acid solutions. Feed material was one of two types: a high-level material (plutonium oxide and impure metal) obtained from foundry casting operations, or low-level materials (residues produced in the recovery/manufacturing process).

The overall process and chemistry of plutonium recovery remained largely unchanged since recovery operations began. Prior to 1965, plutonium recovery operations were originally conducted in batch fashion that consisted of simple, manually operated equipment. At that time, batch operations were sufficient because the limited plutonium casting and machining operations generated little scrap. Similarly, site returns (retired or out-of-specification nuclear weapons or nuclear weapons components) were minimal.

To begin the recovery process, a mixture of nitric acid and plutonium residues was heated and agitated in a beaker inside a glovebox, to dissolve the plutonium into a nitric acid solution. In addition to being very labor intensive, the beaker method released fumes that corroded the electric heaters and caused problems for the glove box handling and filtration system. To improve dissolution, the beakers were replaced in 1965 with a system of continuous, cascade dissolvers. Continuously operating and automatic Control systems were later introduced to increase the recovery capacity of the facility and to decrease radiation exposure of operating personnel.

During the continuous cascade process, steam coils were immersed in the liquid nitric acid solution. The resulting slurry overflowed from the first through the last dissolver in the set. From the last dissolver, the slurry overflowed to a horizontal-pan vacuum filter, which separated the undissolved solids from the solution. The plutonium solution then went to ion exchange process. Solids were scraped from the filter, dried on a hot plate, and packaged for removal from the glove box for treatment and disposal.

After the plutonium was dissolved, the other elemental impurities were separated out of the solution. The plutonium feed was purified by solvent extraction, later replaced by the anion exchange process. The plutonium nitrate solutions were pumped through glass columns, containing anion exchange resin. The anion exchange process purified and concentrated plutonium-bearing nitric acid solutions to make them acceptable as feed for conversion to metal. The solution was concentrated in a steam-heated, natural-convection evaporator. The concentrated solution, called bottoms, was transferred to tanks.

Relatively pure plutonium nitrate solutions received from oxide dissolution, anion exchange, and feed evaporation were blended and adjusted to the proper pH and plutonium concentration before entering the peroxide precipitation process. Feed for the peroxide precipitation process was prepared in batches by blending the available solutions in the proper ratios.

The peroxide precipitation process converted the plutonium in solution to a solid form and achieved some purification of the plutonium from metallic elements, notably americium. The feed solution was pumped into a refrigerated, stirred reactor called a digester. Hydrogen peroxide solution was fed into the digester. Precipitation occurred in the digester

and crystal growth occurred. The plutonium peroxide slurry cascaded through the digestors and into the rotary drum filter basin. Vacuum applied to the filter removed the liquid, causing the plutonium peroxide to collect on the filter surface. The plutonium peroxide cake collected on the rotary drum was cut off the filter wheel, collected in containers, and transferred to the calciner.

The calcination process converted plutonium peroxide to plutonium oxide and drove out residual water and nitric acid, leaving a dry, powdered product. The dried cake was collected, screened, and weighed in batches. Every third batch was sampled and analyzed for impurities for process control. Batches were stored in approved containers in racks in the glove box while awaiting hydrofluorination.

Plutonium oxide was converted to plutonium tetrafluoride in a continuous rotary-tube hydrofluorinator. The plutonium tetrafluoride product was collected, weighed, and transferred in batches to the reduction process. The hydrofluorination process produced high neutron radiation, which emanated from plutonium tetrafluoride.

Plutonium tetrafluoride produced by the hydrofluorination process was reduced in batches to plutonium metal by interaction with calcium metal in an induction-heated reduction vessel. The vessel was heated until the reduction reaction took place, producing plutonium metal and slag. The resulting plutonium metal button was separated from the crucible, sand, and calcium fluoride slag. It was cleaned, sampled, and packaged for storage until the analysis was complete, and the button was sent to fabrication.

### *Fabrication*

At Rocky Flats, plutonium buttons from the plutonium recovery process were first cast into ingots. The casting operation created feed ingots and War Reserve ingots of plutonium metal. The first casting process created the feed ingot. Materials used for the creation of feed ingots included plutonium buttons from recovery processes, briquettes, and scrap plutonium metal. Production control personnel used sampling data to calculate the precise feed ingot mixture which would produce a War Reserve ingot of specific purity from the second casting. The casting process consisted of weighing the metal, placing it in tantalum crucibles, and melting it in one of four electric induction furnaces. Molten metal was poured into molds to form ingots. The War Reserve ingot was used to fabricate weapons components. Samples were taken to verify the chemical makeup and purity of both the War Reserve ingot and the fabricated component.

Plutonium War Reserve ingots were rolled, formed, and heat-treated, and then were cut in a blanking press. Cut blanks were sent to thermal treatment (annealing and homogenizing). Following thermal treatment, blanks were formed into hemi-shells (1/2 shells) in a hydroform press. After forming, the parts were annealed and measured on a density balance.

The hemi-shells went to final machining involving lathes, mills, a drill box, a high-precision drill press, and a hydraulic press. Each part was then marked with a serial number, cleaned, weighed, and inspected. Plutonium parts were welded, then inspected for leaks. Parts were assembled into subassemblies, then into assemblies, and then assembled into triggers. Assembly included such operations as machining, cleaning, matching parts, brazing, welding, heating under vacuum for trace contaminant removal, marking,

weighing, monitoring for surface contamination, and packaging for shipment. The assembled triggers and parts were subjected to final processing steps, final testing, and inspection, then stored to await shipment.

### ***Depleted Uranium Operations***

Naturally occurring uranium ore consists of approximately 1% uranium. That uranium is composed of three isotopes: U-238 (99.28%), U-235 (0.71%), and U-234 (0.01%). Depleted uranium results when the more highly fissile isotope U-235 is isolated using a complex chemical separation process. After removal of the U-235, the resultant material is referred to as “depleted” in that isotope. Depleted uranium consists almost exclusively (99.8%) of the U-238 isotope, which, although it has low radioactivity, is not considered to be very fissile (i.e. able to undergo a fission reaction). U-238 is a very dense, very hard, heavy metal, and shares the toxic properties of other heavy metals when ingested, inhaled, or injected.

Depleted uranium was used as a non-fissile component in the trigger design. Uranium, nearly twice as dense as lead, was also machined at the Plant into sheets used as in military tank armor, using its hardness to provide additional protection from artillery shell penetration. From 1951 until 1955, depleted uranium was shipped to Rocky Flats as derby-shaped parts from Paducah, Kentucky and later as ingots from the Feed Materials Production Center in Fernald, Ohio.

Uranium was cast in the foundry into near-net shapes (close to the final product form) and then sent to machining. Induction-cast depleted uranium, arc-cast depleted uranium, depleted uranium alloy ingots, beryllium ingots, and aluminum shapes were produced in the foundry. The metals were placed in crucibles, loaded into one of eight induction furnaces, and melted in a vacuum atmosphere. Induction casting used radio frequency energy to melt the metal, which was poured into graphite molds to form ingots.

Metal parts containing depleted uranium, depleted uranium alloy, and depleted uranium with traces of iron, silica, titanium, aluminum, or stainless steel were cut in the depleted uranium machining process. Machining operations included turning, facing, boring, milling, and sawing.

After 1956, the uranium ingots were processed into rolling pucks, then rolled and formed, and final machined. The depleted uranium ingots or billets were hot rolled and formed into parts or combined with niobium to form binary metal. Virgin depleted uranium ingots were weighed, immersed in a salt bath, rolled into a sheet and sheared to length. The sheets were annealed in a second salt bath, cooled, and cleaned in water. The sheets were sheared a second time and trimmed to final length into electrode strips. The electrode strips were bent, cleaned in acid, and welded in a box configuration. Electrode filler strips were rolled, punched for bolt holes, and cleaned in acid. Final assembly operations were conducted in Building 991, 777, or 707, depending on the time frame.

Recycled depleted uranium ingots were weighed, cropped, re-weighed, and heated in a salt bath. The ingots were rolled and sheared to length; the sheets were annealed, cooled, and cleaned in water. They were then sheared, cut into discs, heated, and formed into parts. A second forming, called a re-strike, was done to insure proper size.

Depleted uranium recovery operations were not conducted at the Plant.

### ***Enriched Uranium Operations***

Enriched uranium is valued for its fissile nature (i.e. its ability to undergo a fission reaction), and is a primary ingredient in nuclear weapons and nuclear power reactors. It is created from naturally occurring uranium, which consists of three isotopes: U-238 (99.28%), U-235 (0.71%), and U-234 (0.01%). Using a complicated chemical separation process the U-235 isotope is isolated and the concentration is raised to more than 90% (from an original concentration of 0.71%). The resultant enriched uranium is highly fissile.

Enriched uranium was one of the materials used to create the first-stage fission reaction. It was possible to make nuclear weapons either by using plutonium or uranium. The “Little Boy” bomb dropped on Hiroshima was a uranium-type bomb, although most modern atomic weapons used both plutonium and uranium.

### ***Fabrication***

The original trigger design required a large amount of enriched uranium. The primary operations at the Plant included fabrication support, which included the foundry for casting of shapes and ingots; machining and inspection; metal product support, which included recovery of relatively pure materials; and salvage support, which handled recovery of solutions and solid residues with relatively low enriched uranium content.

Processes used at the Plant were based upon those developed at the Los Alamos Scientific Laboratory and the Oak Ridge Reservation, during and after World War II. The processes were refined at the Oak Ridge Reservation Y-12 Plant in the several years preceding the construction of the Rocky Flats Plant although many improvements to the process and equipment were made by Plant personnel.

For the first months of operations, uranium castings were received from the Oak Ridge Reservation in the form of hockey-puck-sized buttons. Once recovery operations were established, uranium buttons produced at Rocky Flats were added to the feed material. In the casting process, uranium metal was placed in a crucible, heated in bottom-pouring induction furnaces, and then poured into graphite molds. Machining operations, including rolling and forming, and computer controlled turnings took place in Building 883 or the 881 Annex.

In 1964, enriched uranium operations at the Plant began phasing out with the advent of the Atomic Energy Commission’s single mission policy. Production of enriched uranium components ceased at the Rocky Flats Plant in 1967, when the Y-12 Plant at the Oak Ridge Reservation assumed sole responsibility. From 1964 to 1966, plutonium production became the focus of operations at the Plant.

### ***Recovery***

Enriched uranium recovery operations were initiated shortly after fabrication operations began. Several different recovery operations were used, depending on the type of initial material. Uranium recovery involved both slow and fast processes. The slow process involved placing relatively impure materials with low concentrations of uranium into nitric acid for leaching and solvent extraction. Impure materials such as slag, sand, crucibles from the foundry operations, and residues from the incinerator were reduced via the slow



process. The materials were crushed into pea-sized feed in a rod mill and placed in various dissolving tanks containing nitric acid. Solutions from the dissolution filters were concentrated in three-story-high solvent extraction columns. The solution was then pumped into various evaporators for further processing.

The fast process handled materials that were relatively pure, including uranyl nitrate, and used conversion and reduction steps to produce a pure uranium button. Materials such as chips from machining operations and black skull oxide contained fairly high percentages of enriched uranium that were easy to convert into pure uranium buttons. Chips and skull oxides were burned to form uranium oxide and then transferred for dissolution in small batches of concentrated nitric acid. The dissolution room housed three rows of controlled hoods known as B-boxes (similar to laboratory hoods). These boxes operated with high air velocities at their openings to ensure that the vapors were contained within the hood. The dissolution process yielded a uranyl nitrate solution, from which uranium peroxide was precipitated. Once filtered, the precipitate formed a yellow cake, which was heated to produce an orange uranium oxide. The dissolution, precipitation, and calcination processes were originally performed as batch processes. By the late 1950s to early 1960s, the process became a continuous operation. The orange oxides were converted to uranium tetrafluoride, a green salt. The green salts were transferred for final reduction to uranium metal.

### ***Beryllium Operations***

Beryllium is an alkaline metallic chemical element. Elemental beryllium is a light, steel gray metal; it is very hard and very brittle. Pure beryllium at high temperatures is very ductile, and can be rolled into sheets. The primary use for beryllium in the nuclear weapons program is as a neutron moderator or reflector. It emits neutrons when bombarded by alpha particles. Another use of beryllium is as an alloying agent, where it imparts a highly tensile strength.

Rocky Flats began production scale operations in 1958, with the newer trigger design. Beryllium was used as a neutron reflector in the trigger design. At room temperatures the material was extremely brittle and required unique handling techniques.

Production operations initially involved only the machining, final inspection, and assembly of beryllium parts which were supplied by an off site vendor. By the mid-1960s, Rocky Flats beryllium operations also included the casting and shaping of beryllium parts to the proper dimensions. By 1957, foundry casting of beryllium on the Plant site had ceased with beryllium supplied in the form of blanks from an off site contractor. Machining of beryllium parts continued in Building 444 until production shut down in the late 1980s.

The “wrought” beryllium process was developed in approximately 1962 through research and development work at Rocky Flats and other USDOE facilities. This process involved casting beryllium ingots, sawing the ingots, “canning” (encasing) them in stainless steel, rolling them into sheets, and cutting the cans away. The beryllium ingots were very brittle, and in order to roll them they had to be encased in stainless steel and heated to a temperature ranging from 900 to 1,000 degrees centigrade. After the stainless steel can was removed, the beryllium sheet was then cut into shapes.

Beryllium machining processes involved sawing, milling, drilling, and lathe operations followed by polishing and abrading operations. Site returns (retired weapons) and components containing beryllium were also returned to the machining area for dismantling. During the Plant's operations, machining has included work on beryllium casings, wrought processing, sintered forms, and bar stock.

Other than the recycling of parts from site returns (retired weapons), beryllium recovery operations were not conducted on the Plant site. Some beryllium-related waste management activities were conducted in Building 447.

### ***Stainless Steel Operations***

Stainless steel is created from an alloy of steel with chromium to create a durable material highly resistant to oxidation. With the nuclear weapons production program, stainless steel had many uses. One of the primary uses for stainless steel at the Rocky Flats Plant was the manufacture of the tritium reservoir, and tritium delivery system components. Tritium was used to aid in the second stage fusion reaction of the later weapon designs.

When enriched uranium operations were phased out at Rocky Flats in the mid-1960s, factors including favorable economics and considerable floor space in Building 881, led to the decision to begin stainless steel machining. The phase-in of stainless steel machining work began in Building 881 in 1966. All stainless steel work on the Plant site was done in that building by 1968. In 1967, Dow, the site contractor at the time, acquired the J-line (code name) stainless steel activities. Stainless steel machining work was previously conducted by American Car and Foundry Industries, located in Albuquerque, New Mexico. Stainless steel work was conducted in Building 881 from 1968 to 1984. In 1984, machining was moved to Building 460, a facility specifically designed for stainless steel machining operations.

Stainless steel casting, forging, or recovery operations were not conducted on a production scale at the Plant. Stainless steel was used primarily to make the reservoirs that held tritium gas within the bomb. Other stainless steel work included fabrication of the tubes and fasteners associated with the tritium reservoir-to-trigger delivery system.

Production operations included machining, assembling, inspection and testing, and support. Depending on technical requirements, methods, and/or equipment needed, the sequence of operations was altered to meet specific project needs. Conventional tools, such as lathes, mills, borers, and presses were used in machining operations. The machined parts were cleaned and inspected prior to being sent to the assembly area. Assembly operations included cleaning, matching, brazing, welding, inspection, testing, and packaging. The parts were then assembled and joined by brazing or welding. Although stainless steel recovery operations were not conducted at the Plant, scraps and turnings were generally collected for resale to an off site recycler.

### ***Assembly Operations***

Plutonium, enriched uranium, depleted uranium, beryllium, and stainless steel components fabricated on site, along with components manufactured from Hanford and Oak Ridge, were assembled into final products, inspected, tested, and placed back in storage prior to off site shipment. Because all of the radioactive components were coated in nickel or encased in plastic, assembly of the early concept design products was conducted in open rooms, not in enclosed glove boxes.

In 1957, production began on a new weapon design, requiring changes in the amount of materials used in the trigger, the amount of machining and handling required, and the need for tighter tolerances. Because of the new design, final trigger assembly took place in the newly constructed Building 776/777. Assembly of older uranium-based weapons continued in Building 991 until the 1960s. A limited number of plutonium-based triggers were also thought to have been assembled in Building 991 during the early 1960s.

### **Major Material Processing Buildings**

#### ***Depleted Uranium and Beryllium - Building 44/444 (Plant A)***

Building 444 was one of the first buildings constructed at Rocky Flats. Beginning in 1953, depleted uranium was both cast and machined in this building. The original building contained the foundry, depleted uranium machine shop, beryllium machine shop, heat treating shop, plating laboratory, carbon machine shop, casting shop, tool grinding shop, welding and brazing shop, pressure and leak testing laboratories, precision measuring laboratories, building maintenance shop, and parts of the precision shop and non-destructive testing laboratory. Some of the former production areas were later used for storage of excess tools and materials.

From 1952 until the end of production, beryllium and depleted uranium casting, machining, cleaning and inspection equipment were housed in Building 444. Depleted uranium was cast into near-net (close to final product) shape in the foundry and then sent to the machine shop. Prior to the construction of Building 883, casting and final machining took place in Building 444. After 1956, the uranium and beryllium ingots were processed into rolling pucks and shipped to Building 883 (Side A) for rolling and forming.

#### ***Enriched Uranium, Non-Plutonium Metals/Alloys (Beryllium and Stainless Steel) - Buildings 81/881, 883, 865, and 460***

Building 881 was one of the four original manufacturing buildings that comprised the Rocky Flats Plant in the early 1950s and was the fourth building to come on line. Beginning in 1953, this structure housed the Plant's only enriched uranium component manufacturing and recovery operations. The original purpose of Building 881 was the processing and machining of enriched uranium into finished weapons components. The enriched uranium process included chemical recovery operations and foundry equipment. A large part of the early work at the Plant took place in this building, because the triggers required a large amount of enriched uranium. The primary operations were divided into the following areas: fabrication support, which included the foundry for casting of shapes and ingots;

machining and inspection; metal product support, which included recovery of relatively pure materials; and salvage support, which handled recovery of solutions and solid residues with relatively low uranium content.

Building 881 operations represent three distinct primary functions: enriched uranium manufacturing and recovery (1952-66); stainless steel operations (1966-84); and recent activities that have taken place in the building since manufacturing operations were phased out, including research and development, laboratories, and computer administration.

Building 881 is an irregularly shaped, multiple level structure that is built into the side of a hill. Building 881 is considered to be a three story structure with mezzanine levels on the first and second floors. The complex encompasses approximately 245,000 square feet. During the period of uranium and stainless steel production, most of the production related activities occurred on the second floor.

### *Building 883*

Building 883 was constructed in 1957 to accommodate fabrication of enriched and depleted uranium and beryllium parts. The sealed, hollow shape of the weapons components required a significant amount of rolling and forming of both types of uranium. Because space in the existing Buildings 881 and 444, (enriched uranium and depleted uranium parts manufacturing) was inadequate, Building 883 was constructed to handle some of the uranium and beryllium rolling and forming operations.

Building 883 is a high bay, single-story building with a 38' ceiling. The majority of the building's area is contained in a high bay metal working area. Eighty percent of the area of the building has been used for metal processing.

The processing areas on the first floor were referred to as Sides A, B, and C. The building was originally designed with two functional areas or sides to prevent cross contamination of radioactive enriched uranium with non-fissile depleted uranium. Side A housed equipment used for rolling, pressing, and shearing of depleted uranium and beryllium operations. Side B housed equipment used for rolling, pressing, and shearing of enriched uranium. Side C, completed in 1985, supported acid scrubbing operations and tank armor plate production.

### *Building 865*

Building 865 was built in 1970 to house metalworking equipment for the study of non-plutonium metals and the development of alloys. The building contained shops and equipment that supported metal fabrication, machining, and processing for both production and development in metalworking. The building conducted metallography laboratory work and decontamination activities for product research and development. The building contained equipment for rolling, shearing, forging, extruding, swaging, grinding, pressing, heat-treating, vacuum induction casting, and vacuum casting. A number of metals were processed and fabricated into prototype hardware.

All metalworking operations were conducted in the high bay area. The metal was heated in electrical resistance furnaces and transferred to the steam hammer for forging. When beryllium and uranium were forged, permanent hoods were used to create airflow

from the workplace and exhaust away from the operator. Beryllium, uranium, steel, and other ferrous and nonferrous metals are press-formed (hot or cold) into the desired shapes.

### *Building 460*

Building 460 was built in 1984 to house equipment, systems, and personnel for fabrication, assembly, and testing of stainless steel components such as reservoirs, tubes, and non-fissile trigger components. The facility was described as the most modern non-nuclear manufacturing building in the USDOE Nuclear Weapons Complex.

Total area of the building is approximately 230,000 square feet, split between the first floor and two second-floor mezzanines. All non-nuclear manufacturing at the Plant was consolidated into this one facility. The stainless steel operations conducted in Building 881 and some non-nuclear metalworking operations from Building 444 were transferred to Building 460 after its completion. Manufactured components were associated with the tritium reservoir-to-trigger delivery system. Operational processes included fabrication, assembly, and inspection. Fabrication of stainless steel and other non-nuclear metal parts included mechanical machining, electrochemical machining and grinding, electric discharge machining, and crush grinding.

### ***Plutonium - Buildings 71/771, 776/777, 707, 371***

#### *Building 771 (Plant C)*

Building 771 was originally constructed as a totally self-contained plutonium fabrication and recovery facility. For the period of May 1953 until 1957, when Building 776/777 entered operation, Building 771 was the sole plutonium facility at the Plant. During this time period, the building housed plutonium parts production-related activities, including casting, fabrication (machining), coating, inspection, testing, and recovery operations; the chemical and physical operations for recovering plutonium and refining plutonium metal; plutonium chemistry and metallurgical research operations and radiochemical analytical laboratory operations; storage of plutonium metal; various laboratories; and other support operations.

The original Building 771 is a two story structure built into the side of a hill with most of three sides covered by earth. The fourth side, opening to the north, provides the main entrance to the building. The plutonium-related operations were arrayed along the southern hallway of the first floor. Plutonium manufacturing operations were located on the south side of the hallway, while plutonium recovery operations were located on the north side of the hallway. Since completion of the original building, six major additions have been constructed.

By the mid-1950s, the space within Building 771 was inadequate to support all plutonium operations needed at the Plant. A new weapon design required more plutonium than that of the original weapons. Additionally, the new weapon design required more machining to achieve the necessary plutonium shapes. An increase in plutonium recovery operations was expected, partly due to the new weapons design. A new major production building, Building 776/777, was built to support the casting and fabrication operations. On September 11 and 12, 1957, a fire occurred in a fabrication line in Building 771.

The fire damaged Building 771 and caused radiological contamination, resulting in an estimated property loss of \$818,600 (Buffer, 1995). Many of the plutonium operations were moved to Building 776/777 after the fire. The fire debris had been cleaned up by 1958. Much of the production and fabrication equipment remained in Building 771 to provide backup plutonium production capabilities for the Plant. From 1957 onward, the mission of Building 771 focused primarily on plutonium recovery.

### *Building 776/777*

As a result of the design changes and increase in workload, Building 776/777 was constructed for plutonium casting, fabrication, and assembly, and quality assurance testing. The main function of the 776 side of Building 776/777 was the casting and fabrication of plutonium parts. The main function of the 777 side of Building 776/777 was assembly of parts and some disassembly of site returns (weapons returned to the site for retirement, upgrade, or reprocessing).

The original foundry was located in the southwest corner of Building 776/777. The foundry contained sixteen furnaces, which were crowded into the room. Foundry operations cast plutonium, either as ingots suitable for rolling and further wrought processing or into shapes amenable to direct machining operations. Fabrication operations involved either direct machining of ingots or cast shapes or conducting the wrought process, which further prepared the ingot for machining operations. The wrought process involved rolling the ingots into sheets and cutting them into circular-shaped blanks to be passed through a press. The pressed blanks were then annealed and machined. Machining involved taking the cast or wrought part and deburring or removing spurs, contouring, drilling, and milling. Machining operations took place on the North-South-East Line.

Assembly operations involved assembling trigger components. The units primarily contained nuclear materials such as plutonium and uranium; however, non-nuclear materials such as beryllium, steel, copper, aluminum, and silver were also assembled. Assembly activities included drilling, welding, brazing, turning, and polishing. After assembly, complete units were packed and shipped off site or to Building 991 for final processing, storage, and shipping.

The first weapons disassembly (site return) work was performed in the 777 side of Building 776/777 in 1958. Increased site-return disassembly activities began in the late 1960s, as old weapon designs were retired and disassembled to recover valuable materials. After disassembly, parts were inspected for unusual conditions and segregated according to material type. Plutonium materials were returned to the 776 side of the building's foundry where they were cast into feed ingots. Depending on assay specifications, the ingot was then sent to the molten salt extraction facility for americium removal. Otherwise, the ingot was sent to Building 771 for chemical purification and returned to the foundry as a fresh button. Enriched uranium parts went to Building 881 for recovery, and depleted uranium and inert components were packaged for disposal at off site disposal sites.

On May 11, 1969, a fire occurred in Building 776 from the spontaneous ignition of a briquette of scrap plutonium. The fire resulted in \$26.5 million in property loss, loss of production capabilities, and the decontamination took two years to complete.

The incident resulted in many new safety features including installation of water sprinklers and firewalls to control the spread of fire, and the use of inert atmospheres for plutonium operations to prevent fire propagation from occurring.

After the fire, the majority of the foundry and fabrication operations were transferred to Building 707. After several months of cleanup, limited production operations resumed in Building 776. The main operation conducted in Building 776 became waste and residue handling, although operations such as disassembly of old weapons (site returns) and special projects continued in the building. Processes conducted in the building included size reduction of large scrap equipment, pyrochemistry, coating operations, and test runs of a fluidized-bed incinerator unit.

### *Building 707*

Building 707 was the primary plutonium fabrication building from 1970 until production ceased in 1989. After two destructive fires in other plutonium production buildings (Buildings 771 and 776/777), the design of Building 707 incorporated extensive control and safety features, including the first-time use of inert atmosphere in the glove boxes. Construction of Building 707 began in 1967 with plutonium operations commencing on May 25, 1970. Building 707A was built in 1971 to accommodate operations moved from Building 776/777 as a result of the fire in Building 776.

Operations in Building 707 included metallurgy, parts fabrication, assembly, inspection, and non-destructive testing. The main floor of Building 707 was compartmentalized into eight side-by-side modules (A through H) which contained one or more of the primary production operations. Each module was 140' × 49' with an area of approximately 6,860 square feet. The modules were arranged from the north side of the building to the south. The main floor of Building 707A was divided into two modules, Modules J and K, which contained plutonium foundry operations and two plutonium storage vaults. One storage vault, on the north end of Module K, was equipped with a remote controlled, computerized retriever (the X-Y retriever) for handling plutonium stored in the vault. The general flow of work and materials was from Modules J, K, and A sequentially to Module H.

### *Building 371*

Building 371 was originally built to accommodate the plutonium recovery operations from Building 771, using advanced technology for plutonium handling, recovery, and safety. Although fundamentally based on the processes and principles developed previously in Building 771, the design of Building 371 incorporated many technological advances and refinements. The design, initiated in 1969, was far more sophisticated and complex than any others at the Plant; Building 371 was designed to emphasize automatically controlled, remotely operated processes, as contrasted with the direct, hands-on operations in Building 771. The operations for the building focused primarily on recovery of plutonium from both solid and liquid wastes. The final product from the process operations was intended to be recycled plutonium metal, which was to be reused in the Plant's primary manufacturing process.

Operations in Building 371 were threefold: recover plutonium from all residues generated by plutonium-related fabrication, assembly, and research activities throughout the Plant; convert the recovered plutonium into high-purity metal buttons; and recover associated americium and convert it to americium dioxide, a saleable product.

Building 371 was originally scheduled for completion in 1976 at a cost of approximately \$70 million. The project was plagued with schedule overruns and construction material substitutions. The stacker-retriever, a remotely operated, mechanized transport system for movement of plutonium storage drums, became operational in 1976. In 1978, the waste treatment process came on line. In 1980, the heating, venting, and air conditioning systems were brought on line. The rest of the building was finally completed in 1981 at a total cost of approximately \$214 million.

In 1982, pilot-scale aqueous plutonium recovery operations began in Building 371. There were not enough operators to run the process continuously, so the process was run in batches, shutting down one phase to start the next. Employees were to be transferred to the new facility when it was fully operational and recovery operations in Building 771 were shut down.

One year after the aqueous recovery process began, the USDOE conducted a plutonium inventory at the Plant. The Building 371 inventory was difficult to quantify. The building had over 770 miles of piping, of which, 70 miles were plutonium process lines. Process lines ran through walls and traversed several floors. In the 1960s, personnel associated with safeguards and security were primarily concerned with the amount of material that went into the process and the amount that came out; the amount currently residing in the process was only estimated. By 1976, accountability was required for every gram of material at all times. The aqueous process was shut down until all in-process plutonium could be located. The majority of the material was found. Designed in 1968, Building 371 was not constructed to meet this type of safeguard and security requirement. Although several projects to upgrade the system were proposed, none were approved. The aqueous process, which never ran at full capacity, was not operational after 1983.

### ***Shipping/Receiving, Assembly - Building 91/991 (Plant D)***

Building 991 was the first building to be completed at Rocky Flats. It was designed for shipping and receiving and for final assembly of weapons components. Administrative services for the Plant were also carried out in Building 991 until Building 111 was completed.

In addition to the handling of materials, a number of research and development projects were conducted in the building. These included: radiation studies conducted from the 1960s-70s; a beryllium coating process from 1964-76; and an explosives-forming project from 1966-74. Most special projects and research and development operations were moved out of the building by 1976.

Building 991 was primarily used for off site shipping of components, assemblies, and other materials associated with past weapons and/or plutonium metal production. The building also housed non-destructive testing operations and other support operations.

Building 991 was used to test the quality of non-nuclear raw materials and parts fabricated by off site vendors and to inventory and store parts for future use. Building 991 took



over storage operations from Building 881 in the 1970s. To insure the quality of the off site materials, a metallography lab was used. In the late 1980s, the handling of nonclassified materials was moved to Buildings 130 and 460. Non-nuclear materials ready for assembly were sent directly to Building 460.

## **Security**

Indicative of the importance of security, the first structure on site was a small guard shed building in mid-May 1951. In comparison, excavation for the first permanent building on site, Building 91, did not begin until July 10, 1951. The Plant was surrounded by 10 miles of barbed wire fence, electric fence, and livestock fence, and armed guards patrolled the perimeter of the Plant. Each of the four lettered plants had its own guardhouse: Building 446 for Plant A; Building 864 for Plant B; Building 773 for Plant C; and Building 992 for Plant D. Building 121 and firing range were constructed for the security force as part of the original Plant. As new production buildings were constructed, individual guardhouses were also constructed for them. Guardhouse 888 was built in 1964, close to the criticality laboratory (Building 886); Guardhouse 461 in 1985, for the stainless steel fabrication plant (Building 460).

Facilities considered to be part of the security force included: Building 119; Building T120A; Building 121; Building 128; Buildings 987 and 993 (munitions storage); Buildings 100, 120, 900, and 920 (personnel access control points); Buildings 372A, 372, 762A, 763, 792A, and 792 (major access control points); Buildings 113, 133, 446, 461, 557, 773, 864, 888, and 992 (guard posts); and Buildings 375, 550, 761, and 901 (guard towers).

Security of the Plant included control of access; preparation for and prompt response to threats or acts of violence; screening of future employees, including a 15-year background check for Q clearance; inventory control of government equipment; and procedures for handling breaches of security. The Atomic Energy Act (Section 161.k) authorized security personnel to carry firearms and arrest without a warrant in order to safeguard the special nuclear material from theft and to keep citizens and workers from harm. This authorization included the use of deadly force, when necessary.

The first security chief at Rocky Flats Plant was James A. O'Brien, a former narcotics and Army intelligence officer. According to a former security director, in the early years, security was concerned with the Cold War, espionage, and the secrecy associated with building nuclear weapons. It was important to safeguard design secrets, and later, the numbers of weapons being produced. Classified information was available only on a need-to-know basis; employees received instruction only on their specific duties. All employees were required to have a Q clearance, a top-secret level for atomic workers requiring a 15-year background check. Employees were forbidden to talk about their work with anyone (Kennedy, 1994:16; Young, 8 May 1992). Employees at the Plant were unaware of the duties of family members also employed at the Plant. There were many instances of immediate family members working at the Plant, with no knowledge of what the other's job duties were.

Cold War fear ran rampant during the early 1950s through the late 1980s, possibly bordering on paranoia. Employees' backgrounds were thoroughly checked; rooms were monitored for bugs prior to meetings being held; information was compartmentalized.

Production information was shared only on a need-to-know basis. Secrecy was a key component of site security. Off site, employees were only allowed to say where they worked and their official labor title (Weaver, 1998 interview). The secrecy was part of everyday life: no one asked for or offered information; most workers did not consider it a drawback, just a fact of working at Rocky Flats.

Very few employees knew what the final product was that was being shipped to Pantex, nor did they consider it important to know what the final product was (Weaver, 1998 interview). Most employees were cleared for work only in the area or building to which they were assigned, and did not know what operations occurred in other buildings or areas. They were required to have a separate badge for each area they entered (*Rockwell News*, 1983). Workers parked outside the Plant area, at the west end (the sole entry point), and were bused to Building 111, where they checked in at the clock room, and then went to their own buildings. A small bus stop (114) was built in the administrative area. By the mid-1950s, cars were allowed onto the site. A guard post, Building 100, was built at the west access road in 1969 to check traffic. By 1964, an east access route off Indiana Street had been built, with guardhouse Building 900.

Secrecy was also extended to the guards; they were not well informed as to what was to be protected. Guards were not given information regarding what to protect within individual buildings; they also worked on a need-to-know basis, gathering knowledge and information from walking the floor. It was not until the mid-1980s that the security force was formally trained on the nature of the materials that they were to protect (Cunningham, 1998 interview).

Formal security sanctions were imposed. The first warning for a security infraction was verbal, the second was written, the third required time off, and the penalty for the fourth infraction was termination (Weaver, 1998 interview). Informal sanctions included embarrassment and ridicule from co-workers. In one group, an eight ball (from a billiards game) was circulated. If someone was written up, the eight ball had to sit on the desk of the division manager as a constant reminder until someone else was written up and the ball was passed on (Riddle, 1997 interview).

Security infractions were considered big events at the Plant: people believed in what they were doing and simply did not talk about their individual assignments or the Plant in general (Richey, 1998 interview). Signs were posted on the outer gates with the number of infractions that had occurred. When one occurred, an investigation took place immediately, and the sign was updated regarding the outcome. Since the Plant community was extremely tight, any infraction was considered a social stigma (Cunningham, 1998 interview).

During the Manhattan Project, plutonium was also referred to as “copper.” If someone was really talking about copper, it was called “honest-to-god copper” (Rothe, 1997 interview). Continuing the practice of using codes, words such as plutonium, uranium, or americium were not spoken at the Plant. Instead, code words like “X,” “Y,” or “Z” were used. Depleted uranium was also known as tube alloy, carried over from British terminology, and enriched uranium was also known as oralloy (Oak Ridge alloy).

In the 1970s and 1980s, security was concerned less with espionage and more with the threat of terrorism and infiltration of the Plant by protesters. Better protection of the outer boundaries of the site became necessary. In 1972, a buffer zone of 4,600 acres around the

existing 1,900-acre Plant (Industrial Area and buffer zone) was purchased to expand the open, undeveloped area providing additional protection. The buffer zone was essentially an open area, surrounded by a barbed wire fence, of the type used to fence grazing cattle from an area.

According to Ed Young, head of security operations at that time, the terrorist attack during the 1972 Olympics led the government to believe that trained terrorists could attack national defense facilities (Young, 8 May 1992). As a result, in 1978 plans were made to install a \$5 million perimeter security zone surrounding the plutonium operations buildings. The perimeter security zone, when finished in 1983, consisted of a double-perimeter fence with closed-circuit television, alarms, and an uninterruptable power supply. Access to the area was controlled at three checkpoint guardhouses: Building 372 at the inner fence by Building 371; Building 762 by 707; and Building 792 by 771. Four guard towers, Buildings 375, 550, 761, and 901, were installed along the inner fence (Buffer, 1995). By 1985, a perimeter intrusion detection assessment system was in place, with its security centered in Building 764, to detect activities at the perimeter security zone (Thompson, 2 July 1993).

In 1983, a new policy required that all vehicles driven onto the Plant site be searched by security forces at the entrance gate. Guard posts and badge check houses were added at the west gate in 1985 and at the east gate in 1986. In 1988, material access areas were established to enhance security inside the production and classified building areas.

The first protests at the Plant brought out the guards in full force, with rifles and ammunition. During these protests, a booking area was established in Building 111 so that arrested protesters were processed on site instead of taking them to the Jefferson County facility. Protesters that crossed onto Plant property were put on a bus and transported on site. Many protesters were frightened by being brought inside the perimeter of the Plant, a response that surprised the security force. Over the years, some 1,500 arrests of protesters were made. As one of the Rocky Flats officials put it to the protesters, "We're equipped to deal with terrorists, but we are not equipped to deal with you people." Nevertheless, the arrests were peaceful and according to the head of security, Ed Young, no one was ever injured (Kennedy, 1994:27; Young, 8 May 1992). The practice of bringing protestors on site ceased due to infiltration concerns (Cunningham, 1998 interview). As protests continued and guards became accustomed to dealing with outsiders, the security forces were not fully armed or in full force.

Guardhouses were established in the west parking lot (133) in 1986 and at the west end of Central Avenue (113) in 1988. In 1990, the private security guard company, Wackenhut, took over the protective services contract.

The Plant protection organization had a security inspector force and a lock and key control group. The security inspectors regulated Plant and interplant access, provided security patrols and checks, and escorted Plant shipments. Lock and key personnel kept records of the locks and their keys, and of safes and their keys and combinations. Security maintained a weapons arsenal, conducted tours for potential contractors, trained new inspectors, investigated violations of Federal laws, and maintained liaison with local law enforcement agencies.

Strategically located cameras detected movement in unmanned, sensitive areas for increased security from unauthorized entry. Camera monitors were located in the nearest Plant protection guard post.

Procedures to heighten security measures were implemented in January 1991 because of the unrest in the Middle East. When the Persian Gulf War began on January 16, 1991, the Plant's emergency operations center was activated and staffed around-the-clock. The USDOE Rocky Flats Field Office provided the operational oversight of safeguards and security at the Plant. EG&G-Rocky Flats and Wackenhut Service, Inc., were the two primary contractors responsible for ensuring that protection program strategies, policies, and procedures were appropriately applied at the Plant to protect USDOE assets.

Document control was governed by USDOE regulations for the control and accountability of classified documents at Rocky Flats. It was responsible for the flow, safe keeping, and disposal of classified records, such as documents, microfilm, and correspondence.

The nuclear materials control group administered a computerized control system that accounted for all nuclear materials. It also supplied the USDOE nuclear materials information system with official material status information and data.

### *Communications*

Communications at the Plant included a combination of commercial and secure telephone lines and teletype services, for secure and non-secure radio contact. Supplemental communication facilities included

- Direct telephone links between the guard posts and central alarm station in Building 121;
- Direct telephone links between the central alarm station and ten key plant locations;
- Two push-button telephone call directors, one in the central alarm station, and one in the shift superintendent's office, with connections to thirty stations on and off the Plant site; and
- A public address system for general Plant or individual building announcements, national emergency alert and attack signals, building evacuation warnings. Direct connections to the nation's warning system and the metropolitan emergency telephone system.

There were two teletype services on site, one commercial and the other secure. The commercial teletype system, Western Union, based in Building 881, provided a printed copy of the message. The secure automatic communication network and a programmable terminal had a teletype center in Building 750. The secure automatic communication network, connected to USDOE headquarters in Maryland, could prepare, transmit, and receive classified and unclassified teletype messages from over forty USDOE offices and contractor locations. A newswire was introduced to the Plant site in 1971. This system, similar to an answering service, was updated each weekday morning and when events of major news would break.

There were twelve separate radio frequencies for two-way communication by departments on site. Radio communication was used by Plant protection, the fire department, Plant Services, the Plant postal service, radiation monitoring, Plant maintenance, and facilities engineering.

Radio communications between the Plant and other sites was also used. There was a two-way connection between the Plant and the Jefferson County Sheriff's Department,

St. Anthony's Hospital, and nationwide USDOE locations and personnel over the emergency radio system. There was a listening watch for Colorado State Patrol transmissions.

## **Fire Safety**

A twenty-five-person fire department provided immediate around-the-clock response to reports of fires and other emergencies. The fire department routinely inspected all Plant facilities for fire hazards; held fire training programs for its own members, as well as for members of building fire brigades and Plant protection personnel; and presented indoctrination courses for employees on fire prevention and reporting.

Fire brigades in the major buildings were trained to act as firefighters until the fire department personnel arrived on the scene. Plant protection back-up teams were trained to assist, where necessary. Security and fire personnel were cross-trained in the event additional backup was needed. Security could help with the hoses and the dress out into protective equipment. Fire brigade personnel were next in line to be given firearms, if necessary, in a security emergency (Cunningham, 1998 interview).

Plutonium is pyrophoric, and small particles will spontaneously ignite in the presence of oxygen. Special precautions had to be developed to prevent and to fight plutonium fires. Initially, the fire danger of plutonium was not completely understood, and preventative measures were phased in over time as the dangers became better known. These precautions to prevent and control fires eventually consisted of using glove boxes provided with argon or nitrogen atmosphere, displacing oxygen with carbon dioxide, and using heat-sensing and smoke-sensing devices and fire doors.

Two major plutonium fires occurred at the Rocky Flats Plant, the first in 1957 and the second in 1969. Buildings were modified and new safety procedures implemented as a direct result of these fires. The 1957 fire damaged Building 771, causing radiological contamination of much of the interior of the building. The fire spread from a glove box window on the fabrication line to the glove box exhaust filters, and the main filter plenum. The main fire was under control within 30 minutes of its discovery, but rekindled several times. Shortly after the fire was thought to be under control, flammable vapors collecting in the main exhaust duct exploded, spreading plutonium contamination throughout much of the building. Security officers discovered flames at around 10:10 p.m.; the fire was declared out by 2:00 a.m. the following day (September 12).

Prior to the 1957 fire, water was prohibited in the plutonium areas because of its moderating effect, potentially allowing a criticality event (spontaneous fission chain reaction) to occur. During the 1957 fire, water was used to extinguish burning combustible materials possibly contaminated with plutonium (i.e. Plexiglas and ducting materials in the exhaust plenum) without a criticality event or fatal consequences. As a result, standpipes and sprinkler systems were installed in plutonium handling areas throughout the Plant. Another result of this fire, which was propagated by combustible and flammable material, was that less flammable materials were investigated for use in glove box construction, specifically, a replacement for Plexiglas windows.

Off site release of plutonium into the atmosphere from the 1957 fire was estimated at approximately one gram. No major injuries were reported as a result of the fire. After that

fire, many of the plutonium operations were moved to Building 776/777. The fire debris was cleaned up by 1958. For a more detailed discussion of the 1957 fire, see HAER No. CO-83-N.

The second plutonium caused fire occurred on May 11, 1969, in Building 776/777 glove boxes. The first notice of the fire came at 2:29 p.m., when an alarm, triggered by a glove box overheat system, alerted firemen. No one was injured in the blaze, but some thirty-three employees were treated for contamination. The fire occurred from spontaneous ignition of a briquette of scrap plutonium alloy metal contained in a small metal can, probably without a lid. The 1969 fire was the first time that water was used directly on burning plutonium (Note that in the 1957 fire, water was used to put out burning combustibles, not burning plutonium). The fire resulted in \$26.5 million in property loss. There was an estimated plutonium release from the building of 0.000012 grams, all contained on the Plant site. Decontamination of the area took approximately two years. For a more detailed discussion of the 1969 fire, see HAER No. CO-83-O.

The fire changed the way that business was conducted at Rocky Flats and in the Atomic Energy Commission complex, and possibly had international influences. Prior to the fire, there was little quality control. After the fire, the complex started applying multi-layers of safety reviews and quality control (Calkins, 1998 interview). Safety features instituted after the fire included the creation of an inert atmosphere in the glove boxes to prevent propagation of fires and the addition of water sprinklers and more fire walls. Because of their efforts, fire department personnel received a Group Presidential Citation for heroism in the 1969 fire for risking their own health and well being to prevent a breach of the building, thus preventing plutonium contamination in the atmosphere.

## **Health and Safety**

### *Background/History*

During initial production and experimentation, little was known about the properties of uranium, plutonium, and beryllium, associated health risks, and allowable levels of exposure. Although specifics were not known, from the beginning of operations, it was recognized that health risks were associated with handling these materials: safety was always a priority within the weapons complex. Throughout the development of Rocky Flats, a great deal of expense and effort was dedicated to reducing identified health risks to both the workers and the environment. Public sentiment against the use of nuclear power, environmental concerns, economic factors, and issues raised by various protest groups helped keep the issue of health and safety a top priority at the Plant.

Plutonium is a radioactive material, emitting alpha and beta particles and gamma rays. Alpha particles are usually completely absorbed by a person's outer layer of dead skin, so are not harmful to the body. Alpha particles are harmful if ingested or inhaled, delivering a radiation dose to the lungs, liver, and bones that may increase the risk of cancer (Sutcliffe, 1995:2). Beta particles are more penetrating than alpha particles, but are less damaging over distances. Beta particles can be reduced or stopped by a layer of clothing. Gamma rays can easily pass completely through the human body or be absorbed by tissue, becoming a radiation hazard for the entire body. As a result, plutonium machining is performed

under controlled conditions inside gloveboxes that include containment, filtering, and shielding (*Citizen's Guide*, 1992:16).

Most beryllium compounds are toxic; if inhaled they can cause a disease characterized as beryllium disease or berylliosis. Inhalation is the primary mode of beryllium entry into the body, and clinical symptoms may be either acute or chronic.

The health effects of enriched and depleted uranium are significantly less than the health effects of plutonium, and therefore can be handled outside gloveboxes with the airborne radiation contamination controlled through building or room ventilation. The principal concern when working with depleted uranium is uranium's chemical toxicity and beta particles. If taken into the body via inhalation or ingestion, uranium may damage vital organs such as the kidneys or lungs. Protective clothing was worn in uranium operation areas (Weaver, 1998 interview).

When the first quantity of plutonium was made in the 1940s, half of it was turned over to health and safety experts to study the impacts of this new material on people. Allowable exposure limits for personnel existed throughout the life of Rocky Flats, changing over time as new information and data was learned. Major improvements and technological advancements occurred in the areas of radiation protection, detection, bioassay, and dosimetry in Building 123. During the production years, funding for equipment and research programs appeared limitless (Trice, 1997 interview). Monies granted for health and safety issues allowed the labs access to state-of-the-art equipment to develop methods to do things faster, cheaper, better, and safer. Although production information was on a need-to-know basis, information, such as an injury or accident, traveled through the Plant like a wild fire (Cunningham, 1998 interview).

In 1963, the first patent granted for a Rocky Flats invention was assigned to John R. Mann, health physicist and Art Wainwright, a former Plant employee. The patent was for an automatic radiation hand counter. Also in the 1960s, the SX-139 supplied breathing air garment was developed at Rocky Flats and approved by USDOE. This apparatus represented a two and one half-year effort to improve the supplied breathing air garments used at the Plant. In April 1995, John Schierloch, a mechanical engineer at Rocky Flats received a patent for a gas generation test canister prototype that measured the buildup of hydrogen inside plutonium residue storage drums.

In addition to the research efforts, accidents that occurred at the Plant spurred a number of new safety measures. The 1969 fire in the Building 776/777 glove boxes resulted in the creation of inert nitrogen atmosphere in the glove boxes and the addition of water sprinklers and more fire walls. As health regulations became stricter and more research on the effects of radiation or inhalation of particles became known, other changes took place at the Plant. In 1966, a personnel decontamination room was added to the southeast corner of the medical building (122), consisting of shower facilities and first-aid equipment. This addition enabled contaminated workers needing medical attention to go directly to the decontamination area rather than through the regular emergency building entrance (Buffer, 1995).

After decades of studies of the health effects to workers and the public living close to the Plant, the results have been inconclusive. One study, conducted on white males employed at Rocky Flats for at least two years between 1956 and 1980, recorded the cancer

deaths in this group. Workers with higher internal plutonium concentrations were found to have higher rates of death from all causes (combining cancer and non-cancer deaths) and also found to have higher rates of certain types of cancer (lymphopoletic neoplasms, digestive system, and prostatic). Workers with higher cumulative external radiation doses had higher rates of certain types of cancer (brain tumors, liver, lymphosarcoma, reticulum cell carcinoma, and myeloid leukemia). The results from both comparisons suggested a possible relation between exposure and observed health effects but were not conclusive (Wilkinson, 1987).

A limited study, conducted in 1990, of chromosome abnormalities in 18 plutonium workers at Rocky Flats was conducted. More chromosome aberrations were recorded in workers with higher cumulative radiation doses. No chromosomal differences were noted in workers from exposures to chemicals.

A 1981 study examined the relation between cancer rates and exposures to plutonium. The study found increases in many cancer types for persons in exposed areas (near the Plant), as compared with those for unexposed areas. This study was replicated in 1987, and although the findings were confirmed, conclusions could not be drawn about an association between plutonium concentrations in the soil outside the Plant and cancer rates. No increase was found in cancer rates for all cancers combined, for radiation-sensitive cancers, or for cancers of the respiratory system in the region within ten miles of the Plant for both study periods.

In 1982, researchers measured plutonium concentrations in autopsy samples from more than 500 persons who died in Colorado. They compared those who lived near the Plant with those who lived far from the Plant, and found a weak relation between plutonium concentrations in autopsy samples and distance from the Plant. However, the researchers concluded that the evidence was not strong enough to link the elevated concentrations to emissions from the Plant.

Researchers at the National Cancer Institute completed a study in 1990 of cancer incidence and mortality around 62 nuclear facilities in the United States. This study compared cancer rates in counties near nuclear facilities including the Rocky Flats Plant with those for counties farther away. The results from this study show slight elevations for some cancers in some age groups, but these data are hard to interpret because of limited information about other cancer related factors.

Colorado Department of Health and the Environment began historical public exposure studies in 1990 to identify the potential health effects of past chemical and radionuclide releases from Rocky Flats to surrounding communities. Preliminary conclusions published in 1993 stated that past public exposures to contaminants from the Plant were minimal. Final results, due to be published in September of 1999, draw similar conclusions (Colorado Department of Health and Environment).

Epidemiologic studies conducted by the Colorado Department of Health and Environment suggest elevated cancer risks for Plant workers, but these results are not definitive. Scientists require fairly stringent evidence for such conclusions. Cancer rates must be high enough to satisfy criteria for statistical analysis, and must be clearly related to exposure to radiation or other hazardous substances that came from the nuclear facility. Epidemiologic studies of persons who lived near the Rocky Flats Plant have yielded conflicting results,



mainly because data on exposures to radiation and toxic materials from the Plant were not sufficient and/or other cancer-related factors (i.e. smoking, etc.) were not considered.

The Rocky Flats Beryllium Health Surveillance Program, initiated in June 1991, was designed to provide medical surveillance for current and former employees exposed to beryllium. The surveillance program identified 27 cases of chronic beryllium disease and another 74 cases of beryllium sensitization out of 4,268 individuals tested. Beryllium disease affects the lungs of its victims, causing fatigue, shortness of breath, and persistent coughing.

### *Safety Programs*

The first major safety program at the Plant was organized by General Manager, F.H. Langell in 1951. The first division physician came on site in 1952 and acted as the construction workers' physician (Buffer, 1995). By September 17, 1959 Rocky Flats had established a safety record of 7 million man-hours of work without a disabling injury. The safety figure eclipsed all performances by Colorado industry in addition to the fifteen other Dow plants (operating at the time) and the eight major facilities comprising the Albuquerque, New Mexico operations of the Atomic Energy Commission. In June 22, 1960, Dr. Leland Doan, President of the Dow Chemical Company, visited the site and presented a bronze plaque representing the President's Safety Award in recognition of the excellent safety record at Rocky Flats.

In 1966, dosimeter badges used to monitor employees' exposure to radiation were a Type-A gamma ray film badge. By 1969, all gamma ray dosimeters were converted to thermoluminescent dosimeters. Dosimeter badges were provided to all employees frequently in production areas. By 1976, all neutron badges used were thermoluminescent dosimeter badges. Rocky Flats was the first nuclear weapons facilities to use the thermoluminescent dosimeter badges. Exposure levels were monitored in the Analytical Health Physics Laboratory (Building 123).

Mandatory measurements for both external and internal doses were taken. Initially, detection limits for plutonium, americium, and uranium in urine samples was 0.15 disintegration per minute; by 1995, the detection limit was 0.02 disintegration per minute. This was due to improvements in procedures and equipment developed in the laboratory over the years.

Filtering of airborne, radioactive particles was done through the use of individual respirators. A respirator fitting program was established in 1964, and in 1971 employees working in production areas were required to be clean-shaven so that the respirators would have a snug fit (Buffer, 1995:1971). In 1972, a system was established for checking the respirators for efficiency in the environmental test chamber of Building 123.

On January 1, 1973, a new safety program was kicked off. The "Life is Fragile – Handle with Care" safety program, designed to increase safety awareness in employees' homes and communities, was put together by and for employees. In 1973, the Atomic Energy Commission allowed state health officials to have access to the fenced, secured areas of the Plant to check on general safety conditions.

In 1974, more direct emphasis was placed on research activity with the formation of health sciences, charged with the various aspects of radiation monitoring and employee health; and environmental sciences and waste control, overseeing all waste control activity and environmental monitoring. Radiation monitoring conducted in the analytical physics laboratory (Building 123) included gamma counting, tritium analysis, beryllium analysis, alpha and beta counting and the dosimetry process.

On July 1, 1991 the beryllium health surveillance program officially began. Employees found to be sensitized to beryllium were further evaluated for chronic beryllium disease (Buffer, 1995). Two medical studies were begun to monitor the long-term effects of exposure to beryllium and radioactive materials such as plutonium, enriched uranium, americium, and others. These studies, mandated by federal law (the National Defense Act of 1993), involve all former Plant workers, and are currently being used to detect early signs of disease.

In late February 1994, the Plutonium Working Group Report on “Environmental, Safety and Health Vulnerabilities Associated with the Department’s Plutonium Storage,” a 28-volume, 8,300-page report, was officially released. The report looked at plutonium environmental, safety, and health vulnerability issues at USDOE facilities complex wide. The report listed Rocky Flats as having five of the fourteen most vulnerable facilities - Building 771 (No. 1); Building 776 (No. 2); Building 779 (No. 7); Building 707 (No. 8); and Building 371 (No. 9).

New technology to detect small amounts of americium, a decay tracer product of plutonium, in employees’ lungs was brought on line at Rocky Flats in June 1995. This technology was the most advanced in the industry and allowed direct measurement of radiation to be taken for a lung count. Two of the three rooms used by internal dosimetry used the new Health and Safety buildings considered primary contributors to the significance of Rocky Flats according to National Register of Historic Places guidelines include: Building 122 (emergency medical services); 123 (health physics laboratory); 442 (laundry for uranium-contaminated clothing); 778 (laundry for plutonium-contaminated clothing); and 886 (nuclear safety facility and critical mass laboratory).

### *Health Facilities*

The original health facilities were located in the medical building (Building 122) and the health physics building (Building 123). A laboratory and administrative area were housed in the health physics building. Equipment used in collecting air samples, control and accountability of radioactive sources, recording limits of surface contamination and radiation exposure, personal protection, surveillance equipment, x-ray equipment, and a nuclear alarm system were also housed in Building 123. Personnel also monitored Plant employees for lung and systemic burdens, using body counting and radiochemical techniques. Analysis of personnel dosimeters and all airborne sample analyses, including stack samples and general room air samples, were conducted in the health physics laboratories.

The medical building (122) housed the doctor and emergency health care facilities. The medical department provided medical services to employees brought to them by the emergency unit of the fire department for diagnosis, first aid, x-ray, and minor surgical treatment, and also provided ambulance service (including helicopter transportation) to several

local hospitals. The medical department performed scheduled physical examinations of all employees. A personnel decontamination room containing shower facilities and first aid equipment was added to Building 122 in 1966. This addition enabled contaminated workers needing medical attention to go directly to the decontamination area rather than through the regular emergency building entrance (Buffer, 1995).

### ***Nuclear Safety Department***

The nuclear safety group was established in 1953. The primary purposes of the nuclear safety department were to generate technical criticality safety information, review operating procedures for nuclear safety, provide guidance for implementing those procedures, and establish nuclear safety policies for the safety of production operations. Nuclear criticality safety can be defined as practices associated with avoiding an accidental nuclear criticality event or spontaneous nuclear fission chain reaction. In a nuclear chain reaction, a neutron splits one uranium or plutonium atom into two smaller atoms, which in turn release energy and neutrons; these neutrons split other fissile atoms, releasing more energy and neutrons. Eventually enough atoms are split and neutrons released that the reaction sustains itself. The chain reaction produces energy that can be converted to electricity or used in atomic weapons. A criticality event would not result in a nuclear explosion, but could liberate a large amount of energy and high levels of radiation. The presence of large quantities of fissile materials in numerous forms on the Rocky Flats site made it necessary to maintain an active criticality safety program. Although a number of nuclear criticality accidents have occurred nationwide, the Rocky Flats Plant had none.

The nuclear safety department was divided into two groups: the criticality mass laboratory, where experiments were conducted, and criticality engineering. The principal functions of criticality engineering included writing criticality limits and procedures for the safe handling of fissile materials, implementing the limits and procedures in all areas that handled fissile materials, training and indoctrinating personnel who handled fissile materials, and performing auditing operations for compliance with USDOE guidelines. Criticality limits, the amount of material allowed in any one place (process line, storage container, etc.) at one time, were strictly enforced. If criticality limits were exceeded, penalties were severe, possibly resulting in termination (Rothe, 1997 interview).

Criticality tests were conducted in the criticality mass laboratory after 1964. Until the early 1960s, criticality testing was done after-hours in the production glove boxes. Experiments were only allowed to go towards criticality, but not allowed to go critical. Values were then extrapolated. The need to obtain more actual values was recognized and in 1964, ground was broken on a state-of-the-art criticality mass laboratory (Rothe, 1997 interview). Investigators would set up the production materials in various arrays to perform neutron-multiplication experiments and make predictions with respect to safe geometries for various kinds of production vessels, spacing parameters, shipping containers, and other items. These *in situ* experiments conducted outside Building 886 were always subcritical; neutron count rates were observed as criticality was approached but never reached.

Experiments at Rocky Flats validating the safety parameters for the storage of fissionable solutions in raschig ring tanks resulted in the design of two substitute storage tank configurations: the annular tank and the poison tube tank. These designs allowed for more

economical solution testing with no decrease in safety. The poison tube tanks were not used at the Rocky Flats Plant due to the change in the overall site mission; however, they were used at other USDOE facilities. Experiments were also conducted to validate the cross-sections and usefulness of materials used at the Rocky Flats Plant.

### ***Critical Mass Laboratory (Building 886)***

To further reduce hazards, criticality tests were moved to a dedicated facility, Building 886. The principal function of the laboratory was to provide accurate criticality data for engineers to use in establishing safe nuclear procedures. The laboratory facility had approximately 12,000 square feet of space for electronics, fissile material storage, and critical mass testing. The actual tests were conducted in a room having 4'-thick concrete walls and a 2'-thick concrete ceiling. The room was leak tested to insure that, in the event of an accident, no contamination would be released to the environment. The room was sealed during experiments. Redundant automatic shutdown mechanisms were built into each experimental system to preclude a nuclear incident. All experiments followed detailed written procedures and were conducted by trained personnel. The criticality safety group at Rocky Flats performed experiments and calculations to identify container or vessel geometries or arrays of nuclear material that had the potential to spontaneously fission. Experiments and calculations were conducted to evaluate the potential for criticality under varying conditions and to validate computer programs used for criticality safety analysis.

The first experiments in the building were conducted in 1965 with highly enriched uranium. Between 1965 and 1992, approximately 1,600 critical mass experiments were conducted on enriched uranium metal and solution, plutonium metal, low enriched uranium oxide, and several special applications. Additional testing programs were instituted after 1969 when the critical mass program at Lawrence Radiation Laboratories was shut down and transferred to Rocky Flats (Rothe, 1997 interview).

After 1983, experiments were conducted primarily with uranyl nitrate solutions, and did not involve solid materials. Experiments continued until 1987, when testing programs were temporarily stopped for routine equipment modifications, contamination control, and ventilation repairs. Before needed corrections and modifications were completed in 1989, operations at the entire Rocky Flats Plant were curtailed due to the FBI raid. Criticality research at the criticality mass laboratory never resumed.

## **Heating, Ventilation, and Air Conditioning Systems**

### *Containment Zones/Filtration*

Heating, ventilation, and air conditioning systems confined hazardous materials within process areas to prevent the dispersion of radioactive aerosols, noxious fumes, and vapors into areas normally occupied by personnel. They also controlled the release of such contaminants from a production facility to the lowest practicable levels, both under normal operating conditions and under accident conditions. Heating, ventilation, and air conditioning systems included not only air ventilation capability but also, in many buildings having

nuclear materials, inert gas ventilation that provided environmental control and fire protection for specific areas.

For confining radioactive materials, individual buildings were divided into several zones (Zones I-IV), separated by physical barriers. The ventilation pressure was increasingly negative from zone to zone toward areas of potentially higher radioactivity. Ventilation atmosphere flowed from areas having the least potential for radioactive contamination toward areas having progressively higher potentials. Definite pressure differentials were maintained between the zones.

Zone I, the primary confinement zone, included glove boxes, canyons, vaults, and their exhaust atmosphere handling and cleaning systems (i.e., areas of highest potential radioactive contamination). There was either one additional, less critical zone between a Zone I area and the final containment barrier to the outside environment, or a monolithic concrete floor, wall, or roof with no penetrations to the outside environment. Zone I atmosphere was negative with respect to the atmosphere in all other zones.

Zone IA (buffer zone) included access air locks to glove boxes and canyons, downdraft table enclosures, downdraft tables, hood enclosures, tank vaults, and their exhaust atmosphere handling and cleaning systems. Zone IA areas were essentially open containment areas (hoods, and downdraft tables) where the capture velocity of the ventilation atmosphere was utilized and controlled rather than a fixed pressure differential maintained.

Zone II (secondary confinement) included the process rooms and work areas containing the Zone I and Zone IA confinement areas, enclosures, and systems. Zone II atmospheres were maintained at a pressure less than that of Zone III.

Zone III (tertiary confinement) included access areas, individual process control rooms, decontamination areas, and the corridors surrounding Zone II and adjacent to the outside shell of the building itself. Zone III also housed the air supply and return system and utility systems that potentially could contain slight radioactivity. The pressure in Zone III was negative relative to that in Zone IV of the building.

Zone IV space included such areas as heating, ventilation, and air conditioning control rooms and general non-radioactive utility and support areas. Zone IV pressure was slightly negative relative to outside ambient air pressure.

The air pressure balance between zones was maintained by differential pressure-sensing instruments and was controlled by inlet and outlet zone dampers. The pressure differentials maintained air flow toward Zone I areas, then to final filtration, prior to being exhausted to the outside atmosphere.

The outside shell of the building provided the final containment barrier for radioactive materials. There were no openings in those portions of the building shell that separated Zone I, IA, and II areas from the outdoors. Passage from Zone III through the building outer shell to the outdoors was through air locks.

### ***High Efficiency Particulate Air Filter Testing Laboratory (Building 442)***

Air exhausted from facilities handling beryllium, plutonium, and uranium was exhausted through several stages of high efficiency particulate air filters. The high efficiency particulate air filters were purchased from various manufactures and tested by the filter testing group prior to use. Each plutonium production building was fitted with at least two

banks of high efficiency particulate air filters. The filter testing group was formed in 1979 to act as an independent group to test the quality of high efficiency particulate air filters (ChemRisk, 1992:95).

Operations in the high efficiency particulate air filter test facility were considered critical. Production buildings were continuously monitored for radioactive contamination. Air exhausted from the stacks of process and research buildings was monitored to detect releases of particulate radioactivity and toxic dusts and chemicals. Also, ambient air was monitored for airborne particulate matter, both on and off the Plant site.

Construction of the original section of Building 442, which housed the filter laboratory was completed in 1953. The original building, containing 2,480 square feet, is a one story, reinforced concrete structure. The newer part of the facility (constructed in 1975) is a pre-engineered metal building. This addition housed the warehousing operation.

### *Breathing Air System*

Clean, dry, breathing-quality air was available for personnel who were required to wear protective suits or masks to perform operations where the atmosphere had less than 19.5 percent oxygen, was radioactive, highly toxic or noxious, or could be hazardous. Air was supplied in personal tanks or canisters. Typical of these kinds of operations where supplied air was used include cleaning liquid storage tanks, changing contaminated filters, spraying a toxic paint or coating, or entering a smoke-filled room to extinguish a fire. Workers in plutonium process buildings were the most frequent users of supplied breathing air.

The most extensive breathing air system was in the 700-area buildings. Either one of two compressors in Building 708 could supply breathing air to Buildings 707, 771, 774, 776, 777, and 779. Portable compressors also provided Buildings 333, 444, 559, and 881 with breathing air capability.

### *Inert Gases*

An inert atmosphere (nitrogen and less than 5 percent oxygen) was used in various glove boxes and storage areas to minimize the possibility of fire. Total nitrogen consumption during fiscal year 1975 was 515.6 million cubic feet; in 1976, nitrogen consumption was at the rate of 58,000 to 60,000 standard cubic feet per hour.

Gases used in the inert atmosphere were normally supplied from an on site, liquid nitrogen production plant that was owned and operated by a commercial supplier. A secondary supply was a liquid nitrogen storage facility that received liquid nitrogen from the on site plant or by truck or rail shipment from an off site commercial supplier. Distribution of the nitrogen began at Building 223 with an underground, closed-loop distribution line. From there, the gas was sent to Buildings 371, 701, 707, 771, and 776. The nitrogen could be delivered in either clockwise or counterclockwise directions, should one side of the loop have become inoperable. An interior system delivered the gas from the 776 to the 777 area in Building 776/777.

Another inert gas system was a manually controlled argon system used in several plutonium fabrication, assembly, and research buildings. It consisted of a supply tank with distribution headers to various stations. It was used as a shield in arc welding and to provide an inert glove box atmosphere.

Nitrogen and argon gases were used as conveying mediums for solid samples in the close-carrier transfer systems of Building 371. Argon was also used in Building 371 to safely indicate leaks in calcium metal storage facilities; was mixed with fluorine, as make-up in a fluorination process; used to provide an inert atmosphere for molten plutonium metal that was being purified; and used as a purging agent.

## **Health and Safety Practices**

With the exception of those employees working in low-contamination areas such as the laboratories, all the men (women initially were not allowed to work in the production buildings) wore white clothing - coats, pants, hats, underwear, socks, and booties - provided by the Atomic Energy Commission/USDOE (B. Richardson, 1995). Depending on the area and task involved, at least 20 percent of an employee's time (1.5 hours per day for each 8-hour shift) was dedicated to issues and practices relating to safety. At a minimum, each employee changed out of their protective clothing for morning, lunch, personal, and afternoon breaks. After each break, the process was reversed (L. Wilson, 1998 interview). In addition to the time required for clothes changing, individuals were routinely monitored with hand scanners and other mechanical devices. This protective clothing was laundered in various buildings; originally, Buildings 771, 881, and 991 had their own laundries, and Building 442 laundered the clothing from Building 444. When Building 778 was constructed, the laundry for the plutonium-related buildings was washed there; after 1976 — when Building 442 became the filter test facility — all laundry on the site was handled in Building 778 (ChemRisk, 1992:96).

### *Plutonium*

Preventing employee contamination and exposure was the number one priority at the Rocky Flats Plant. Many of the systems developed to protect Plant employees and area residents were exclusive to the Rocky Flats Plant; they were not needed in other manufacturing plants. Glove boxes and stainless steel enclosures were designed for plutonium handling. Rubber gloves, usually impregnated with lead oxide, were affixed to the glove boxes to facilitate the handling of plutonium. The glove boxes also had lead-glass windows and 0.125"-thick lead shielding to protect personnel against gamma rays and x-rays. Water walls and hydrogenous materials were used where neutron shielding was required.

Containment and shielding meant that plutonium was machined inside lead- and water-lined glove boxes. Plutonium was moved from workstation to workstation within the six modules in Building 707 in a system of interconnected enclosed glove boxes and lines that ran for several hundred feet. In addition, Building 707 was connected to Building 776 via a glove box conveyor line (B. Richardson, 1995). In 1971, the operations in the waste treatment building (774) were enclosed, providing containment of radioactive airborne particles. Additional shielding, using lead, leaded glass, and Benelux and Plexiglas was added to the glove boxes and conveyor lines in Buildings 776/777 and 771 in 1968 to reduce exposure to radiation (EG&G, 1994). From the outset of operations in the late 1950s, employees wore dosimetry badges to measure external radiation exposure, and radiation and health physics monitors watched operations in the production buildings (Buffer, 1995).

Certain glove boxes had inert nitrogen atmospheres containing a maximum of about 5 percent oxygen to protect against fire propagation. Additional protection was provided via the use of heat- and smoke-sensing devices, roll-down fire doors, and fire doors with fusible links within the glove box system, and quick-connect fire extinguishers.

Plutonium ingots and parts were generally stored in closed containers within a large vaults. An inert atmosphere was maintained inside some vaults. One inerted vault had 10"-thick concrete walls with 7.25"-thick windows made of laminated glass enclosing gelled water. Material was introduced and removed from the vault by means of a computer operated retriever able to be manipulated in three different directions.

Safety in the plutonium fabrication and assembly operation was assured by the following physical and administrative features:

- The operations were enclosed within steel glove boxes, and operating personnel wore protective clothing;
- Certain steps were performed in an inert atmosphere to reduce the chance for combustion;
- Contaminants were filtered from liquid coolants and inert atmospheres;
- Heat, radioactivity, and oxygen levels were continuously monitored;
- Equipment was shielded to protect personnel from exposure to gamma, x-ray, and neutron radiation;
- Fire doors confined fire, and there were effective fire-suppression systems in place;
- Plutonium was handled remotely, whenever possible;
- Criticality limits were posted for easy reference;
- Safety inspectors maintained a constant vigil for unsafe conditions and practices; and
- There was adequate indoctrination and on-the-job training of personnel.

### *Beryllium*

Protective measures against dust containing beryllium particles required proper ventilation that included the use of specialized exhaust hoods, immediate availability of respiratory equipment performance of certain operations under wet conditions, and continuous monitoring at all workstations. Employees in beryllium areas wore protective clothing and had to wash themselves before eating, drinking, or smoking, and prior to leaving the area.

### *Uranium*

Workers in uranium fabrication areas wore protective clothing; before leaving their workstations and before eating, drinking, or smoking, they were required to wash adequately.

### *Non-Radioactive Materials*

Regulations for the safe use, storage, shipment, and disposal of various chemicals and materials at the Plant were found in such publications as the material hazards manual, the chemical safety data sheets of the Manufacturing Chemists' Association, the health safety and environmental manual, operational safety analyses, and individual building rules. In its list the material hazards volume records such information as composition, ignition temperature, irritants, odor threshold, toxicity, reactions with other materials, flash point, flammable limits, and human tolerance limits. In addition, audits, inventories, and reviews were frequently conducted at the Plant.



## ***Nuclear Criticality Safety at Rocky Flats***

### **The Early Years**

The introduction of fissionable materials at the new site mandated some kind of nuclear safety program. Management had to decide exactly how to incorporate important safety features such as criticality safety, radiation safety, contamination control, nuclear material security, and material accountability under the same or separate umbrellas. From its inception, the plant decided to break these responsibilities up into different departments. Matters dealing with material security and accountability were divided between two separate departments. Radiation safety and contamination control were lumped under the general designation: “Health Physics.” Nuclear criticality safety was administered by a new department called “Nuclear Safety.”

A bright and innovative young man named Clarence Lee Schuske was hired away from the Oak Ridge National Laboratory early on. His task was to establish some form of criticality safety at the fledgling facility. Soon after arrival, Schuske hired another scientist, Jerry Arthur, to assist him. These two provided the entire criticality safety program at Rocky Flats throughout the rest of that first decade (1950s). Although only in his mid-thirties, Schuske showed a remarkable talent to use “hand calculational methods” in determining critically safe working parameters for a wide variety of routine plant operations. His calculations were done on a slide rule or, at best, an electro-mechanical calculator. The modern

electronic desk-top calculator would not be invented for many years. Occasionally, other experimental data *appeared* close enough to be used directly. In retrospect, nuclear criticality safety during that first decade might be described as an “educated art form” rather than a true science.

No computer codes were available. The computer, indeed, had yet to be invented. A paucity of experimental data existed, even considering subcritical cases. With so few aids available, the best tool was a good understanding of nuclear reactor theory. That theory did provide a reasonable basis for many hand calculational methods. Still, considerable uncertainty existed. A recognition of the tenuous nature of what little experimental data did exist as well as the sometimes questionable applicability of theoretical “models” to not-so-similar plant situations naturally mandated a very cautious approach. This led to, in turn, a very conservative “margin of error” applied to any safety evaluation provided the plant.

Those criticality safety pioneers at the plant also had to apply their expertise to *two* potentially hazardous fissile elements: plutonium and enriched uranium. Theirs was not an easy task. Considering the difficult circumstances under which Schuske and others worked toward such an important safety goal, they are to be commended greatly that Rocky Flats never experienced a nuclear criticality accident. The plant never even came seriously close to one. The plant’s overall criticality safety record is, indeed, enviable.

One of Schuske's favorite hand calculational methods (one of several available in the 1950s) was called the "equilateral hyperbola" model. This is offered briefly as an example of clever ways to determine unknown critical cases from a paucity of data. In that model, long pencils of fissionable material are parametrically similar to large-diameter thin disks of the same material; only the height-to-diameter ratio changes. Critical dimensions for both pencil and slab may be known as explained below; but the goal of this model is to predict criticality for right circular cylinders of any intermediate height-to-diameter ratio. The mathematical form of this relationship is:

$$(D - D_0)(T - T_0) = \text{constant.}$$

The unknown case would be a right circular cylinder (larger in diameter than the pencil) of diameter,  $D$ , and thickness,  $T$ , (thicker than the slab). The known asymptotes,  $D_0$  and  $T_0$ , would be the critical diameter of an infinite cylinder and the critical thickness of an infinite slab. Both are easy to estimate from elementary models. Then, one parameter ( $D_0$  or  $T_0$ ) can be calculated provided the other is known. On the other hand, if asymptotes were not known for some case, a minimum of three measured critical measurements would allow the unknowns  $D_0$ ,  $T_0$ , and the constant to be determined by routine curve-fitting techniques. Once determined, any other critical point along this curve can be estimated with some confidence.

Buckling calculations was another reactor-theory-based hand calculational tool. It could be used to convert one known critical cylinder to another of different height-to-diameter ratio. As simple as they are, these methods were surprisingly accurate.

Schuske hired an additional four scientists late in the decade. The plant's

role in the nation's weapons program was increasing; and additional help was necessary. The talented four included George H. Bidinger, who continues to play an active role in the nuclear industry even though now retired from the United States Nuclear Regulatory Commission (NRC), Aurel Goodwin, Jr., Arthur N. Nickel, and Donald F. Smith. The tenure of these young scientists lasted only until about 1962. Personnel are discussed in greater detail in the next chapter and will not be repeated here.

As time moved on, methods of obtaining much-needed data improved; and most of that data was experimental in nature. Many early experiments had been performed at Los Alamos in New Mexico and at Oak Ridge in Tennessee, the oldest such laboratories. During the 1950s and 1960s, half a dozen other laboratories reached their experimental zenith. Even Rocky Flats contributed, although limited to subcritical studies, until the CML could be built. The era of experimental research in the field of nuclear criticality safety began to explode almost exponentially. Professional meetings of the American Nuclear Society (ANS) presented paper after paper publishing new-found experimental results. The experimental basis for criticality safety evaluations was beginning to become much more solid.

The year of the first subcritical experiment at Rocky Flats, sometime in the 1950s, is not known; but these were called "*in situ*" experiments. They were subcritical approaches *toward* criticality performed on location in one or another production building around Rocky Flats where the very same components under study were being manufactured. In these experiments, fissile components were carefully stacked by hand in an *intentional* approach toward criticality but without actually attaining

that state. Although they always remained safely well subcritical, critical parameters would be determined from an extrapolation of the data. The parameter watched was the ever-increasing *reactivity* of the assembly—closely related to another parameter called *multiplication*. These experiments were inherently more risky to personnel because workers were physically present while fissile material was being added. For that reason, they were performed “off shift” when not many workers would be in the building. Perhaps the philosophy “Risk the few, but spare the many” seemed noble at the time. Several experimental programs involving both enriched uranium and plutonium in solid, powder, and solution forms were studied by this intriguing method.

*In Situ* experiments were always plagued by large experimental uncertainties. This is so because rather long extrapolations were required. Experiments involved the measurement of the ever-increasing neutron count rate,  $C(x)$ , relative to an initial rate,  $C_0$ , as some physical parameter,  $x$ , was carefully pushed in the direction of criticality. In theory, the growing rate and, therefore, the ratio  $C(x)/C_0$ , called the “Multiplication,” would approach infinity as criticality is approached. The safety limit to the Multiplication allowed in these kind of experiments was ten. In practice, the *reciprocal* of this multiplication,  $C_0/C(x)$ , was graphed because this conveniently approached zero. Safety dictates that successive increments be quite small because the actual shape of this “Reciprocal Multiplication” curve is not at all known as the experiment unfolds.

Three curves of Fig. 2 illustrate this discussion about extrapolation uncertainty. In this completely hypothetical example, the critical value is arbitrarily selected to be 10.0 in some units. Extrapolations from a multiplication of ten are shown by dashed

lines. Criticality, however, must be estimated by extrapolation from whatever data has been collected to the point the curve is developed. For example, at a Reactivity Addition Parameter of, say, 5.0, the lower curve under-predicts criticality by some 20%. This is an unnecessarily conservative approach and would require several more measurement intervals to reach a multiplication of ten. Even at the limiting multiplication, a linear extrapolation misses the true critical point by a considerable amount. The upper curve is far more dangerous because a linear extrapolation from even 90% of the critical Reactivity Addition Parameter suggests the experiment is still very far from criticality. These two curves illustrate uncertainties introduced by long extrapolations using curves of unknown curvature. The safest and most desirable curve would be one that was almost linear or with gentle curvature—the middle curve. There, the extrapolation is reasonably short; and fair confidence exists in its prediction. The two curves also highlight tradeoffs resulting from shape. The upper curve has a shorter extrapolation but continually over-predicts criticality—a dangerous situation. Experimenters never know when or how abrupt the curvature might be. Regardless of the curve’s shape, the *In Situ* method suffers from considerable uncertainty, often several percent.

## The Critical Mass Laboratory

Uncertainty could be greatly reduced if criticality were, in fact, achieved during experiments. Then, actual physical parameters of a truly critical assembly could be measured: no extrapolations would be required at all. Uncertainties would be reduced to those of material dimension and composition. Those same uncertainties still

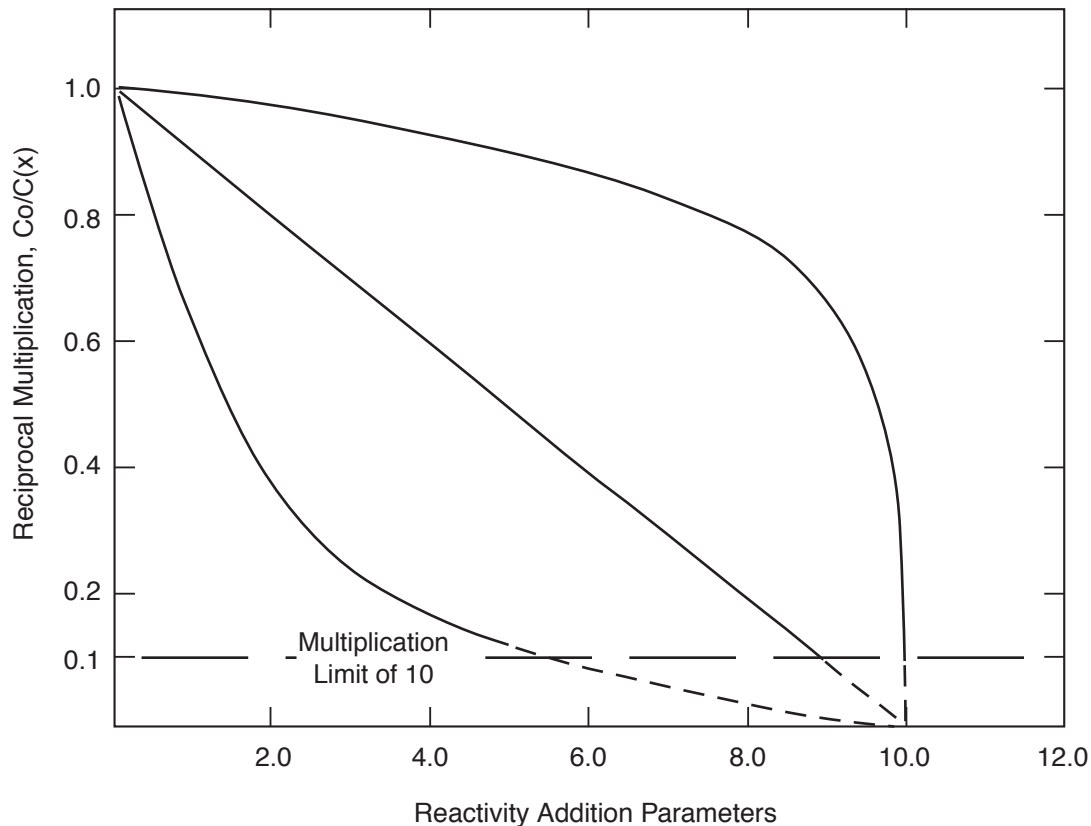


Fig. 2. Three hypothetical reciprocal multiplication curves reveal why a nearly linear one is the safest, most efficient, and most accurate extrapolation of subcritical data to criticality. The top curve lulls researchers into thinking the critical parameter is much larger than it really is; the sharp knee would be a non-conservative surprise from a safety perspective. The bottom curve continually points to too small a critical parameter; and this requires many more data points than necessary. Furthermore, the extrapolation is much longer and curved and, therefore, less certain.

also existed in the *in situ* method, of course; but they were simply overshadowed by the much-larger extrapolation uncertainties. The only complication with critical measurements would be the need to measure the reactivity variable remotely since personnel ought not be physically present during criticality. Radiation levels could be dangerously high. All this could be accomplished in a Critical Mass Laboratory (CML) where a well-protected room could be devoted to the careful attainment of actual criticality. The room would possess features for remote measurements of certain parameters; and it would be well

able to contain the consequences of the worst imaginable nuclear accident.

Recognizing its advantages, Schuske proposed such a laboratory be built at Rocky Flats in the early 1960s. His proposal was accepted and funded by the Atomic Energy Commission. Considering current construction costs, the price tag of only \$850,000 seems quite reasonable. Built in 1964, it was certified by the AEC for operation on January 28, 1965.<sup>9</sup>

<sup>9</sup>A personal note is that this author's wife gave birth to their third child that day. The event was important for the laboratory too; so close attention was paid throughout the day to both events.

After construction, Schuske published an internal report, RFP-607, about the facility: “A New Criticality Control Laboratory for Experiments with Processing Equipment and Systems.” This was published in September of 1965. Unfortunately, no copy of it is known to exist.

Prior to constructing the CML, persons performing *In Situ* experiments were the same ones evaluating criticality safety throughout the plant. The Nuclear Safety Group was small; but everyone wore many hats. The division of manpower between experiments and plant safety only evolved during the late-1960s. Schuske hired a few people specifically to perform experiments; but the rest applied whatever data was available to plant problems. At first, even this distinction was a little vague. Evaluators participated in a few experiments; and, to a lesser extent, experimenters became involved in plant-wide criticality safety. That distinction became much clearer during the early 1970s when the AEC introduced the requirement that people performing critical experiments should somehow be “certified.”

For many years, the entire Nuclear Safety Group consisted of only 14 persons. This included three hired to perform experiments at the CML and one who served as a technical/mechanical/electronic support person. Schuske had one secretary for the whole group and an Administrative Assistant. The remainder, always the larger group, worked closely with all buildings on plantsite housing fissile materials to ensure nuclear criticality safety.

The three experimenters included Mr. Grover Tuck, Dr. Douglas C. Hunt, and this author. All three were hired in 1963 or 1964. The first two are now deceased. The support person was Warren Robert (Bob) Sheets; he, too, is now deceased. Later, even he became

certified and assisted with experiments until his retirement. Personnel in both groups remained unchanged for many years. Schuske often boasted that his 14 persons had a combined couple hundred years of experience in this fledgling industry! Today, few facilities, including Rocky Flats, have many employees with more than a few year’s experience.

The CML began life intending to perform experiments on both uranium and plutonium in a variety of chemical forms. After all, the plant processed both materials; so this seemed natural. Enriched uranium had arrived at Building 886 for experimental use in two forms by 1965. Both were already well involved in experimental plans when the plant’s direction changed under government mandate. Uranium operations had been transferred to Oak Ridge in the late 1960s leaving Rocky Flats primarily a plutonium processing plant. This left the CML with a large inventory of enriched uranium while the plant dealt mostly with plutonium. The CML justified its continued use of uranium in critical experiments arguing that:

- (1) Uranium experiments were much cheaper and safer than ones using plutonium.
- (2) The functional shape of any criticality data for the two fissile materials is expected to be very similar to one another.
- (3) Uranium data could be “normalized” to plutonium by only a couple of plutonium experiments.

This was a noble plan; and it would have worked well. The points were valid; but, unfortunately, it never quite happened that way. Eventually, adjustments from one fissile element to the other would be normalized calculationally.

Routine day-to-day operations at the CML are described in detail in another chapter. A summary of CML experimental programs is outlined in still another.

Finally, a more extensive discussion of personnel is contained in a third. This chapter ends with an overview of that portion of the Nuclear Safety Group which ensured nuclear criticality safety throughout the entire plant after 1965.

## Operational Criticality Safety

Rocky Flats has never had a criticality accident or even a “close call.” That is a record about which any plant could be justly proud. Almost half a century of many diverse plant operations involving two fissile elements in a variety of chemical forms without ever having a criticality accident is a credit to the plant’s outlook on criticality safety. Other safety disciplines may not have as enviable a record as evidenced by the nation’s worst industrial fire in May of 1969 and contamination incidents discussed elsewhere in this book; but nuclear criticality safety was always taken seriously. This proud record flies in spite of the true observation that criticality safety had not always been administered on plant site as formally as it later was. One word accurately describes this safety arena at Rocky Flats—that word is *Evolution*.

A quality criticality safety program contains three major aspects. Establishing safe operational limits for any plant operation is one of these. That is not always easy. The critical condition for a similar system must be determined and a suitable safety margin applied. Then, the importance of differences between the critical system and the plant process being evaluated must be considered. This leads to increased safety margins which never is an exact science. Setting “Crit Limits” may sometimes appear more an art form than a science; but this is discussed more later. The second aspect of criticality safety is the routine surveillance of plant operations

to determine compliance with applicable limits. How often and to what depth these “audits” should be conducted always remains a question. After all, the very next operation following an audit could exceed the safety limit. The final aspect of plant-wide criticality safety concerns the consequences of a violation. Not every violation of a safety limit would produce a nuclear accident. Many only intrude upon a portion of the safety margin. Guessing at consequences of procedural violations is subjective at best.

Each one these aspects of criticality safety has evolved over the last half century. What began as a good program in the 1950s has grown into a tightly administered one with excellent supporting documentation and traceable proofs of safety. These three evolutions are discussed below.

## Nuclear Safety Limits

Early criticality safety advice did not possess the significance it now carries. Managers of various plant operations sought *advice* and *guidance* from Schuske and his team; but that input was neither considered binding nor limiting. Important safety information bore the innocent heading: “Nuclear Safety Recommendation.” That such important safety documents should ever have been relegated to the status of *recommendation* is somewhat surprising. To management’s credit, recommendations were taken seriously and always followed faithfully; and that fact is partly responsible for the absence of a nuclear criticality accident on plant site over its half century. An example of this early form is a 1969 safety memo presented in Fig. 3.

Such memos were easy to come by; and turnaround was quick. This safety advice may have been requested only hours

March 4, 1969

O. E. Heady  
Attn: J. F. Towell

**CRITICALITY RECOMMENDATION: VOLATILE FLUORIDE  
SCRUBBER SYSTEM**

An in-line array of 5" diameter schedule 40 pipes on 18" centers can be safely used for scrubbing gases from the gloveboxes.

*H. W. King*  
H. W. King  
HWK:cln

cc:  
✓File

Fig. 3. The Nuclear Safety Group, as it was called then, did not have much power behind safety declarations. Managers would have been free to ignore this "Criticality Recommendation" in favor of production schedules. To their credit, they never did.

before it was written, approved, and issued. The sole basis for issuing this document was the criticality safety knowledge and experience of the signers. Their instinctive wisdom often was sufficient. No formal validation was required. Often, a basis for approving one safety request was that it was somehow *obviously* less reactive (further subcritical) than another already approved safety limit.

This author also recalls once finding an ancient and long-lost hidden sign suspended from some seldom-used equipment in a deep, never-visited, recess of one of the plant's more-remote production areas. This sign, discovered over 30 years ago, contained small hand-written black letters on a simple, white-painted, rectangle of

metal. The text was headed simply: "Crit Recommendation;" and this was followed by a few terse words of advice. Had this been saved, it would have made an interesting comparison against modern postings. Sadly, it was not.

A greater respect for this important safety information developed by the 1960s. The phrase, "Criticality Limit", had come into use. The very change to the word "limit," alone, underscores enhanced understanding. The document was colloquially referred to as simply a "Crit Limit," language continued to this day. During the 1980s, a new phrase was introduced: "Nuclear Materials Safety Limits" (NMSLs). Sometime later, color and better graphics—so easily obtained on

computers—were introduced to draw better attention to the more-important aspects of a posted safety limit. This improvement came to be called “Criticality Safety Operational Limits” (CSOLs). Distinction between the two terms faded during the 1990s such that some buildings used NMSLs and others, CSOLs. The generic expression “Crit Limit” was still heard from old-timers as well.

The style, format, and posting requirements of Criticality Limits also evolved. As late as the mid-1960s, some limits were still issued verbally. Though not usually the case, last-minute changes in planned operations sometimes called for the Operations Manager to seek verbal modification of a written limit. This was occasionally given. Verbal criticality approvals were prohibited by later that decade. After that, all limits—including changes—had to be written and approved. The vast majority of Crit Limits were typewritten and carried several approval signatures. Signatures included at least two Criticality Engineers (as this faction of the Nuclear Safety Group was called) along with members from the Operations Group requesting the limit. That had become the standard approval format by the late 1960s and persisted for many years. Occasionally, however, last-minute changes would be requested; and these were sometimes issued on randomized scraps of paper. At least, they were in writing and carried an approval signature. This less-than-formal procedure ended altogether in the early 1970s.

All buildings possessing fissile material were issued a “Building Manual” by the Nuclear Safety Group.<sup>10</sup> These loose-leaf binders contained an orderly collection of all Criticality Limits applicable to that

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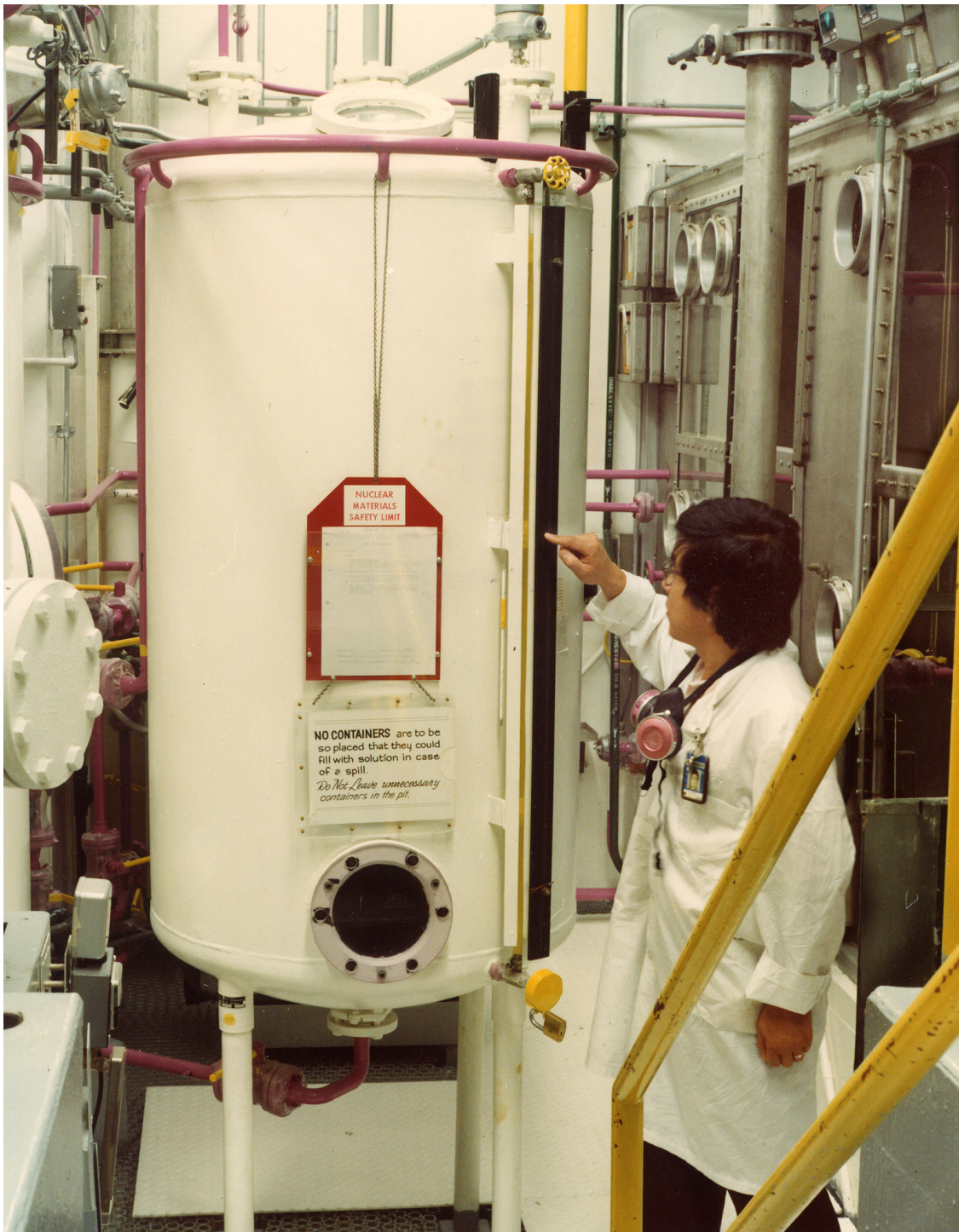
<sup>10</sup>One other Manual, called the Plant Shipping manual, governed all fissile material shipments about the plant site.

building. Often, they were organized by room and, if appropriate, by gloveboxes within the room. Copies of these pages would be taped on some surface near corresponding operations; and that constituted “posting” the limit.

Taping loose pages to a wall or a glovebox window had been a popular way of posting; but this was not really very satisfactory. Pages could become torn or dog-eared or inadvertently removed altogether by passing equipment rubbing against them. A standardized display was needed. A red-painted, metal placard holder became the answer. This was a rectangle with its upper corners truncated to give it a quickly recognizable shape. A thin sheet of transparent plastic held away from the backing by standoffs allowed the relevant page copied from the Building’s Manual to be slipped in for easy viewing. This was a much-improved method of posting. One of these is shown in Fig. 4 suspended from Tank #445 in Room 103 of Building 886 in 1979. The sign hanging below it was removed years later because it did not contain the precise wording of a properly approved limit. The legal status of that lower sign really remains a mystery. Did it constitute a limit; or was it merely strong advice?

Presentation of Criticality Limits was improving. Bright-colored standard-shaped placards gave the posting instant recognition. The plastic cover protected the written limit. Text was readable because that cover was transparent. Not all problems, however, were completely resolved. The text was simply typewritten. Important words were small and numerical values did not stand out. The limit was not understandable from a distance. Improved graphics and stand-out colors would greatly enhance the display. All of these improvements became simple with the advent of computer





*Fig. 4. The truncated rectangle in the middle of the tank holds the legal “Nuclear Materials Safety Limit, or NMSL. Long-standing history finds employees still calling it a “Crit Limit.” The wording on the Limit does not show up in this photograph. The advisement hanging below it is close to a valid Crit Limit; but it should not have been displayed in a non-standard holder.*

technology in the 1990s. An example of one of these colorful limits, associated with some plant process in some building, is presented in Fig. 5. This example was supplied directly from a computer memory and, so, does not show signatures. It does

reveal Site Wide applicability, the date, a specific Limit number, and identifies the evaluation process. All criticality limit postings have been colorful and contained enhanced graphics for easier understanding since the late 1990s.

Site Wide Limits  
Page 3.3-2  
Page 1 of 1

NMSL/CSOL 00-XXX  
Evaluation ABC-60-1/1  
11/20/00

**FOUR POSITION CART**

- **Each cart position is limited to ONLY ONE of the following (1, 2, 3, 4, or 5):**
  1. **MAX 3000g Fissile Material in non-liquid IDCs in ONE 4-LITER MAX inner container; or**
  2. **MAX 3000g Pu in Ash IDCs ONLY** (044, 310, 333, 368, 372, 373, 374, 378, 393, 419, 420, 420p, 421, 422, 423, 425, 428, 601, and 655), **in ONE 6-LITER MAX inner container (MAX 200g Uranium OK); or**
  3. **MAX 200g fissile material in liquid IDCs, in ONE 4-LITER MAX inner container; or**
  4. **ONE item from an approved part carrier contents list, in any sized container; or**
  5. **MAX 4400g unmoderated Pu in ONE 4-LITER MAX container**
- **DON'T** put carts in vaults or under gloveboxes unless allowed by specific limits
- Any amount of shielding on individual containers, and lead aprons, **allowed** without restriction

---

\_\_\_\_\_  
Criticality Safety Officer

\_\_\_\_\_  
Criticality Safety Engineer

Reviewed for Classification/UCNI: \_\_\_\_\_

By \_\_\_\_\_

Date: \_\_\_\_\_

Fig. 5. Nuclear Material Safety Limits after the 1990s are colorful, user-friendly and human-engineered for clarity as revealed in this arbitrary example from the plantsite. Printed copies of this book may not show the different colors.

One of the more important evolutions behind the composition of Criticality Limits concerned the technical basis behind setting these important safe limits. Methods and technology to accomplish this evolved right along with the plant's understanding of their importance. As already stated, the Criticality Engineer's wisdom, coupled with knowledge of reactor physics and experienced judgement, had been sufficient to set a Crit Limit in the early years. Critical curves representing the sparse experimental data of barely similar systems were the best guides available in more difficult cases. Often, an unfamiliar problem would be discussed with other Engineers; and several sources of data—both experimental and theoretical—would be researched to establish a confident limit. In summary, however, the issued limit would typically be based on an innate but educated intuition. Criticality Limits in these early decades were significantly less-well justified than limits issued later. That the plant never experienced a criticality accident is a testimony to two truths: Criticality Engineers were, indeed, knowledgeable, careful, resourceful, intuitive, and, occasionally, lucky. Secondly, they accommodated these limitations by including large safety margins.

Safety margins prompted one other complication in granting Criticality Limits. These pertained to four levels of fissile materials involvement:

- (1) a planned operation for which a limit was requested,
- (2) the actual limit issued,

(3) the maximum possible limit which could have been issued under safety envelope guidelines, and

(4) nuclear criticality accident conditions. Levels (1) to (4) obviously correspond to increasing closeness to criticality; and the important question is: Where should the middle two stand relative to the first (planned operations) and the last (an accident)?

The safest approach—and one often adopted at Rocky Flats in the 1970s and 1980s—was to grant the requested limit with only a small operational excess. This excess, if large enough, saved the Operating Group from having “technical” violations of no consequence simply because the posted limit pressed too closely upon actual practice. For example, if an operation was expected to involve routinely 150 g to 250 g of fissile material, the Criticality Limit might well have been written for 300 g. This limit, then, would be issued even though a possibly much larger one could have been issued and still remain within the safety envelope<sup>11</sup> required by Criticality Engineering. At one time, that safety envelope was based on calculations and specified two conditions:<sup>12</sup>

(1) *Normal operating conditions* of the operation under consideration shall not have a calculated  $k_{\text{eff}}$  above 0.90.

(2) *Upset conditions* shall not have a calculated  $k_{\text{eff}}$  above 0.95.

Safety margins were never revealed to the Operating Group lest they intentionally exceed the posted limit thinking to infringe on that margin.

<sup>11</sup>That safety envelope was defined as the maximum limit which could ever be granted for a given operation. It was safely subcritical; but any greater limit would exceed at least one of two conditions given in this paragraph.

<sup>12</sup>Later, that early policy was replaced. The present policy is that two independent upset conditions are required to cause a criticality. This is accepted almost regardless of the value of  $k_{\text{eff}}$  for “normal” conditions. Still, considerable experience is needed to identify not-so-obvious—yet quite possible—upset conditions and to be aware of all reasonable upset conditions. This is not always a simple task.

That two-pronged approach was later dropped because it never stated how bad or how many upset conditions must or may occur before a criticality accident might happen. It was replaced during the 1990s by a different concept of Double Contingency. Here, a “contingency” is defined to be an unlikely upset condition with a low probability of occurrence. Simply stated, the current Double Contingency policy allows that criticality *may* result after two upset conditions have occurred. The policy does not say that an accident *will* occur—only that one is possible.

Criticality Engineers were often faced with the dilemma of whether to issue an *adequate* limit or a *maximum* one. If a plant operation only required a very small limit, should the approved limit be close to the requested amount; or should it be close to the maximum amount possible? Valid arguments can be made on both sides. The first could lead to a technical violation which in no way compromises true safety. The second, much larger than necessary, treads much closer to criticality such that a violation could lead to an accident.

The following hierarchy presents fissile masses for a purely hypothetical and intentionally unspecified plant operation. Increasing risk moves down the chain; the bottom reflects a serious accident:

Operating Group plans a routine operation involving between 150 g and 250 g fissile material.

They request a Criticality Limit for this new operation.

Criticality Engineering writes a Criticality Limit for 300 g fissile material to prevent inconsequential violations.

but...

Criticality Engineering could have written a limit for 3000 g and still be within the safety envelop.

The calculated safety envelope is, say, 3200g.

In reality, however, the lowest mass under which an excursion would occur might be, say, 5000 g.

The 3000 g limit *could* have been issued; but *should* it have been? One resolution to this dilemma probably hinges on the severity of consequences levied against minor violations of Crit Limits. An attempt to illustrate this complicated dilemma—where the “Crit Limit” should fit between the actual conditions and an accident—is suggested in Fig. 6.

This author received his baptism into this dilemma only a few months into his employment. Schuske had assigned him the responsibility of the uranyl nitrate solution even before it arrived at the facility. Ten drums of very pure, high concentration, solution were to be delivered to the CML. The average uranium concentration was calculated, before delivery, to be 450.8 gU/ℓ. Responsible to his obligations, this fresh, young, PhD duly requested and received a “Crit Limit” for this liquid at just that concentration! Documents taped to the lid of each drum identified contents by volume and concentration. All ten drums contained approximately 106 liters; but concentrations, on the other hand, varied widely between 404 and 574 gU/ℓ. The first drum transferred into the tanks—properly posted with their *eventual* average concentration—just happened to contain something over 500 gU/ℓ. About that time, a Criticality Engineer, Donald R. Ferguson, wandered into the area out of idle curiosity and questioned the disparity. Ferguson was quickly assured that “the limit would soon

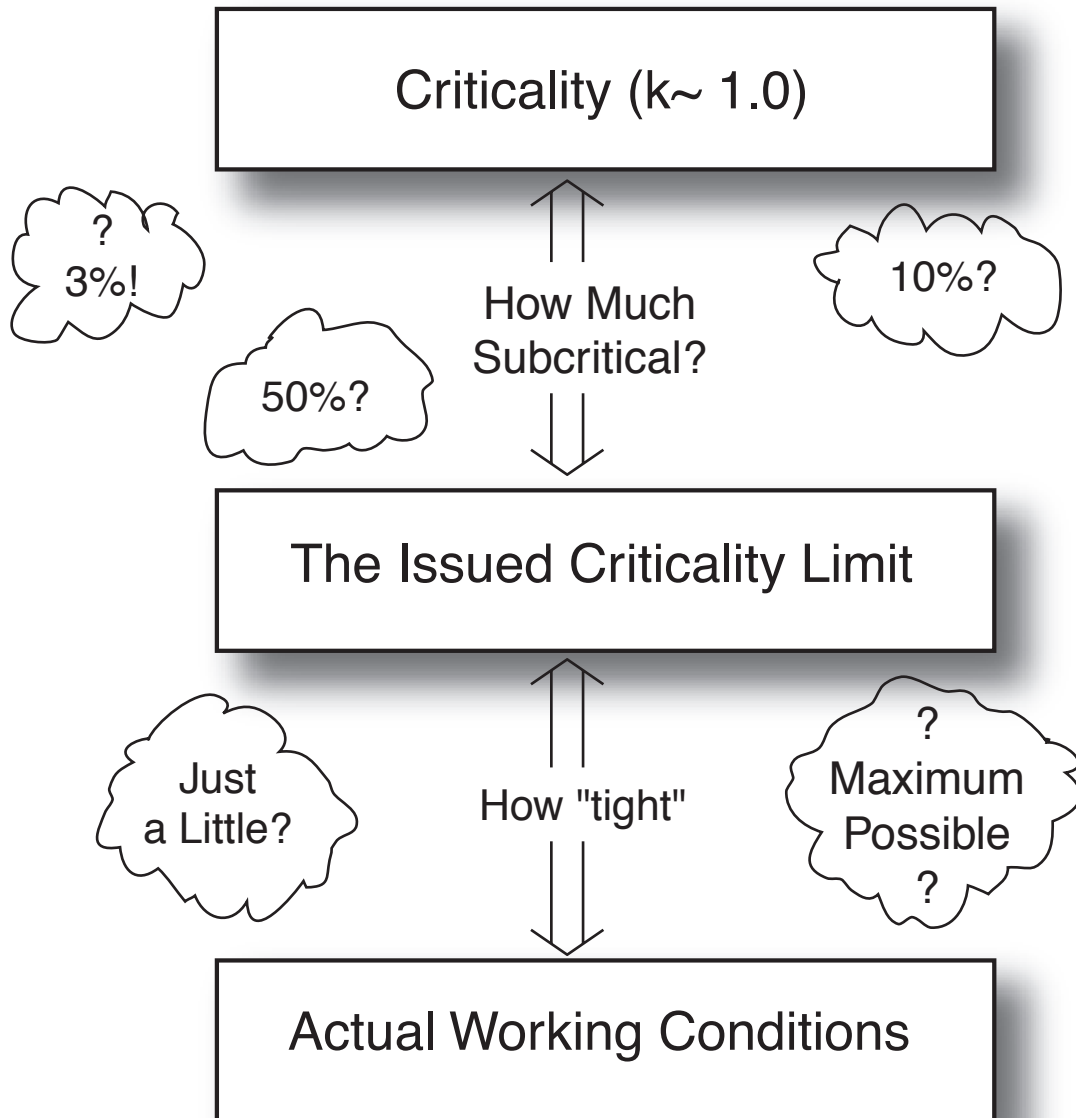


Fig. 6. Whether Criticality Limits governing actual operations should be tight against the plant situation being protected or as large as possible while remaining subcritical to some undetermined degree was always a difficult question to answer. Clearly, the Limit had to lie between the operating situation and criticality; but exactly where was the question.

be met since later additions had a lower concentration.” The offender was oblivious of his offense, however unintentional it may have been.

The criticality limit had been issued precisely as requested. Not even a small operational cushion had been included. A much larger limit could have been issued with no compromise to safety. The shipping drums contained the same environment (Raschig rings) found in the storage tanks; so, if solutions were safe there, they should have been safe in the tanks. That disparity was resolved by requesting, receiving, and posting a much higher Criticality Limit (540 gU/ℓ) for the solution in these tanks. That limit remained until the solution was removed from the facility in the mid-1990s.

### ***Calculational Methods***

The next innovation to influence the preparation of criticality limits was the computer. Computer codes had the ability to calculate critical systems. Some calculated critical parameters directly using reactor transport theory. Later, other codes were developed which would calculate the neutron reproduction factor,  $k_{\text{eff}}$ . All the Safety Engineer had to do was reduce the calculated critical configuration by some reasonable safety margin; and the limit was determined. Benefits were obvious. Calculations are less expensive, much faster to perform, and considerably safer than critical experiments. Calculations give off neither energy nor radiation when  $k_{\text{eff}}$  exceeds unity. Even in the 1970s, calculational techniques appeared to be the wave of the future. Still, the method wasn’t quite the panacea it first seemed. Many concerns remained.

Critical conditions may become known either by experiment or calculation;

considerable confidence existed there.

The engineer, however, still had to apply a somewhat arbitrary safety margin. How that should be done was not at all obvious. Furthermore, the physical similarity—or lack thereof—between the calculational model and the plant system under evaluation was almost just as troublesome as the similarity between experimental configurations and operational systems had been.

The earliest calculations were based on diffusion theory; but these met with limited success. One such code was called the Multigroup Diffusion Code (MDC). Slightly later codes were transport type calculations; and they were limited to only three geometries: spheres, infinitely long cylinders, and thin slabs of infinite extent. In spite of geometrical limitations, these transport calculations proved to be very useful. They served the nuclear safety industry well for a number of years.

The next advancement in computations was Monte Carlo codes. These involve a statistical treatment wherein thousands of “neutrons” are tracked as they move through materials in various geometries described into the computer. The computer’s memory contains nuclear cross sections as a function of neutron energy for various reactions which can happen to neutrons. This includes elastic and inelastic scattering, absorption, and nuclear fission. These cross sections are described in considerable detail. What happens to the fictitious neutron upon each event is determined purely on a statistical basis. Each neutron is tracked until it is lost altogether either by absorption or escape. The ratio of thousands of “neutrons” in one generation to the number in the previous one is related to the neutron reproduction factor for the system in question. Today, these codes are limited only by one’s ability to describe the geometry and

composition of the model under study accurately. Most of the cross section parameters have been well-tested yielding predictable and well understood biases.

The first of these Monte Carlo codes was called KENO after the gambling game. In the 1970s, the world's very largest computers were required to handle this massive computational challenge. Problems were submitted one day and retrieved the next. Calculations were costly. Close on its heels, other codes included the Oak Ridge Random Research Reactor Routine (O5R) and MONK. Advancements in computers over the next two decades now permit these enormous calculations to be run quickly and on quite small personal computers.

The introduction of Monte Carlo codes brought a whole new era to critical experiments. Instead of basing limits directly upon experimental data alone or experiments of complicated geometry coarsely compared with *approximate* computer geometries, experimental studies in many laboratories began to be tailored specifically to match computer codes. Experiments were specifically designed for easy description into the computer—both in geometry and composition.

The purpose of this change in philosophy was to provide a *validation* of the calculational method. Computer codes always yielded a neutron reproduction factor.<sup>13</sup> The question was whether calculated and experimental results for critical systems agreed with one another. If they did, the calculation was said to be “validated” by the experiment. Calculated results could then be used for quite similar systems with considerable confidence. If a difference did exist, the comparison mea-

sured the “bias” in the code for that kind of system. Calculations could still be used; but that bias would have to be properly taken into account. A bias could be conservative or non-conservative. A conservative bias predicted criticality when the corresponding experiment would still be subcritical. A non-conservative bias was the other way around.

Experiments after about 1980 were designed to validate computer codes. Geometries were selected which were easy to model. With that goal in mind, some experiments at Rocky Flats involved metal cylindrical solution container(s) in a cube-like reflector. Both materials and geometry were easy to model. In still other programs, fissile metal was either spherical or cylindrical. Materials with well known compositions were used; or, when more complex materials were necessary, considerable effort was expended determining an accurate and complete elemental composition. For example, concrete is a complex material important to many programs; but its composition was always well analyzed.

Both computer codes and experiments would yield critical parameters ( $k_{\text{eff}} = 1.0$ ); and this could be used to validate the code. Suitable safety margins—so important in a criticality safety program—were not so easily obtained. Codes did yield  $k_{\text{eff}}$  values less than unity for subcritical configurations; but no confident correlation exists between lesser  $k_{\text{eff}}$  values and the *degree* of subcriticality. Rigorous mathematics of ideal systems does not always carry over into practical cases. For example, reactor theory stipulates that the neutron reproduction factor and the multiplication of a fissile system are related as follows:

$$k_{\text{eff}} = 1 - 1/M.$$

<sup>13</sup>A critical system corresponds to  $k_{\text{eff}} = 1.00$ . Below that, the system is subcritical; above, an accident condition prevails.

This relationship is always valid; but the count rate ratio,  $C/C_o$ , encountered in every experiment, does not always accurately represent the Multiplication,  $M$ . Therefore, the reciprocal of the multiplication limit of ten used in *In Situ* experiments did not always accurately correspond to  $k_{\text{eff}} = 0.9$ . Furthermore, many cases can be cited where it came nowhere near corresponding to 90% of the critical parameter.

In summary, this code validation procedure worked well to show the experiment/calculation bias, if any; but that was not the end of the difficulties. These simple experimental systems, now, no longer seemed to replicate the actual, more complicated, system found in the plant. A new question arose: How closely must the complicated plant system resemble the simple experiments which validated the computer to consider use of the code “applicable?”

### ***Area of Applicability***

The last major challenge to Criticality Engineers has been called “The Area of Applicability”. This concerns just that question: How close must a system (experimental or calculational) used in forming the basis for a limit be to the operational system being evaluated for the application to be valid? For one thing, exactly the same geometry and composition of materials can almost never be found—usually, at least one differs. How different can they be and still trust the validated calculation? Another question: Can data obtained from a sphere be applied to a plant problem involving an equilateral ( $H=D$ ) cylinder? How far can the cylinder depart from equilateral before comparison is no longer valid? Even more subtle questions arise: Can parameters from a system having an acrylic plastic reflector be applied to a plant problem using polyethylene? A larger question often

asked: How can data obtained from uranium experiments be applied to plutonium situations? None of these are trivial questions. They emphasize the importance of experience, an understanding of reactor physics, and conservatism in composing criticality limits. The Rocky Flats CML lived with variations of these questions its entire life. Indeed, a considerable amount of “art” still exists in the science of being a Criticality Safety Engineer even today.

Figure 7 attempts to illustrate the dilemma faced by Criticality Engineering at different times during the evolution of their art. Before the emergence of calculational capabilities, experimenters had to tailor their work (bubble to the right) to resemble plant situations. This is suggested by the top half of the figure; and these kind of experiments are called “Prototype Experiments.” The few calculational models then available would be pretty far removed from any similarity to the plant problem, itself. Many years later, after calculational schemes became the vogue, experiments could be made to match calculational models quite closely;<sup>14</sup> but they seldom represented the plant situation very well at all. This situation is illustrated in the bottom half of the figure. In truth, experimental setups never really duplicated either situation (plant condition or calculational model) precisely.

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<sup>14</sup>One example, drawn from actual CML history, found one simple cylindrical tank (a very simple geometry easily described in a computer model) made of aluminum (a neutronically innocuous material and one with well-defined cross sections in computer files) suspended in free space in the middle of a very large room (for minimal reflection and little impact of peripheral apparatus *not* described to the computer). The composition of the solution was very well known, too; with, again, well-known cross section sets. The measured experimental critical height, then, clearly was designed to benchmark a computer-description of the configuration.



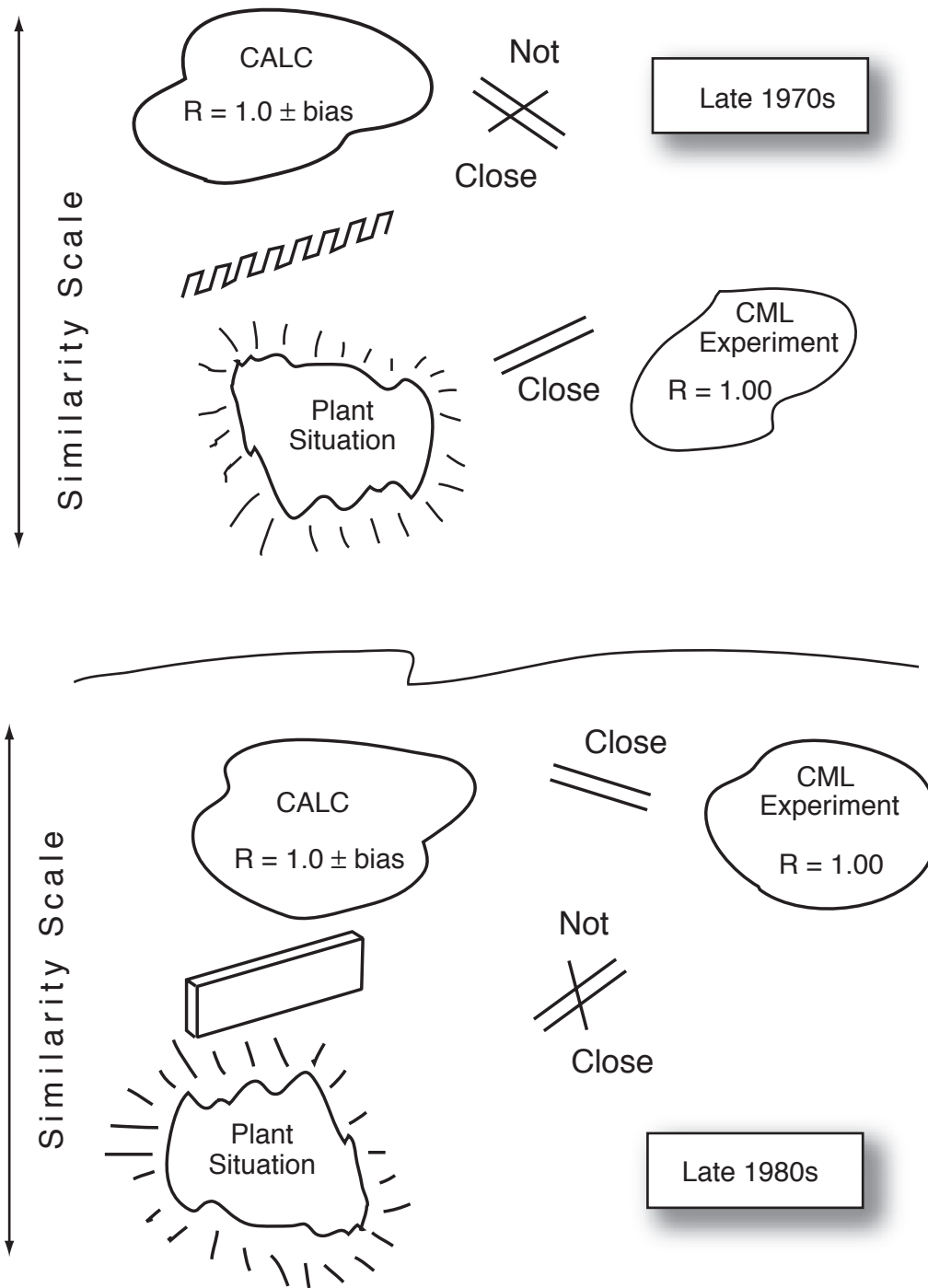


Fig. 7. Critical experiments could never duplicate precisely either the plant situation being protected or a calculational model of it. Naturally, all three would hope to resemble one another as closely as possible; yet the nagging differences caused continual concern. This issue is called the Area of Applicability. Before calculations became sophisticated, experiments tended to mimic plant situations ("Prototype Experiments"). Later, experiments were tailored more to "Benchmark" computer simulations. Neither approach is completely satisfactory. The plant situation icons represent the plant situation unintentionally extended to criticality instead of its normal subcritical configuration.

They may have been close; but gnawing differences always existed. The effect of these differences was often difficult to estimate. Safety margins had to be made larger because of that uncertainty.

The experiment could be made to approximate closely either calculations or the plantsite situation. It seldom could accomplish both goals. Finally, the plant situation almost never accurately reflected the simple calculational model. The question of just how close did either an experiment or a calculation have to come to matching the plant situation for the observed criticality data to be applied is an issue. This dilemma formed the Area of Applicability question. It has never satisfactorily been answered.

### ***Signature Approvals***

Signatory approvals of issued Crit Limits yielded another evolution spanning history. Early verbal approvals had no signatures. Engineers were taken at their word; and compliance by Operations was assumed. Up until the early 1970s, a single signature was often sufficient for written memo limits. This might be especially true for hand written criticality approvals or, more likely, modifications to a more-formally approved limit. The list of those whose signatures *could* approve (were authorized) a crit limit was not well defined. No formal list had been established. Evidently, anyone belonging to the Nuclear Safety Group and having a scientific background could approve a limit. Even this author has, on rare occasion and in his earlier days, signed Criticality Limits for plant operations. They were always simple limits and obviously safe. Still, he had no training or special qualifications other than an understanding of nuclear criticality and reactor theory. This flawed arrangement

did not last long. Sometime during the 1970s, multiple signatures were instituted for any approval. These included at least two Criticality Engineers as well as members of the Operating Group using the limit. A somewhat informal understanding was that only Criticality Engineers could approve a crit limit; even CML staff members were not allowed. In time, a “certification” process was put in place. Both signatory approval and engineer certification became much more formal.

At present, crit limits are considered formal documents. Each one is composed by a certified engineer whose findings have been confirmed by another certified engineer. Both signatures appear on the issued limit. Furthermore, a complete trail of calculations, data, and other considerations leading to the conclusion of criticality safety is fully documented. Multiple signatures from members of the Operating Group also still appear on the colorful and graphically designed criticality limit. Regardless of who signed the limit, that limit is applicable to the operation itself and is to be followed by all workers in the affected area.

### ***Audits***

Another major responsibility of Criticality Engineering was the performance of criticality safety audits of plant operations. These audits compared existing conditions against relevant limits. These limits could be those posted at the site or those not posted but written in the Building’s Manual. Both were subject to audit. Following all important safety limitations, whether posted or not, was incumbent on all workers in the affected Operating Group. Violations could be inadvertent in nature (due to mis-interpretation or lack of understanding), a consequence of forgetfulness

on the part of the operator, occasionally intentional (due to a furtive attempt to accomplish a task more simply by usurping part the safety margin), or caused by any number of other reasons. They could be major violations of mass limits, minor encroachments on spacing requirements, technical departures from wording, or any combination of major and minor infractions. Nonetheless, any departure from the applicable limit must be—and was—taken seriously. Unannounced audits were one means of policing compliance with safety measures.

These audits were sometimes unannounced but often scheduled. Sometimes, they were random “spot checks” of isolated locations or operations. Other times, thorough wall-to-wall audits of every limit in an entire room or the whole building were performed. By 2000, Plant Management conducted their own audits of their own operations. Selected areas must be audited monthly; but plant policy calls for a detailed audit of all operations annually. Criticality Engineering personnel continue to be involved in these audits.

Two long periods of time in the 1970s and, again, in the early 1980s saw a unique twist to audit philosophy. Staff scientists from the CML were assigned buildings to audit. These did not *replace* any other audits by Criticality Engineering; they were considered merely an auxiliary audit. The notion was that “a fresh pair of eyes,” especially belonging to trained persons with good backgrounds in criticality physics, might find problems overlooked by more jaded eyes. These responsibilities lasted a year or more on both occasions. They were useful to plant safety and instructive to the CML staff members. Overall, audits were an important aspect of the criticality safety program at Rocky Flats.

Operating groups were sincere about following limits. Their safety was at stake. They routinely policed themselves. Sometimes, they even conducted their own criticality safety audits. Occasionally, an operating group might even report their own violation to Criticality Engineering instead of simply correcting it when found. That is as it should be; but consequences accompanying an infraction sometimes may have prompted less-than-honorable subterfuge in this regard.

### ***Crit Infraction***

A violation of a limit was called a “Criticality Infraction”, often shortened to “crit infraction”. Many examples come to mind. A waste drum with a certain gram limit for fissile material may have been counted by the radiometric drum counting device and found to have more fissile material than allowed. A glovebox with quite high limits because no hydrogenous (neutron moderating) liquids were allowed may have been discovered to contain a bottle of some liquid degreasing agent—an hydrogenous liquid. A certain required spacing between containers may have been nudged closer than allowed due to routine movement within the glovebox.<sup>15</sup> An employee may have intentionally exceeded a mass limit by a small amount knowing that safety margins were built into the limit. Fortunately, intentional violations happened rarely.

Consequences of receiving a criticality infraction were another aspect that has evolved to some extent over the years. In early years, consequences were a little inconsistent; but now, they are much more formal and well-defined. A one time, the offender’s manager might just have

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<sup>15</sup>These mistakes could be minimized by providing fixed locations for containers.

talked to the worker about the importance of safety limits. Sometimes a written reprimand accompanied the talk, sometimes, not. Flagrant, intentional, or seriously large violations merited greater consequences. Frequent offenders also received greater penalties. Occasionally, investigation resulted in reassigning a worker to duties that did not include handling fissile material. Infrequently, a more-significant violation earned a few days off work without pay. Rarely was an employee terminated. More significant infractions were reported to DOE.

The severity of consequences stemming from an infraction may have played a role in one improper response by a few workers in one building. This author was conducting an audit in that building. The limit clearly specified that the glovebox in question must not have any containers in excess of four liters in volume unless that container had holes drilled in its side which would limit accumulated liquid. A commercial, metal, machinist's toolbox was discovered inside the glovebox. It measured about 500 mm long by 200 mm wide and 250 mm high—considerably in excess of four liters. An inspection revealed no holes in the toolbox; so the finding was written up as a criticality infraction. A few days later, the Operating Group called to contest the finding. A subsequent inspection, which included all parties, revealed holes properly drilled through the box. Furthermore, exposed metal edges of the holes even appeared aged. That was pointed out by the infraction candidates. The infraction was withdrawn; but the opinion has always been held that these holes had been drilled after the report had been issued and edges probably aged with acid to make them appear long-standing. No proof of this allegation existed; so the matter was dropped.

Today, consequences are much more formal and formally administered than they were decades ago. They are not necessarily more severe. Management, as well as workers, are more aware of the importance of *verbatim* compliance with every aspect of a limit. Currently, four levels of a criticality safety violations, sometimes softened to “non-compliance,” are now practiced at the plant; but only the first three are reported formally to DOE.

(1) A nuclear criticality accident. Clearly both safety contingencies were violated.

(2) Both contingencies were violated but an accident had not occurred for other reasons.

(3) One safety contingency remained in place; but the other was violated.

(4) Some technical violation of the limits occurred but both contingencies remained intact

In these four, the word “contingency” might be construed as the “upset conditions” discussed earlier in this chapter.

## ***Training***

One final responsibility of Criticality Engineering concerns training of plant personnel in the arena of nuclear criticality safety. Rocky Flats employees came from a broad spectrum of work experiences, personal backgrounds, educational levels, innate intelligence, interests, and a host of other human factors. Few understood nuclear reactor theory or the physics behind nuclear fission. All were naturally interested in their own personal safety; but few were aware of the consequences of a criticality excursion. They needed to be trained. They had to be taught the importance of nuclear safety in everyday life.

Brand new employees received a nuclear criticality safety indoctrination before they ever saw their workplace. This training continued with periodic follow-up indoctrinations, occasional lectures, and informal talks. These occurred throughout a worker's entire career at the plant. Criticality safety at Rocky Flats was an open topic. Many employees were treated to a tour of the CML; and this would include a description of its purpose and the importance of that purpose. This author was often called upon to lecture small groups of employees about the physics of nuclear fission; and a discussion of the consequences of an excursion (explosive yield, prompt radiation burst, and fission fragment formation) was always included.

Perhaps the zenith of worker training at Rocky Flats revolved about a "Criticality Simulator" device. This was an attractive, cabinet-quality, demonstration unit with all the features of fine furniture. It had the capability to simulate a nuclear criticality accident. Bright blue lights flashed and a harsh horn sounded as "critical conditions" were attained in the model. The unit featured two "critical accidents." One was a Raschig ring filled tank with an intentional large void space at the top as though ring settling had occurred. The model was built of transparent material to allow viewers to watch the "accident" occur. Yellow-colored water simulated uranyl nitrate solution entering the tank. As the solution filled the void space, the "criticality" occurred. The bright flash of blue light and the harsh wail of the criticality alarm was enhanced further by a belch of compressed air passing through the tank. To add to the effect, radiation meters were programmed to be driven way off scale. The effect was most convincing.

The second simulation consisted of two stainless steel machined hemispheres. The radius was such that the combined mass of both pieces would have been 6.2 kg if the material had been plutonium. That mass was chosen because of historical significance. One 6.2 kg  $\delta$ -phase plutonium metal sphere led to two criticality accidents at the Los Alamos National Laboratory in the mid-1940s. Both accidents resulted in fatalities. The shiny silver color even resembled the nickel plating on the early hemispheres. The two hemispheres were made to approach one another until the separation became too close. The "criticality accident" caused the two hemispheres to fly apart and produced a similar blue flash with the accompanying alarm sound. It, too, was very convincing.

This demonstration unit contained a number of other worthwhile training features. It was not intended to frighten workers. Its purpose was to instill respect for criticality limits. The device was donated to Los Alamos National Laboratory sometime around the time of the FBI raid on Rocky Flats. LANL still has that first prototype plus they have constructed a copy device for use at their TA-18 site.

Even this author stepped out of his role as an experimental research physicist and taught a number of classes aimed toward improving the plantsite's understanding of nuclear fission and the concept of criticality. This was taught to groups from all over the plant; and they came from a variety of educational backgrounds. Such classes were a welcome and useful diversion from experimental research.

In conclusion, nuclear criticality safety was always an important component of life at Rocky Flats. This probably, at least in part, accounts for the fact that the plant never had a criticality accident in its first five decades!



## ***Nuclear Safety Personnel***

Most of the people associated with the Nuclear Safety Group *before* the CML was built have been mentioned in another chapter of this document; and this information will not be repeated here. That in no way lessens their significant contribution to plant safety. This Section will, instead, attempt to identify all persons associated with the CML—those involved with critical experiments—in Building 886 from its construction in 1964 through its closure as a functioning facility in early 1990. Even those persons, important as their role was, associated with plant-wide criticality safety, called Criticality Engineers, are not discussed. Additionally, other persons devoted to a timely shutdown of the facility are also ignored. These omissions are not intended to diminish important contributions of either group; but they are an attempt to remain within the scope of this book. Although considerable effort has been expended to include all personnel ever associated with the CML, one or two may have been overlooked. This author apologizes for this, claiming no intention to slight them.

Rocky Flats was managed under different governmental contracts during its lifetime. The first and longest contract was held by The Dow Chemical Company. This lasted from 1952 until 1975. For perspective, the CML was built in 1964 and authorized to perform experiments January 28, 1965. Rockwell International took over custody in 1975 and retained that role until 1988—13 years. A company better known by its initials, EG&G (Edgerton, Germerhausen & Greer),

was awarded the contract from then through 1994 at which time Kaiser Hill took possession. By this time, the plant was clearly headed toward decommissioning; so Kaiser Hill might be described more as a company in charge of plant shutdown. Kaiser Hill chose to manage this task by introducing a number of second-tier companies across plant site. The nuclear criticality safety group, now completely devoid of any association with a CML, was operated under Kaiser Hill by Safe Sites of Colorado (SSOC) between 1995 and 1997. After that, the array of companies involved became quite confusing. Criticality Safety Engineers belonged to SSOC, Rocky Mountain Remediation Services (RMRS), a spinoff group from the Westinghouse Corporation family of companies (Washington Group International), as well as employees working as private contractors.

### ***Nuclear Safety Manager***

Clarence Lee Schuske was the manager of the Nuclear Safety Group (or that same group under other names in later years) when Building 86—later renumbered to 886—first opened its doors. The group numbered 14 persons and remained quite stable for many years. Most contributed to plant criticality safety by writing and monitoring safety limits. A very small number (4 persons) were responsible for critical experiments. Interestingly, Schuske was known by his first name when married to his first wife and before the move to the new building. His marriage to a second wife just before the move brought about

use of his middle name. On a personal and somewhat humorous note, this author had been interviewed by *Clarence* in June of 1963 and began employment under *Lee* in August of 1964. He was confused at first by this name change. Years later, Schuske was tragically killed in an automotive accident during the summer of 1977. He had been out to dinner with his three children and drove into the rear end of a city bus enroute home.<sup>16</sup> No explanation for C. L. Schuske's accident has ever come to light.

John D. McCarthy was soon appointed interim manager following Schuske's death; and that jelled into a permanent assignment in a few months. Schuske and McCarthy were the only Managers during the entire period of productive experimentation at the CML. Shortly after EG&G assumed control, they replaced McCarthy with Douglas W. Croucher. McCarthy still lives in Colorado, although he is no longer associated with the nuclear industry in any way. Even though the CML would never perform experiments under Croucher's regime, hope for reopening the laboratory was not given up completely until much later in the decade. By 1991, the CML became non-functioning except to retain this author more in the role of "custodian" than anything else. He oversaw the fissile materials still present as well as the equipment once associated with experimental operations. A number of small problems, discussed elsewhere, cropped up and needed the attention of some small professional staff. Croucher continues living in Colorado and is still productive in the field of nuclear criticality safety. In 1992,

David G. Satterwhite replaced Croucher; but after the mid-1990s, Building 886 and its once-proud CML were headed for total demise. Names of Management after that seem irrelevant.

### ***CML Manager***

This position did not exist at all under C. L. Schuske. He managed both experiments and criticality safety issues on plantsite. In 1976, McCarthy elected to clarify the distinction between CML staff and Criticality Engineers. He appointed Grover Tuck as the first CML Manager the same year. Tuck retired in a few years; and a relative newcomer, Dr. John S. Pearson, managed the CML from 1982 to 1985 when Pearson decided to accept another professional position in California. Dr. Robert E. Miles was next appointed by McCarthy as "Project Manager," neither the CML's outright Manager nor an Acting Manager. Neither the distinction between his title and either Manager position nor the reason for this unusual title was ever clear. Miles was replaced by another newcomer to the CML, Dr. James Wu, in 1988. Wu served as CML manager between 1988 and 1990. Wu had very little experience in the field.

When D. G. Saterwhite took over the reins of the larger group, he appointed Dr. Jerry N. McKamy to replace Wu as CML Manager. McKamy remained in this role until he left Rocky Flats for a position with DOE in Washington in the mid-1990s. For some time, McKamy and this author were the only persons affiliated with the dying remnants of a CML.

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<sup>16</sup>Compounding tragedies for his second wife, Rochelle, their son, Gregory, was also killed in a hit-and-run accident in Cambodia in the spring of 2002.



### ***Administrative Assistant***

In 1964, Schuske foresaw the need for an assistant to handle budget matters, nuclear material forecasting, and other related support services. He hired Lynn E. Jackson for this job even before the 1965 move into the new building; and Jackson remained there until sometime in the 1970s. By then, his role was being handled by individual members of the CML staff. No one was ever hired to replace him.

### ***Secretary***

One of the most important cogs in any smooth-running business is an efficient secretary. Schuske had hired Marilyn E. Douglass before the move to Building 886; and he kept her for the first several months in the new facility. Douglass elected to accept another secretarial position at Rocky Flats; so Schuske hired Geraldine Ferguson. Ferguson seemed capable and efficient so reasons for her short tenure are not known. She was followed by another short-term secretary named Barbara Schneider whose father was well-known at the plant. Schneider left to get married. In April, 1968, Schuske hired a very young woman named Carla Norviel. Three years later, marriage changed the last name to Fisher. She became a pillar of the group serving Schuske, McCarthy, Croucher, and Satterwhite with great professionalism and cool patience. She always maintained good humor even while working for an increasing number of eccentric scientists and engineers. Fisher was still associated with Rocky Flats although no longer officed at the plant and no longer associated with Building 886 until her retirement in the early 2000s.

### ***Senior Experimenters***

When Schuske's proposal for a CML was finally approved, he set out to hire qualified professional staff. None of those mentioned in another chapter and associated with *In Situ* experimentation (before the CML) chose to remain at Rocky Flats. Schuske's first employee for the new facility was Grover Tuck who brought with him considerable experience in the nuclear industry even though he lacked a PhD degree. Tuck was innovative, knowledgeable, and a careful researcher. His background in the nuclear industry had come through Idaho.

Early on, Schuske assigned Tuck the lead responsibility for designing, obtaining, and using enriched uranium metal components for critical experiments. Tuck rose to the task admirably. He designed a set of nesting hemispherical shells machined in like pairs so full spherical geometries up to 294 mm in diameter could be constructed. These shells are described in detail elsewhere; but they proved to be a remarkable tool for experiments spanning three decades. The entire set has been donated to the critical experiments facility at LANL. Tuck retired from Rocky Flats in 1982 leaving an internationally known legacy for careful work in a potentially hazardous field. He was especially knowledgeable in the area of nuclear criticality excursions (accidents). Tuck became interested in criticality accident analyses and was well-versed in the French CRAC experiments. Tuck died of natural causes several years later.

The second employee was Dr. Douglas C. Hunt. Although less experienced than Tuck, Hunt was a creative thinker and understood reactor theory quite well. He was assigned the responsibility for designing, obtaining,

and using plutonium metal components for still other experimental programs. Hunt decided to copy Tuck's hemispherical design. The need for smaller reactivity increments, however, led to plutonium hemishells being half the thickness of uranium ones.

Hunt's components had a less glorious history. Rocky Flats knew from experience that plutonium was unstable in some atmospheres; but detailed knowledge was somewhat limited in the 1970s. As a result, his plutonium metal hemishells were handled in an ordinary glovebox with only an ineffective dehumidifier to remove moisture from the air. Within a few years, one shell decomposed into a pile of yellow-green powder inside its storage container; and all plutonium hemishells were removed from the facility promptly in response to that problem.

A few years later, Rocky Flats had the opportunity to inherit 125 canned plutonium metal cylinders (3 kg each) from the Lawrence Livermore Laboratories (LLL). Hunt became custodian for these components, too. They arrived in single containment (aluminum cans with rolled steel lids). They could not be used in critical experiments without a secondary container; so Hunt designed this. The aluminum-canned plutonium cylinders were sealed in secondary stainless steel enclosures. Unfortunately, these cylinders also reached an ignominious end in 1983. One cylinder turned to powder upon inadvertent contact with moisture. This problem is discussed in detail in another section; but the metal's presence in Building 886 was doomed. All cylinders were removed from the building and returned to the plant's production stream the same day the powder was discovered. Hopes persisted well into the 1990s that a replacement set of machined

plutonium metal cylinders might be obtained for further experiments; but these hopes dimmed and finally extinguished.

Hunt left the CML for a managerial position at Rocky Flats sometime in the late 1970s or early 1980s. He was a good experimenter, although weakest in experimental design. Hunt was very creative in the application of nuclear criticality theory. He even devised a means of calculating criticality using Collision Probability Theory; and this is published in the open literature. Hunt was killed in a tragic mountain climbing accident a few years after leaving the CML.

This author was the third scientist hired by Schuske to staff his new laboratory. Still very young, his doctor's degree had yet to be conferred when Schuske interviewed him in June of 1963. Security restrictions prevented free discussion about the nature of the work; but enough could be shared to peak the young scientist's interests. The work would involve safety at a plant that handled plutonium and enriched uranium. Only when this naive graduate student returned to the University of Wisconsin did an off-handed remark by one of his professors clarify the scope of his future life. His comment was: "Rocky Flats? Oh, that's the *nuclear weapons manufacturing plant* out in Colorado!"

This author was a fresh PhD in 1964. He lacked professional experience; and he had never even had a college-level course in nuclear reactor theory. He knew little about properties of either fissile material. Was he the right person for the job? His PhD thesis had dealt with nuclear interactions involving charged particles (deuterons) and the lightest nuclei (helium); and now he would be studying uncharged particles (neutrons) and the heaviest of nuclei (uranium and plutonium).

Schuske was, indeed, taking a chance. This young-but-eager person was assigned responsibility for the third nuclear fuel maintained at the CML during its lifetime: a very large inventory of uranyl nitrate solution. He did not even know what this material, yet to be delivered, looked like. His lack of experience revealed itself as three leaks, discussed in another chapter, occurred the first month the solution was in his control (July, 1965).

This author is comfortable about acknowledging his own professional “growing pains” because, overall, he had a very satisfying and successful career. He learned relatively quickly from mistakes and was not prone to repeat them. He participated in almost all 1700 experiments performed at Rocky Flats. He feels good about his contributions to the nuclear industry. During his professional career, he earned his company’s highest world-wide award for scientific achievement among other awards.

His only professional position ever has been at Rocky Flats. His career<sup>17</sup> and the entire life span of the CML are almost coincident. He joined Rocky Flats on August 10, 1964, while the building was under construction; and Building 886 was certified on January 28, 1965. The eventual demise of the CML slowly became evident in the early 1990s; and he retired in 1993. He did maintain office space, however, at the plant through 1996 in order to write about CML experiments under a DOE contract. From then until the present, he has worked out of his home. He has remained closely associated with the CML even to and through its explosive demolition in April of 2002.

<sup>17</sup>Like his colleague, Hunt (who died in a mountain climbing accident), this author suffered a 20-meter fall down a mountainside that interrupted his scientific career for several months in 1986.

This author is amused by noting that he has held one job during one career in one building with one objective while the company he worked for has changed four times and the governmental agency which administered that company’s contract has changed three times. Such longevity flies in the face of modern professionals who tend to move from job to job every few years. His career is somewhat of an enigma.

The 1960s did not know the title “Senior Experimenter.” The three identified above were only *presumed* to lead experiments; but this situation was more understood than official. The three would work in pairs to conduct experiments, although, early on, any knowledgeable scientist drawn from Building 886, including Criticality Engineers, was allowed to assist. Life was pretty relaxed in the late 1960s; and decisions were made more on good judgement than documented policy. This all began to change sometime in the 1970s. The above three became designated: “Senior Experimenter.” Experimental assistants were labeled “Experimenters”; and even knowledgeable Criticality Engineers were no longer allowed to assist in performing experiments. Distinctions grew even more clearly defined as annual classroom training and facility-specific, tailored, examinations—administered by Schuske but reviewed by AEC (Atomic Energy Commission) auditors—became mandated. These training records still exist in the LANL Archives (Box/Folder 33/3 to 9 and 34/1). Eventually, a full list of approved Senior Experimenters and Experimenters, with dates of certification, was maintained on file. Toward the end, three remaining certified personnel and certification *expiration* dates were posted right on the Control Console to make certain no unauthorized person ever took part in an experiment.

On January 20, 1992, certifications expired for this author as Senior Experimenter and for R. E. Miles and J. Wu as Experimenters.

### ***Experimenters***

Even Criticality Safety Engineers were allowed to assist on experiments during the first few years, as already stated. No policies limited roles; the CML Manager's judgement was considered adequate. A partial list of those involved in one or more experiments includes Bruce B. Ernst, Howard W. King, and Lynn A. FitzRandolph. Any omissions are this author's oversight with no intent to ignore contributions. Ernst was the only one of those who seemed to hold "dual citizenship" in Building 886. He was a Criticality Engineer responsible for a certain set of buildings on plant site; but he also took an active role in many experiments. He even led one entire experimental program, colloquially called the "Christmas Tree" study (1967), even though he was never designated Senior Experimenter. His name appears in many Console Log Books spanning many experimental programs. FitzRandolph, on the other hand, had been hired as a "foil activation analyst". The original thought had been that this technique might be employed frequently at the CML in research; but this never came to pass. Still, he found a niche as a Criticality Engineer for a few years before leaving to become a successful Health Physicist in one of the southern states.

Even C. L. Schuske took part in the occasional experiment although, to his credit, he never assumed the role of Senior Experimenter. Participation was infrequent, however; he preferred to let his staff do their jobs. One of the Electronics Technicians (next category) served as an

Experimenter for many years and, eventually, was even certified as such.

Other experimental assistants during the 1960s and early 1970s included Harold E. (Herc) Clark, Merlyn R. Boss, E. E. (Tim) Hicks, and Donald L. Alvarez, although none of them were ever designated Experimenters. The 1970s added Dr. Inki Oh, George Goebel, and Norman Gaylord. Obviously, persons joined and left for one reason or another at different times; so the number of experimental assistants at any one time varied. The total number of scientists in the CML portion of employees in Building 886 ranged from about four to eight.

Tragically, Gaylord was killed in a vehicular accident while jogging along the access road into the plant site. This happened only months after Schuske was killed in a traffic accident. Poignantly, Schuske and Gaylord had become good friends socially and had only recently experienced a "falling out" over a silly disagreement.<sup>18</sup> That situation had not been reconciled by the day Schuske's death became known. Gaylord came to work that morning unaware of events and noticed the long faces filled with grief and reflection. When informed, Gaylord turned, left the plant without a word, and was not heard from for several days. Even efforts to contact him at his apartment were unfruitful. Possibly, Gaylord lamented the absence of reconciliation before that healing process could occur.

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<sup>18</sup>Gaylord had made a scientific observation about some no-longer-remembered technical point with which Schuske disagreed strongly. Subsequently, the former was proven right and the latter somewhat heatedly scolded him for "...not having been more forceful in his argument." This point is made in no way to discredit Schuske, the competent criticality safety expert, but more to show the very human defensive response to an embarrassing situation.

The very early 1980s added Dr. John S. Pearson, Dr. Steven H. Manglos, and Dr. Robert E. Miles. The label Experimenter had, by then, become official; and all three bore that title. Within a few months, Pearson had been named CML Manager and was in training to become a Senior Experimenter, to replace Hunt who had left for another position at Rocky Flats. Pearson served this capacity a year or two but eventually decided to further his career by entering a teaching/research position at a branch of the University in California. He never earned the label: Senior Experimenter. Miles had been associated previously with the facility's computer capabilities when he slowly merged into the additional role of Experimenter. He never was really happy with this identity. He always retained clear recognition as an expert in computer calculations, his preferred role. He did serve a short while as "Project Manager" for the CML; but that label was never clearly defined. Dr. James Wu joined the CML a little later and was eventually appointed CML Manager (1988 to 1990). This, even though he participated in only three experiments as a certified Experimenter.

Later in the 1980s, two other very talented young scientists joined the CML as Experimenters. They were Dr. Richard E. (Rick) Anderson and Dr. Jerry N. McKamy. Both of them had a clear vision for the direction criticality safety experimental research should go; but this differed from that of the Nuclear Safety Group's Manager, J. D. McCarthy. Anderson moved on to become Group Leader at the Critical Experiments Facility, called the Pajarito Site, at LANL. He remains at present at LANL in a different capacity. McKamy became Manager of the CML during the first few years of the

1990s. His task was to oversee the orderly shutdown of the CML and to supervise just one person (this author) as, together, they attended this closure. Later, McKamy moved on to Washington D.C. and joined DOE. Both men have distinguished themselves within the nuclear industry after leaving Rocky Flats. Finally, Dr. R. David Sachs came to the Rocky Flats CML. He, too, remained active in the nuclear business after leaving the plant.

One Criticality Engineer decided to use critical-approach (*In Situ*) experiments directly to solve a couple of plant-related safety problems. He did this before policy determined who was eligible to perform experiments. Donald R. Ferguson designed and performed two of his own experimental studies in the late 1960s. One involved a significant fraction of the world's supply of plutonium metal at the time. The other concerned stacking of waste drums containing plutonium contamination. Both have been documented (with Ferguson's permission) by this author as part of the latter's INEEL contract. Ferguson continues to live in Colorado and was still involved with safety at Rocky Flats as a private contractor, although he left that position in the summer of 2002.

Two other persons—never connected with Rocky Flats in any way—participated as assistant experimenters in two closely related programs. Both happened in 1966 and involved special materials in conjunction with the machined uranium metal components designed by Tuck. Oak Ridge National Laboratory sent E. Charles Crume to assist G. Tuck and B. B. Ernst in a single measurement. Three months later, Norman L. Pruvost, then associated with Lawrence Livermore Laboratory, assisted this author in a set of nine additional experiments involving a different special material. Both studies remain classified.

## ***Electronic Technicians***

Schuske hired Warren Robert (Bob) Sheets to be responsible for maintaining electronic instruments and smaller mechanical components associated with the CML. Bob died during the writing of this book in December, 2001. Sheets was very innovative in his chosen field. His obituary described him as a “self-educated electronics engineer.” He even invented some much-needed instrumentation. An electronic instrument called “A Reciprocal Multiplication Meter” is one of them. This device continuously divides an electrical current proportional to the existing instantaneous neutron counting rate into a current proportional to a preset rate at the start of an experiment. These meters were used to ensure safety and to obtain required data for almost every experiment ever performed at the CML after that time. They functioned remarkably well for many years.

Sheets displayed cleverness early on. In the late 1960s, reciprocal multiplication data calculated on electro-mechanical calculators (then in vogue) were either not reproducible or appeared to deviate markedly from that expected based on other instruments. His detective work exposed the fact that the functioning of electro-mechanical calculators during the time counting channels were tallying up neutrons contributed spurious counts. These came from electrical noise. After that, these calculators were not used while collecting data. Later, the question became mute as modern-day electronic calculators no longer caused the problem.

Sheets began assisting experiments along with many others in Building 886; but he progressed to the official designation of Experimenter when that position opened. He continued in this capacity up

until about 1980 when he left the CML for another position at Rocky Flats. He retired in 1982; but he continued to reside in Colorado until his death. He has occasionally aided this author’s recollection of certain aspects of the laboratory via telephone contacts.

Sheets was replaced by Douglas E. Payne who served the needs of the CML until he died of cancer in the mid-1980s. He was followed, but briefly, by a third electronics technician named Daniel Hensley. He did not stay long. Finally, Howard C. Bachman provided this service for about another decade until the eventual demise of the CML became apparent. Sheets, Payne, and Bachman are now deceased; Hensley's status is not known.

## ***Computational Experts***

Schuske hired two persons in the 1960s to develop and maintain whatever computational capability might be available to the fledgling laboratory: Donald C. Coonfield and George G. Risley. Calculations were severely limited at that time. Hand calculational methods and models derived from reactor theory were well known; but they were not very accurate nor generally applicable to any but the simplest of geometries. By the mid-1960s, the Multi-group Diffusion Code (MDC) was available and the subject of their attention. Risley left the plant in the late-1960s; but Coonfield saw the introduction of transport codes and the earliest statistical (Monte Carlo) codes. Coonfield died many years after leaving the plant.

Deanne Dickinson (later, Pecora) came on board about 1970. She managed the ever-popular KENO code, one of the earliest Monte Carlo type statistical programs, with great skill and creative ingenuity. She was a great asset to the CML and

its programs. Still in the 1970s, Schuske hired Dr. Sidney J. Altschuler for additional work on computer code development. Altschuler's special skill was a creative view of the nuclear world and how to apply it. Both persons drifted away from Rocky Flats for reasons no longer recalled. Altschuler is still somewhat active in the industry; Pecora, not. Robert E. Miles (already mentioned) followed in Pecora's footsteps.

Personnel associated with the CML and its support functions (electronics, computers, etc.) were both varied and innovative. Personalities differed as much as their backgrounds, strengths, and weaknesses. Still, each one of them became a valued friend during this author's long association with the CML Facility, discussed next.





## ***The CML Facility***

Clarence Lee Schuske's dream of a Critical Mass Laboratory at Rocky Flats began to assume the form of concrete and cinder block early in 1964. More than a decade of attempting to provide important safety information based on extremely meager data would soon come to an end. The new facility would greatly improve nuclear criticality safety at Rocky Flats. The birth of the Rocky Flats CML precisely coincided with the very beginning of this author's professional career. Sadly, its demise closely followed his retirement. Poignantly, the building found itself nothing more than a ghostly shell replete with the faint hollow echos of a once-proud past at the start of this book's writing and an unrecognizable pile of rubble upon its publication.

This chapter is quite lengthy because so many details spanning three-and-a-half decades bare importance. To facilitate locating specific topics, a number of sub sections are identified. Major headings are larger and bold faced. Secondary categories are smaller font but still bold faced. Lesser headings appear in italics; and even lesser ones are set off between dashes. More important rooms are discussed in greater length and show more subheadings. The building, itself, and at least each of the more important rooms contain the following details: (1) the purpose of the room, (2) dimensions including floor elevation relative to the main level, (3) wall, roof, and floor thicknesses, composition, construction, and maintenance policy, (4) door and window details, (5) ventilation, (6) security procedures, safeguards

measures, fire or heat detection, and criticality alarm coverage when not discussed elsewhere, and (7) normal room occupancy.

A separate outline is presented on the next page because this is such a lengthy chapter. This outline for just this chapter is similar to a book's Table of Contents. It aids the reader's rapid search for specific information about a particular aspect of interest. An interesting observation is that many photographs in the first pages of this chapter depict the block-upon-block construction of the building while those in the closing pages show the demolished structure.

### **Site Location**

The specific site selected for construction was just south of the main road passing east/west through the plant—later named “Central Avenue.” It was also toward the eastern end of the plantsite. The office area would face north with experimental areas looking south. That particular location on this plantsite made sense in the 1960s. This new facility would handle *both* enriched uranium *and* plutonium. Other buildings on plantsite associated with uranium handling were to the south and west of the new facility while “plutonium buildings” were just across the street to the north. One (Building 81) had been part of Rocky Flats's earliest construction and was heavily associated with processing enriched uranium metals and solutions.<sup>19</sup>

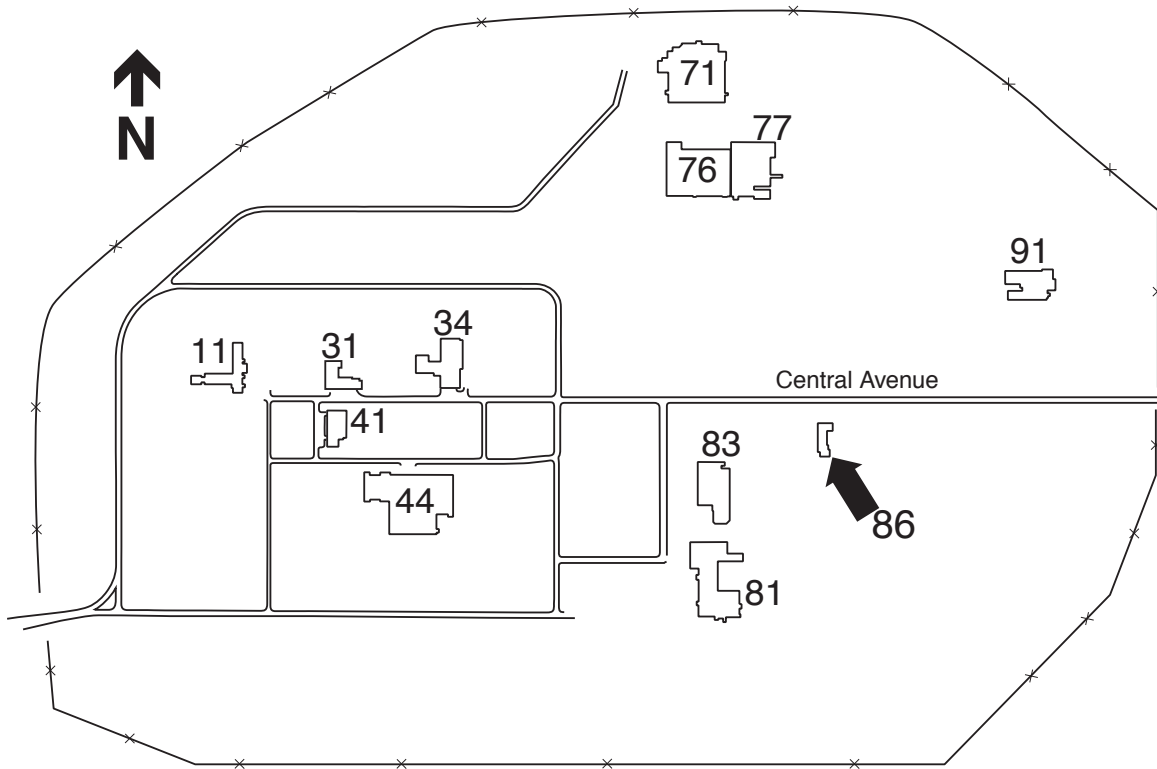
<sup>19</sup>The building, constructed during the early years of the Cold War, extended many floors below grade as a measure to foil espionage attempts to learn the capacity of the building's operations by knowing floor areas.

Chapter Outline

Site Location	Hallway
Initial Construction	Airlock
Assembly Room (Room 101)	Cold Area – Initial Construction
Initial Construction	Related to CML Experiments
Assembly Room Leak Rate	Control Room
Assembly Room Access	Control Console
Ventilation	Behind the Control Console
Walk-In Hood	East Wall
Elevated Platform	The “Shop”
Miscellaneous Items	Foil Counting Room
The “Four Reactors”	Mechanical Room
Vertical Split Table	Electrical
Solution Base	Water
Horizontal Split Table	Criticality Alarm
Liquid Reflector Apparatus	Ventilation
Vault Room (Room 102)	Room 106
Initial Construction	Office Area
Room Modifications	Office Area Modifications
Enlargement	Ancillary Features
Mixing Room (Room 103)	Filter Plenum – Initial Construction
Initial Construction	Building 875
Uranium Solution Handling System	Holding Pit
Fissile Solution Tank Farm (1964)	Portable Waste Water Disposal Tank
Evolution of the Uranium Solution Tank Farm	Evaporator
Uranium Solution Handling System in Room 101	Storage Shed
Tank Farm Plumbing	Sewage Lift Station
Uranium Solution Pumps	Transformer Pad
Other Tank Farm Changes	Fences
Changes Other Than Tanks or Plumbing	Building 986
Walkway	Decontamination < .... < Demolition
Rings on the floor	Uranium Oxide
“Plutonium” Glovebox	Uranium Solution
The Upper Level	Raschig Rings
Initial Construction	Tank Removal
Other Uses of the “Upper Level”	Uranium Metal Hemishells
The Plutonium Metal Handling Facility	Equipment
Down Draft Room	Miscellaneous Steps Toward Shutdown
(Handling bare plutonium)	March 18, 2002
Plutonium Glovebox	April 13 and 14, 2002
(Handling Procedures)	Epitaph
Waste Handling	
Solid Waste	
Liquid Waste	

Two other “uranium buildings” were also on the south side of the plant: Building 83 and Building 44. Buildings associated with plutonium processing, on the other hand, were located on the north side of the plant. Buildings 71, 76, and 77 had been constructed early in the site’s history and were already entrenched in plutonium recovery, reprocessing, and fabrication associated with the nation’s nuclear weapons capabil-

ity by the time the Critical Mass Laboratory even began to sprout. Finally, the building from which all fissile materials were shipped or received, Building 91, was located on the northeast corner of the plantsite. A map of the site as it existed in 1964 is shown in Fig. 8. Several principle buildings are included but not all are shown.



*Fig. 8. The Rocky Flats Plant Site approximately as it was in 1964. Building 86 is highlighted by an arrow; and most major production building associated with the plant's mission are shown. A number of non-production buildings extant in 1964 are not shown for clarity. Buildings predominantly associated with uranium include Buildings 41 & 44 and 81 & 83. Plutonium buildings north of the main road (later called Central Avenue) include Buildings 71, 76, and 77. Building 91 was associated with shipping fissile materials. The only non-production buildings shown include Building 11 (main administrative building), Building 31 (Fire Department), and Building 34 (craftsmen's shops). The drawing was copied from a much later version and may have a few errors in road placement for 1964. The fenced perimeter is not accurate.*

This division of the plant, with the north side supporting plutonium processing and shipping and the south side associated with uranium processing and the CML, began to make less sense in the 1960s. That is when the government decided to transfer essentially all weapons-related functions involving enriched uranium away from Rocky Flats in favor of the Oak Ridge facility in Tennessee. That left the north side of Central Avenue with almost all the plant's fissile material. Only the CML was left south of that road with a significant inventory of fissile materials. A couple of other buildings had vestigial amounts of

uranium; but some possessed so little that their criticality alarm detection units could be safely disabled.

That distribution of fissile materials around plantsite made even less sense when increased world-wide political tensions prompted the government to require greatly enhanced security around buildings containing major amounts of fissile material. This happened in the late 1970s. The north side of the plant became a "Protected Area" (PA) and was often referred to as the "Protected Security Zone" (PSZ). Two very secure fences separated by a wide expanse of defoliated

land surrounded the PSZ. Elevated Watch Stations were built to provide continuous visual surveillance of this zone. Other security measures were also implemented. That the CML was not included within this protected area was always an embarrassing problem. Special security measures had to be implemented for just this one building.

Naturally, the plant grew during its first 20 years. The number of buildings multiplied rapidly. Two-digit building numbers would soon prove inadequate. So, in 1968, all building numbers were increased to three digits. The new number was added as a prefix to the existing number; and these prefixes were strongly associated with regions of the plant. Buildings close to the CML received an additional “8.” Thus, Building 86 became Building 886. Building 81 became 881 and so on. Often, buildings were referred to by number alone. Plutonium buildings fell into the 700s, although two large buildings—added much later toward the western end of the site—were numbered 371 and 374. Fissile material was still shipped in and out of Building 991. Administrative buildings fell into the 100s and were at the western end of the plantsite. Generally, the higher “hundreds” were further east. Building 991, in fact, was close to the eastern boundary.

The foothills to the Colorado Rocky Mountains rise sharply out of the plains just a few miles west of the plant. The entire plantsite slopes gently downhill from west to east. The contour lines passing through the location of Building 886 are quite close to 1829 m (6000 feet). The floor of the office area was 1825.3 m above sea level. Elevation and ground slope are somewhat important in considering some of the water leak problems discussed elsewhere.

## Initial Construction

The new facility would be a single building in the southeast quadrant of the plant. That building would be surrounded by a fence set far enough from the building to provide some measure of security against unauthorized access as well as protection against the possibility of radiation danger from a nuclear criticality accident within the building. Access to this area was controlled through a security post and would both protect classified information and safeguard fissile material. A considerable amount of classified information was handled there although little was associated with experiments. In addition to the building, only an underground pit west of the structure and a small facility associated with sewage disposal marred the barren earth within the fenced boundary.

Building 86, later 886, was a relatively small single-story structure. The building measured 54.7 m long (north/south) by 18.3 m wide. Most of the building stood only 3.2 m high to the eaves. The tallest point was 10.4 m above surrounding ground. Similar facilities at Los Alamos and Oak Ridge were considerably larger; the one at Hanford, only a little larger. A floor plan of the original facility is shown in Fig. 9. Construction made rapid progress during the summer and fall of 1964 as portrayed in Figs. 10 to 16. Most figures show two closely related photographs revealing almost week-to-week growth. The first pair of photographs (Fig. 10) show the Assembly Room under construction but the office area not yet begun. These were taken in July 1964. The six photographs of Figs. 11 through 13 show growth through the end of August. Workers in the bottom photograph of Fig. 13 could see inside the Mixing Room; and the Holding Pit is seen in the lower foreground.

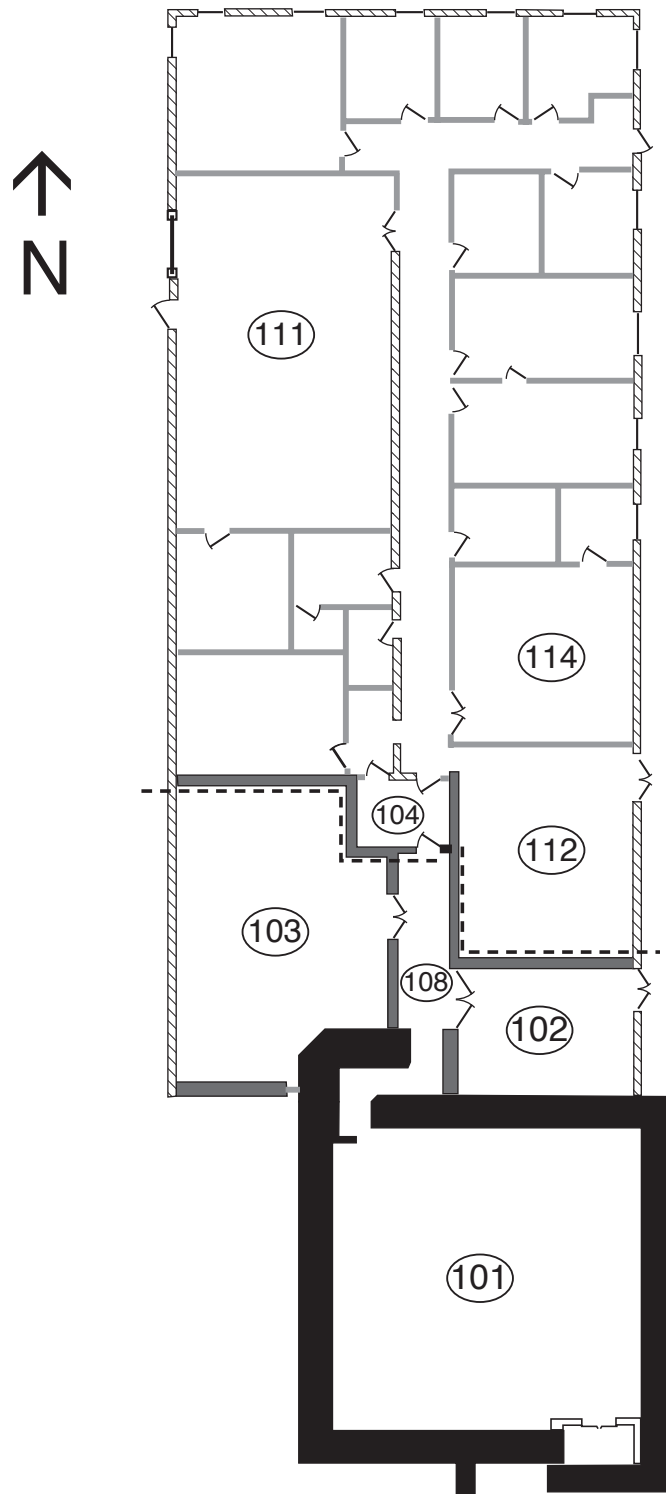
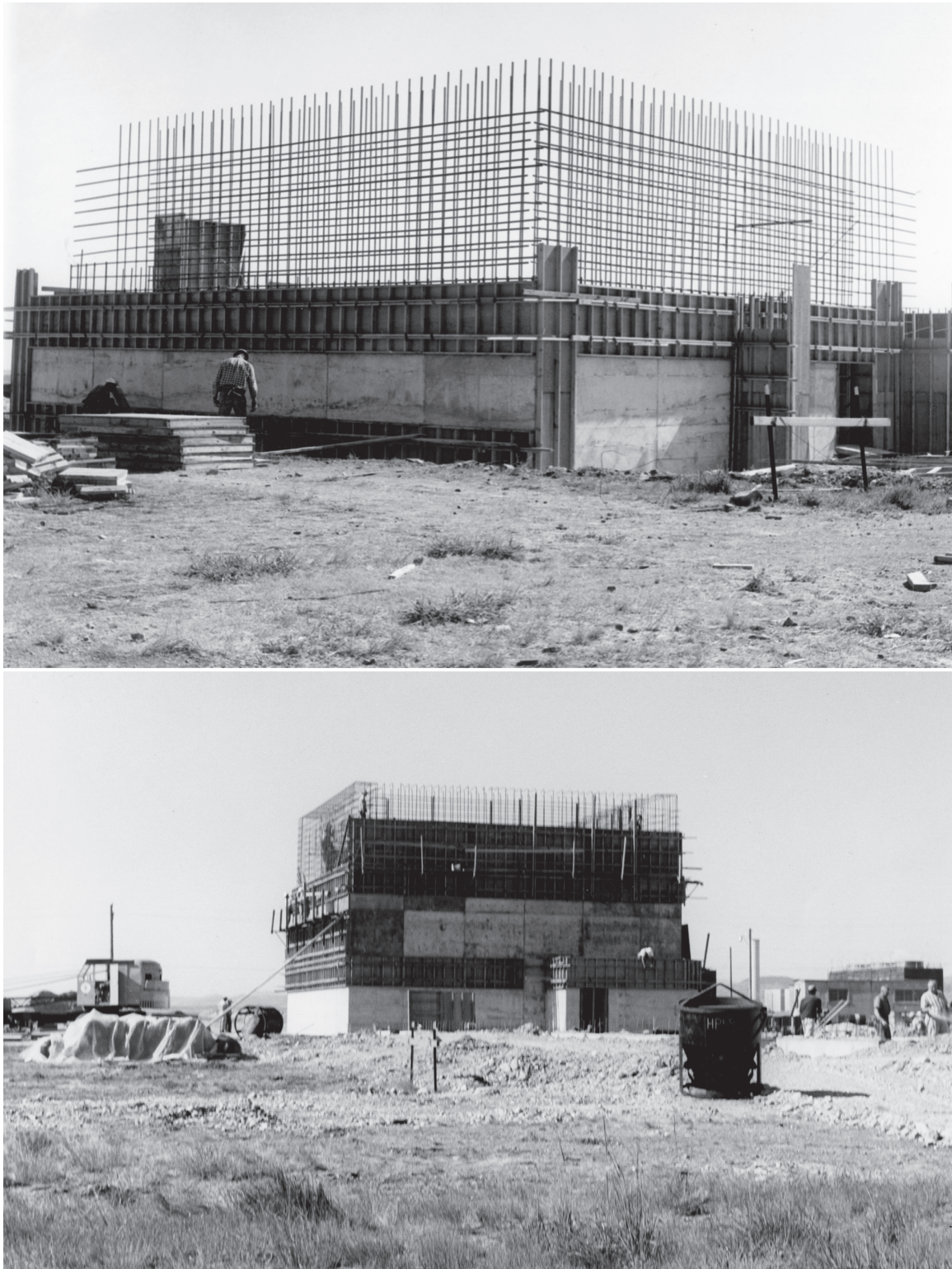


Fig. 9. This plan view of Building 86 in 1964 shows the offices and other “Cold Area” rooms north of the “Hot Area.” Dashed lines separate the two. The Hot Area consisted of the Assembly Room (101), the Storage Vault (102) where most solid fissile materials were stored, the Mixing Room (103) where the uranium solution was housed, and their common hallway (108). The Control Room, which was used for controlling reactivity addition devices remotely and monitoring critical experiments, was Room 112.



*Fig. 10. The Assembly Room is shown just started in this July 8, 1964, photograph (top). The camera is looking northeast. That same month, July 23rd (bottom), rebars are bent at the top to tie into the thick concrete ceiling. The view looks almost straight north.*

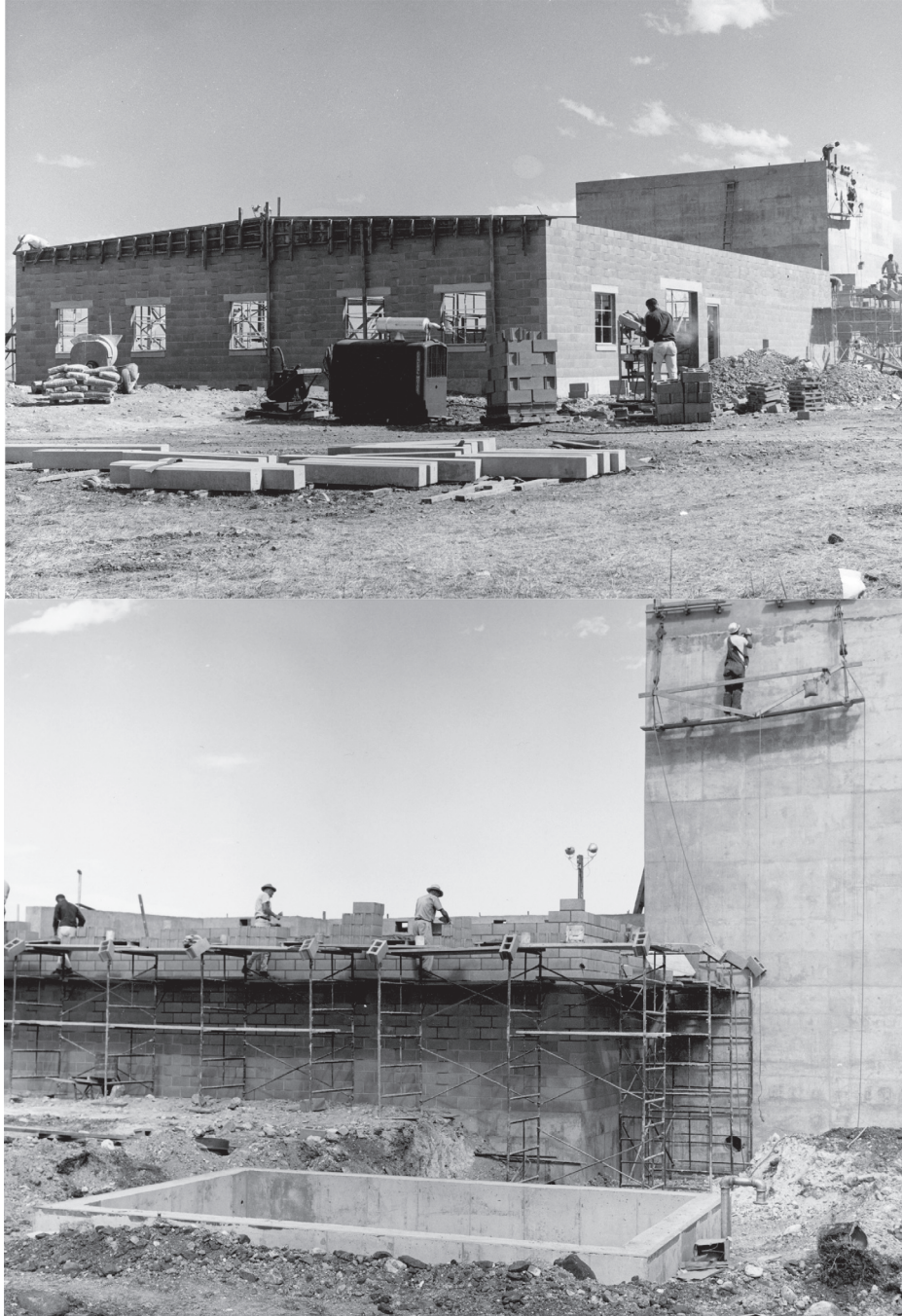


*Fig. 11. The walls of the office area had just been started by August 20, 1964, (top); but 11 days later, the north wall (bottom) was essentially finished. Cinder block along exterior walls and one interior north/south wall along the hallway was backfilled with rebar and mortar to provide load-bearing walls. The Assembly Room had been completed some time prior to August 20 since concrete forms are being removed in the top photo.*



*Fig. 12. Conduit along the south wall of the Control Room (top) eventually carried electrical and electronic cables into the Assembly Room (bottom) and the rest of the Hot Area. The two sets of three and two sets of two large-diameter conduits in the Control Room (top) in this August 31st photograph match up with the same conduits along the north wall of the Assembly Room (bottom) in this July 23rd photograph. The top photograph is looking south; the bottom, north.*





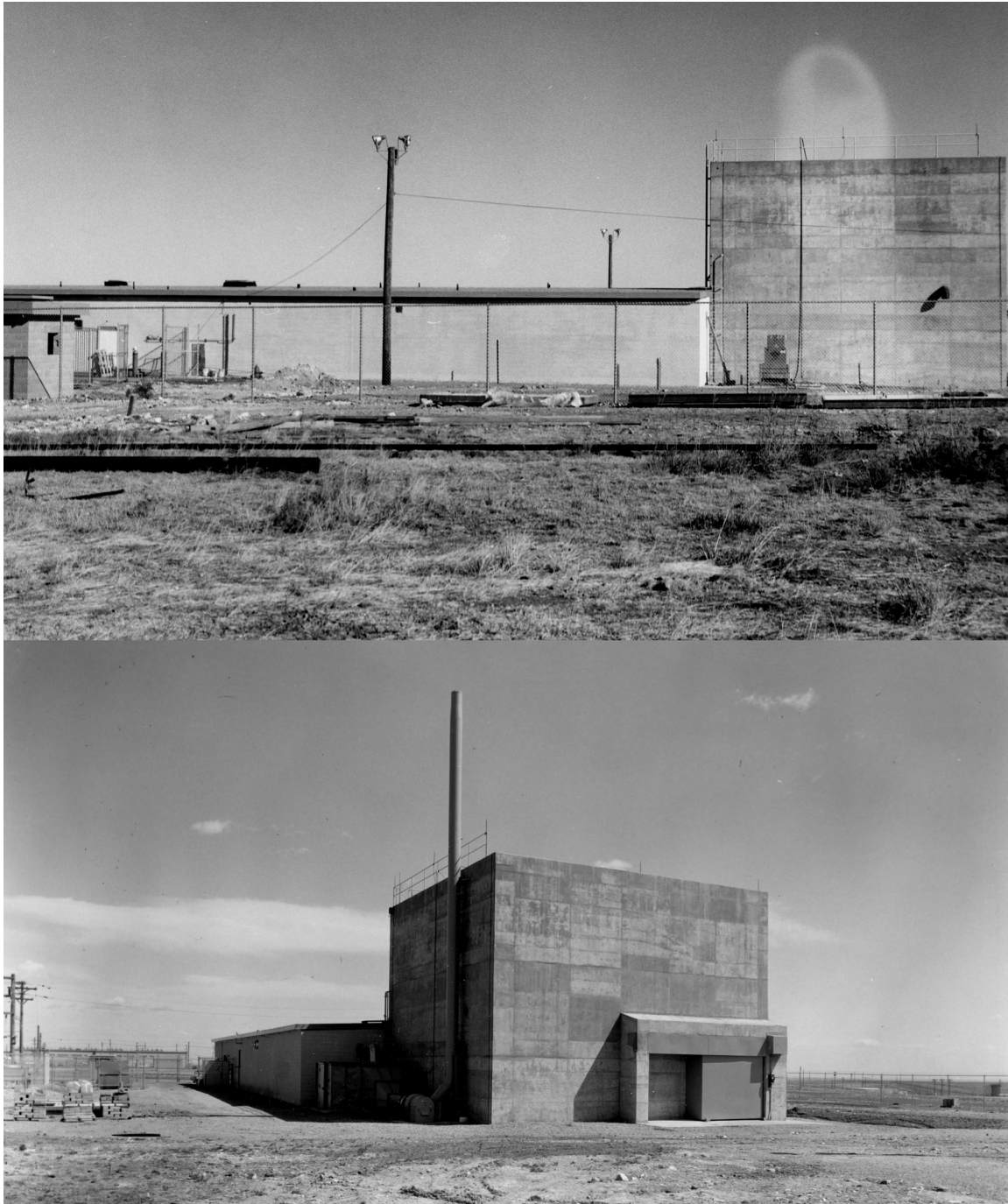
*Fig. 13. Sun bathes the nearly completed west wall of the office area in this view looking south and a little east on August 31, 1964, (top). Scaffolding to the extreme right, seen again in the bottom photograph (looking east and a little north) on the same day, reveals that the west wall outside the Mixing Room was not quite complete. The bottom picture illustrates two other important features. The deep Holding Pit, which would later house three Raschig ring filled tanks, shows clearly in the foreground. The below-grade hole in the Assembly Room wall—seen just behind one leg of the scaffolding—would later connect the building’s Hot Exhaust filter system inside the Assembly Room with the yet-to-be-built outdoor Filter Plenum structure. This 250-mm-diameter hole is part of the buried line that still contained some small amount of uranyl nitrate salt following the 1967 contamination incident discussed in the text at the time of demolition in April 2002.*



*Fig. 14. Shadows grow on the Labyrinth wall in the depressed pit area of the Mixing room in this August 31, 1964, photograph. The notch in the upper level (foreground) will have steps to the Pit Area which later will house the Tank Farm.*



*Fig. 15. The entire Building 86 appears nearly finished in this October 24, 1964, photograph (top). The view is looking southwest with the east wall bathed in sunlight. Two light-weight steel doors have not yet been installed. The near one opened to the Control Room. The one next to the wheel of the road-grader led to the Storage Vault—interesting in light of more modern safeguards measures. This room would contain several hundred kilograms of enriched uranium and plutonium metal. The cinder block wing projecting from the wall near the north end of the building was a shield against strong Colorado winds protecting the would-be main entrance to the office area. The bottom photograph was taken the same day and looks north and a little west. The heavy, thick, concrete Shield Door will be installed in the concrete projection off the south wall.*



*Fig. 16. By November 11, 1964, the perimeter fence had been installed (top). The Filter Plenum structure is still absent at the far right of the picture. The dark area just above the top rail of the fence and on the west wall of the Assembly Room is an air intake duct leading to the Air Handling Unit just inside the Assembly Room. The odd shape of this duct is the result of the sun's shadow on the wall. The Lift Station for pumping sanitary waste is the small, square, cinder block building to the extreme left. The bottom photograph presents the completed building on May 5, 1965, three months after the facility was officially certified to become a Critical Mass Laboratory. This happened January 28, 1965. The Filter Plenum structure, its tall exhaust stack, and the concrete Shield Door are in place. The air intake duct has been made flush with the wall to make room for the stack. This was, perhaps, the first modification to the originally-planned building.*

One detail figure (Fig. 12) shows sets of conduits that would later carry control cables between the Control Room and rooms inside the Hot Area. Another detail (Fig. 14) taken August 31, 1964 shows the truncated corner of the Labyrinth at the south end of Hallway Room 108. By late October, both views of Fig. 15 show the building nearly complete; only a few doors and landscaping needed be done. The bottom photograph of Fig. 16 shows the completed facility in May 1965, a few months after its official certification as a Critical Mass Laboratory on January 28, 1965.

— Documentation —

Details of the initial construction of the building are contained in two important documents. One of these is a thick book called

“SPECIFICATIONS for NUCLEAR SAFETY FACILITY, BUILDING 86, USAEC ROCKY FLATS PLANT, DENVER, COLORADO”

This formal document constituted a binding agreement between the owner, the U. S. Atomic Energy Commission, Albuquerque Operations Office, Rocky Flats Field Office, Denver, Colorado, and the builder, Stearns-Roger Corporation, 660 Bannock Street, Denver, Colorado. No date is given on the sole remaining copy of this book; but it was in response to “Invitation No. 292-64-22.” The “64” is presumed to refer to 1964. The second document mentioned above is a set of D-sized construction drawings for the facility. These “As Built” drawings, so certified on June 23, 1965, bore two numbers. First, Stearns-Roger numbered them RF-AC-86-X-yy where “X” represented a letter characteristic of particular phases of construction such as architectural (A), structural (S),

mechanical (M), and so on; and numbers “yy” represented sequential drawings within that category. The Dow Chemical Company, the government’s prime contractor at the time for Rocky Flats, numbered these same drawings 14823 through 14852 with several drawings having extended sequential numbers “-z.” Many details expressed in this document originally came from this author’s memory but were verified by referencing either or both of these important documents. Copies of these documents held in the author’s possession may well be the last remaining copies; but all will be donated to the LANL Archives upon publication of this book.

— Construction Summary —

Most of the building was constructed using ordinary commercial cinder block. Outside walls to the east, west, and north were also backfilled with mortar into which rebars had been inserted. These filled interior holes cast into the commercial block and yielded load-bearing walls. One long, north/south wall along the west side of the interior hallway was similarly back filled; and this provided the central load-bearing wall to support the roof.

The roof, itself, was a sheet metal pan surface overlaid with tar and gravel. Roof supports were light-weight, open-mesh, truss-like “girders” welded together from metal rods and angle stock. Trusses were spaced 1.22 m apart. The roof’s gentle slope was about 16:1. The floor in this part of the building was a simple slab of concrete 152 mm thick.

The entire building was divided into two areas with respect to radioactive materials. The portion to the north presented little risk of radioactive contamination or hazardous radiation; so this was called the “Cold Area.” Offices and support rooms serving the CML as well as offices

for the plant's Criticality Safety Engineers were contained there. The rest of the building, to the south, housed large amounts of fissile materials used in critical experiments. Both radiation and radioactive contamination were an ever-present possibility in this area; so it was termed, in contrast, the "Hot Area."

The Hot Area consisted of three rooms joined to a common hallway. Critical and nearly critical experiments were mostly performed in the Assembly Room (Room 101). Both references to that room (name and number) are used interchangeably throughout this document. The other two rooms provided storage for fissile materials. Room 102, sometimes called the "Vault Room," became the residence for solid fuels. Again, both description and number are used to refer to this room. These materials included the double set of nesting enriched uranium metal shells, the doubly-canned machined plutonium metal cylinders, and cans of compacted low-enriched uranium oxide powder. Only the bare plutonium metal shells, of the solid fissile materials, were stored elsewhere. A number of neutron and two gamma ray sources<sup>20</sup> were also housed in Room 102 when not in use. The third room was the Mixing Room (Room 103); and, here again, both terms are found throughout this document. This room housed the large inventory of enriched uranyl nitrate solution in a storage tank farm. This farm was situated in a depressed pit. The pit was an engineered safety feature limiting solution movement in case of a solution spill or leak in a tank. Room 103 also ended up housing

<sup>20</sup>Uranium experiments required small capsules which contained neutron generating materials such as mixtures of Polonium and Beryllium or certain isotopes of Californium. These are referred to as "neutron sources." A similar gamma ray source was needed for daily testing of a gamma ray detector in the Assembly Room.

the set of bare plutonium nesting metal shells simply because the floor area above the pit had enough room for the required glovebox and attached Downdraft Room.<sup>21</sup> Initially, the depressed pit area was operationally segregated into two regions. One was open and contained uranyl nitrate solution storage tanks. The other contained tanks within an enclosed stainless steel room along the west wall. It was naively thought, in the 1960s, that plutonium solution would be housed there at some time in the future. A glovebox enclosing valves to be associated with the movement of plutonium solution was built contiguous to the stainless steel room. Both the stainless steel room and the glovebox later became an extension of the uranium solution handling system. Finally, one corner of Room 103 had a small L-shaped laboratory area for chemical operations related to managing thousands of liters of hazardous fissile solution.

All three rooms in the Hot Area branched off a common hallway although this hall took a Z-shaped approach to Room 101. This peculiar passage was called the "Labyrinth" and was a radiation safety measure. Radiation from a possible nuclear excursion in Room 101 could not stream down the hallway because of this offset route. This hallway, including the Labyrinth, was given a room number: Room 108.

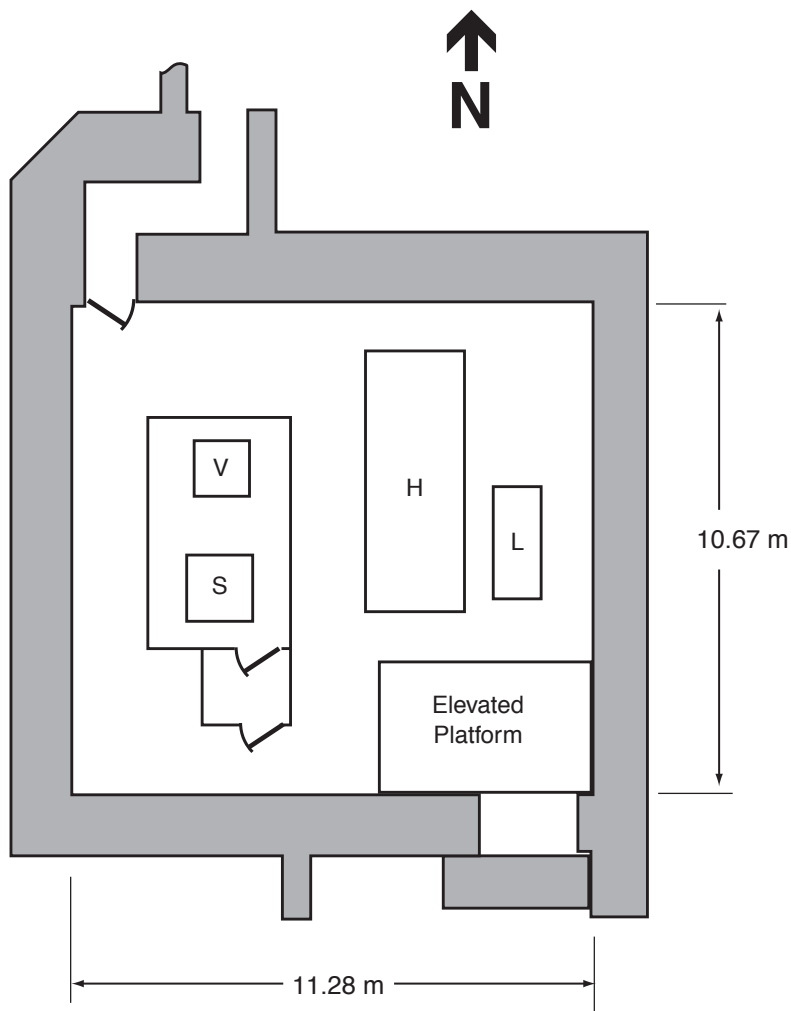
The four above-named rooms are described below in much greater detail. These rooms are integral to CML activities, so this additional description seems prudent in this document. These descriptions always begin with the initial conditions of the mid-1960s. The discussion then continues, presenting modifications, expansions, abandonments, etc. for each room.

<sup>21</sup>Bare plutonium metal cannot safely be handled out in the open.

### Assembly Room (Room 101)

The office area was constructed one way; but the rest of the building was constructed differently because it served a very different purpose. The Assembly Room—inside of which about 1700 experiments were to be performed throughout the active lifetime of the CML—was a large concrete room containing only a few items large enough and/or close enough to experiments to provide any significant neutron reflection. A floor plan of this

room is shown in Fig. 17. Major components which might reflect or moderate neutrons are also shown. This includes the four Reactivity Addition Devices recognized by DOE, the rectangular walk-in hood which surrounds two of them, and the concrete-and-steel Elevated Platform situated just above the Blast Doors in the southeast corner. All these features existed in 1964 except the Elevated Platform and the Liquid Reflector Apparatus shown close to the east wall in the figure.



*Fig. 17. The Assembly Room, at the south end of the building, contained four “reactivity addition devices” which were defined to be “reactors” by DOE Order 5480.6. Two of these, the Vertical Split Table (V) and the Solution Base (S), are shown in the west half of the room enclosed within the Walk-In Hood. The Vertical Split Table was never actually used. The Horizontal Split Table (H) was another “reactor.” The fourth was called the Liquid Reflector Apparatus (L). It was the only somewhat portable machine although it generally remained to the east or south of the Horizontal Split Table during its lifetime. This apparatus did not exist in 1964 but was constructed for the very*

*first uranium metal studies in the fall of 1965. The Elevated Platform in the southeast corner also did not exist upon completion of the building; it was built for the first Annular Tank program in the fall of 1980. Two Blast Doors under the Elevated Platform are not shown.*

### Initial Construction

The interior of the Assembly Room measured 11.28 m in the east/west direction by 10.67 m north/south. The room was 9.75 m high to the ceiling. The north wall was 1.52-m thick; but the other three were only 1.22 m thick. The north wall was made thicker because people occupied rooms to the north; and the small additional shielding would further protect them from radiation during experiments. The ceiling was 0.61-m thick. The floor was 0.20-m thick but rested directly upon compacted earth. The Assembly Room Floor was 150 mm lower than the floor throughout the rest of the building. Interestingly, the floor was isolated from the walls by thin rubber pads; so the floor was, indeed, free to creep small amounts over long times without cracking.

The floor also had cast into it a total of 22.5 m of “cable trenches.” These were troughs in the floor designed to carry electrical wiring, coaxial signal cables, hydraulic lines, and a myriad of other hardware associated with experiments. The trenches were “U” shaped and about half a meter wide by slightly deeper. One solution spill in the late 1960s allowed some uranium solution to flow into the trenches. Only then was it recognized that criticality could easily occur in these troughs if a large spill ever were to occur. To combat that possibility, the trenches were cleaned as well as possible<sup>22</sup> and back-filled with fresh concrete. The concrete was leveled off to a height only 76 mm below the floor level; and this dept would be critically safe in the event of any spill. This work was done in January of 1980. Still later, overhead metal cable trays were installed;

<sup>22</sup>Some contamination is certain to have remained behind. Persons involved in demolition were made aware of this possible source of contamination.

and the contents of shallow floor-level cable-ways were raised to just overhead. Additional concrete filled in the cable trenches completely in the spring of 1985 — leaving a second possible level of uranium contamination buried in concrete.

Concrete walls and ceiling were to have been formed in one continuous, monolithic (seamless) pour in 1964. This author wonders, however, how a monolithic pour can be spread over more than two weeks as Figs. 10 and 11 clearly depict. Nonetheless, the building’s Specifications spelled this out explicitly. One drawing, however, in the As-Built construction set dated 1965 may address this question. That drawing shows an approved *revision* that allows three construction joints over the height of a wall, one being where the roof overlapped side walls. Each construction joint had a rectangular keyway cast into it and a 150-mm-high vinyl waterstop barrier embedded in the concrete at these cold joints. Final resolution of this detail may never be known for certain. The goal of any construction method, however, would be to avoid leaks which might affect the room’s ability to contain radioactive fission fragments following an assumed nuclear excursion. That goal seems to have been met whether or not the pour was truly monolithic.

The concrete was quite common in industrial applications of the day. Type I Portland cement was used with a density of 307 kg/m<sup>3</sup>. The maximum content of chemically pure water in the fresh mix was 30 kg/m<sup>3</sup>; and water was allowed to have been added to the dry mix no more than one hour prior to the pour. The allowed aggregate sizes ranged from 6 to 18 mm. This rock was required to be low in amorphous siliceous materials. Walls were strengthened with two layers of crossed steel rebar. These are clearly seen in both



photographs of Fig. 4. One layer was about 80 mm in from the outer surface; the other, the same distance from the inner surface. Horizontal rebars were #8 on 0.3 m centers; vertical ones were #6 on the same centers. Approximately 7000 kg of steel strengthens the concrete of the entire room.

Walls were not yet painted in 1964. Both inside and outside walls were eventually painted and periodically repainted thereafter throughout the life of the facility. Interior walls were painted to seal concrete against absorbing contamination, providing a brighter interior, as well as attempting to improve the room's ability to contain fission fragments in the event of an accident. Exterior walls were painted also; and this was often associated with the same attempt to improve the room's leak tightness. Painting almost always happened just prior to an annual leak rate measurement, although repainting was not required every time because of this. Exterior walls were painted with the inside of the Assembly Room isolated from the environment and subjected to a partial vacuum. This would tend to suck wet paint deeper into any crack improving the seal. Conversely, the interior of the room was painted with workmen sealed into the room and working in a somewhat pressurized room. This, too, would tend to push wet paint into cracks. The interior color was always an off-white with walls and ceiling the same color. The floor was usually painted with a grey epoxy paint. The exterior was given some color for cosmetic purposes. Shortly after Rockwell International took over management of Rocky Flats, the building was painted blue which happened to be the company color.

### *Assembly Room Leak Rate*

Integrity against air leaks was important for environmental protection because one possible consequence of a nuclear excursion (prompt criticality accident) could be a sudden air pressure increase within the room. A leak-prone wall could permit escape of radioactive nuclides into the environment. Recognizing this potential, an annual leak rate test of the room's integrity was implemented. The original pass/fail criterion was that the Assembly Room shall not leak more than 0.5% of the room's volume per hour; and this leak-tightness must be maintained for six hours. This leak rate measurement must begin with an initial overpressure of 1.13 g/mm<sup>2</sup>. Test results mandating both an hourly leak rate and six times that for the six-hour leak rate ensured a linear leak rate.<sup>23</sup> The origin of these parameter specifications is no longer recalled; but the starting pressure probably resulted from some estimate of the maximum pressure from some hypothetical assumed maximum excursion. Within a few years, however, one CML staff member (D. C. Hunt) proved that adequate environmental protection could still be guaranteed with a less restrictive leak rate; and he succeeded in getting the AEC-approved leak rate relaxed to 2.0 volume percent per hour over a span of six hours (12 vol-%). The initial overpressure remained the same, however. This change was approved by the AEC in April of 1967.

Even the more-restrictive leak rate was successfully passed the first few years. As the facility aged into its first decade, the room often passed the less restrictive leak rate; but, occasionally, a preliminary

<sup>23</sup>Theoretically, passing the first hour's leak rate almost ensured passing the six-hour test. Any loss of pressure in that first hour meant that subsequent hours were subject to smaller overpressures—and a smaller pressure differential—than the initial one.

hour-long measurement showed the full six-hour test would fail. Even these failures did not greatly exceed the allowed leak rate. Whenever they did occur, however, experimental programs would take a back seat in favor of proper maintenance to ensure the better leak rate. This maintenance often was satisfied by just painting the Assembly Room inside and/or outside. Painting the outside was occasionally preceded by sand-blasting first to ensure better penetration. Repainting the outside always used the reduced interior pressure technique mentioned above while repainting the interior was done with a slight overpressure inside the room.

Before the test, itself, a careful examination of the room's physical condition would reveal any gross potential leaks. For example, interior wall surfaces were inspected by hand using a child's soap-bubble solution while the room was under a reduced pressure. Soapy liquid would be brushed onto the wall watching for air bubbles to rise through the solution. These bubbles indicated leaky areas.

Other efforts were made to ensure the room's leak tightness. The need for containment integrity was recognized even prior to construction; so the several large-diameter conduits connecting the Control Room to the Assembly Room (see earlier construction photographs) were back-filled with a beeswax-like substance called Chico<sup>®</sup>. This product was added to the conduits after all cables were in place. It filled the spaces between cables and between cables and the conduit itself and would prevent air escaping from the intentionally overpressurized room. Recognizing that the addition of Chico would never permit introduction of later cables and wires, a number of spare lines were installed in 1964. Then, Chico was introduced both at the Control Room end and also at

the Assembly Room end of the conduit runs. The soap bubble procedure was often used at both to ensure no bubbles were seen.

Another attempt to ensure the room's containment concerned the walk-in Hood. As built in 1964, the Hood's stainless steel floor exhibited a slight tendency to flex under foot when walked on. The flexure was not large but might have had safety implications. This problem was solved by "shooting" nails through the metal into the concrete floor. Nail heads were welded to the floor itself to contain spilled liquids. Nailing was done in a square pattern about half a meter on a side. The improvement worked well; the floor never again flexed under foot. The few dozen nails shot into the concrete floor, however, raised a concern over their impact on leak rate measurements. Nails might easily have caused tiny cracks in the concrete floor which, in turn, might be an escape route for overpressurized air. To counter this potential, a sticky solution of Water Glass<sup>®</sup> (sodium silicate) was poured into the perimeter trough surrounding the base of the Hood. The liquid was allowed to seep under the floor between stainless steel and concrete. In theory, it would plug any cracks caused by the nails. The product remains a viscous liquid when not exposed to air; so the fix was expected to last a very long time. The value of this step is not known with any great degree of confidence.

This sodium silicate solution was the source of one anomalous event discussed in another chapter. After decades of service and proper containment, some of this liquid finally leaked out from under the Hood along its west wall. Now exposed to air, it hardened and turned an off-white color. The suspicious color and unknown source of the finding gave rise to speculations it might be some form of fissile contamination. That was, of course, not the case.

The entire history of results for the Leak Rate Measurement—1965 to 1987—is presented in Table I. The first three years passed even the most stringent requirement (0.5 vol-% per hour and 3 volume-% over six hours). A scan of the table reveals a trend toward increased leak rates. Early rates of 2 to 5 % slowly grew to between 6 and 8% in the final few years. Still, no results even closely approached the allowed 12 vol-% maximum leak rate. The table shows dates of measurements along with observed leak rates and the initials of the person(s) conducting the test. These are spelled out in the list below:

- WRS: Robert Sheets
- CLS: Clarence Lee Schuske
- DEP: Douglas Payne
- GT: Grover Tuck
- DLA: Donald Alvarez
- HEC: Harold Clark
- DCH: Douglas Hunt
- NDG: Norman Gaylord
- RER: Robert Rothe
- GRG: George Goebel
- HCB: Howard Bachman
- JSP: John Pearson
- SHM: Steven Manglos
- REA: Rick Anderson
- JNM: Jerry McKamy
- RDS: David Sachs
- JMW: James Wu
- REM: Robert Miles

Interestingly, this list names almost all personnel ever employed at the Rocky Flats CML. The only names missing belong to Bruce Ernst and Inki Oh who, apparently, never helped with Leak Rate measurements. Early written reports of leak rates were quite lengthy. The 1965 report, for example, became a formal plantwide formal document (RFP-684) and was 22 pages long. Later, reports became both much shorter and more casual.

**Table I. Assembly From Leak Rate Measurements Between 1965 and 1987**

Date of	Mesured Leak Rate	Initials of Personnel Performing the Test or (Source of Data)
8/4/65	2.06	Probably WRS
12/28/65	2.33	Probably WRS
4/4/66	2.30	Probably WRS
5/23/67	4.19	WRS
3/5/68	2.43	(letter from Loren Matheson)
11/13/69	4.67	(letter from CLS)
1/9/70	4.39 or 4.10	Probably WRS
1/27/71	4.48	WRS, DEP, GT
2/29/72	4.48	WRS, DEP, DLA
5/10/73	3.10	WRS, DEP
2/7/74	3.87	WRS, HEC, GT
4/22/75	2.82	WRS, DEP, GT, DCH
5/5/76	3.43	WRS, DEP, GT
4/14/77	5.36	WRS, DEP, GT, NDG
12/7/77	3.06	WRS, DEP
11/7/78	4.00	WRS, DEP
11/14/79	6.30	WRS, DEP
7/17/80	4.45	WRS, DEP, GT, RER, GRG
1981	missing	
4/21/82	7.98	HCB, GT, RER, JSP, SHM
3/24/83	4.25	HCB, JSP, SHM
3/24/84	6.71	HCB, JSP, SHM, REA, JNM
7/1/85	6.25	REA, JSP
6/27/86	7.83	HCB, RDS
8/20/87	6.95	RDS, JMW, REM

Volume-% over 6-hour test period from an initial overpressure of 1.13 gm/mm<sup>2</sup>.

Two slightly different methods were used to measure the leak rate. One was called the “Absolute Method”; and this measured the room pressure relative to the atmospheric pressure of the out-of-doors. This later parameter could change if a storm were coming into the area. The second method was called the Reference Vessel Method. Here, the room’s pressure was measured relative to a sealed vessel located within the Assembly Room itself. Almost certainly, the results quoted in the table were from the Reference Vessel method.

The leak rate measurement, itself, was probably more destructive than beneficial. That it was of questionable value with respect to room integrity is this author’s opinion and readily subject to argument.

The problem is that the required overpressure subjected the ceiling of the Assembly Room to an upward force of 136,000 kg. The entire concrete roof, itself, only weighed about 177,000 kg. Thus, the required pressurization of the room reduced the effective weight of the roof by about 77%. Viewed as a semi-rigid slab, the concrete probably flexed upward in response to this pressure; and new cracks could be introduced by this flexing. Furthermore, flexing could also seal off leak paths which might have existed without abnormal pressure (normal conditions). Either case would render the measurement relatively meaningless. Certainly, the annual flexing of the room was not conducive to maintaining a leak tight room. Still, the test was performed every year; and the room always passed with or without a fresh paint job.

#### *Assembly Room Access*

Only two doorways penetrated this room. One at the west end of the north wall was a 1.0-m-wide by 2.1-m-tall passage way used for personnel access. Small experimental components were introduced here too. The passageway extended the full thickness of the north wall plus 1.2 m before making a 90° turn east. A similar turn back north about 2.5 m further east completed a Z-shaped labyrinth. The purpose of this labyrinth was to prevent radiation streaming out of the room in the event of a nuclear criticality accident. The wall at the end of the passageway was also very thick. The result of this design was that radiation from the hypothetical accident might pass through the closed steel door to the room; but it would not make the two right angle turns to propagate down the hallway. The second doorway was diagonally across the room. It was in the south wall but at the east side. This was an equipment door way

connecting to the out-of-doors. The opening was larger to accommodate movement of larger and heavier components. It measured 2.4-m wide by 2.1 m tall. Two doors the size of the one diagonally across the room closed on this area. They sealed against a central “mullion” which had been designed to be removable for the introduction of really large items. In practice, this option was rarely used because the mullion was too difficult to return after removal. Apparently, the massive weight of the concrete wall above the opening caused just enough sag to render reinsertion of the mullion difficult. This limitation really never proved to be a problem. Hardware was simply designed recognizing the limitation. For example, the tall, large-diameter, annular tank for the second Annular Tank program was built in two cylindrical sections—each less than the width of a single door. Later, the full height was attained by bolting the two together.

This equipment opening in the southeast corner of the Assembly Room was backed by a massive, concrete, sliding Shield Door. This radiation shield was 1.07-m thick by 3.1-m-wide and 2.8-m-high. This thickness would effectively stop any radiation streaming out of the room due to some hypothetical accident. It weighed about 22,000 kg; and the door was opened and closed electrically. A hefty motor caused a massive chain drive to move the door. To gain access, the door moved west until both Blast Doors were exposed. Afterward, the door would be closed again (east) before experiments could resume. An electrical detection circuit assured closure before the Control Console could be activated. The Shield Door was not needed frequently; sometimes, a year or two might pass between use. After one long idle period, the door refused to move in response to the urging of the huge motor. Electrical connections

proved to be in good order; the inability to function was a mystery. Finally, the problem was discovered. A couple of years of pigeons roosting in the protected overhang of the door's drive mechanism left such an accumulated long mound of pigeon droppings that it totally disabled the drive mechanism. After removing debris, restoring movement, a metal screen cage was installed to evict unwelcome resident birds. This simple expedient was installed in the summer of 1977. This problem with bird droppings is discussed in another chapter.

Sometime in the 1980s, security measures throughout the nation's nuclear facilities were being enhanced. The Shield Door was considered a vulnerable point. Terrorists might, it was conjectured, wedge explosives between the door and the wall. If they could blow the door just a short distance west, unauthorized access to the building might be gained. This threat was satisfactorily mitigated by a very simple expedient. A one-third-meter-thick slab of concrete was cast which just fit the space the door would need to open. When authorized access was needed, a fork-lift truck could easily set the security measure aside. Security personnel deemed it unlikely the terrorists would have ready access to a fork-lift truck.

Both door openings into the Assembly Room were protected against radiation streaming from a hypothetical accident. The labyrinth to the north and the Shield Door to the south provided this as discussed just above. Two other consequences of a hypothetical accident, however, would be 1) the formation of a large inventory of radioactive daughter products from the fission process, and, 2) possibly, a very small explosive blast. Some of these daughter products would be gaseous and all needed to be contained. The worst possible explosive yield has been estimated to be

much less than a single stick of dynamite. The containment of these two side effects was accomplished at the two openings by the use of strong Blast Doors. The doors closed upon a spongy rubber seal between them and the room. One such seal existed at the personnel passage way; and two were used at the heavy equipment opening. These seals mitigated the containment issue. The blast issue was simultaneously addressed since each door was 1.2-m wide by 2.4-m high and 0.15-m thick. The fairly thick door was constructed as a honeycomb to reduce its weight without sacrificing strength. All three Blast Doors were made of steel and can be modeled as two 13-mm-thick plates on either face separated by a 10-m-long honeycomb of material 13-mm thick by 130-mm wide. Each blast door weighed about 750 kg. A suggested computer model for each Blast Door would be the two 13-mm-thick plates, already mentioned, separated by the honeycomb steel uniformly distributed over the 1.2 m by 2.4 m by 124 mm space between them.

### *Ventilation*

The Assembly Room required unusual ventilation because of the need to isolate the room from the outside, during critical-approach experiments. Between experiments, the room needed to be well-ventilated to sweep away radioactive airborne contamination as well as gaseous fission fragments. During experiments, the room had to be stagnant to contain completely the consequences of the worst possible accident.

The latter was accomplished by completely closing off all ventilation routes into or out of the room. This closure plus the three closed and sealed doors plus the leak tightness of the room ensured that the physical environment within the Assembly

Room would be isolated from the out-of-doors. This important step was always ensured for experiments because it became an integral part of the Pre-Run Check Sheet for every experimental program. An air intake valve just inside the room but connecting to the out-of-doors via a large-diameter duct several meters above grade level near the south end of the west wall was closed. The output pipe for this can be seen clearly in early construction photos of the 1960s. In addition to that valve, a “butterfly” valve in the 250-mm-diameter room-exhaust duct was also closed. This valve was inside the room and just above the floor. This duct entered the floor close to the doorway at the northwest corner of the room, turned underground, and eventually led to the Hot Exhaust System. This is the same duct involved in one of the largest and most persistent contamination incidents discussed in another chapter. To this day, the residual hold-up of uranium salts in that line remains uncertain.

The former full ventilation condition was ensured by opening both these valves. Then, outside air would be drawn through a stage of several filters before being passed through a heating or cooling stage (as indicated by the seasons) and allowed to enter the Assembly Room. Exhaust air then passed through a pre-filter assembly within the room itself before moving down a vertical duct eventually leading to the Hot Exhaust Plenum. This Plenum will be discussed separately later because it took two different forms at different stages of the CML’s existence.

The ability to merely circulate air from within the building through the heating or cooling coils was another option, although details of just how this was done are not accurately recalled. This became necessary if outside weather was either extremely cold or very hot. In either case, drawing

outside air into the system might exceed the temperature control capabilities of the heating/cooling system.

In addition to the underground Hot Exhaust duct mentioned above, one additional smaller exhaust duct existed. It joined the larger duct under ground. This duct exhausted the glovebox, only a short distance away, initially intended for use with plutonium solutions in the Assembly Room. Since the glovebox was never used for that purpose,<sup>24</sup> this valve was probably uncontaminated. It also probably closed and opened in concert with the other two valves mentioned above; but that fact is not recalled with confidence. This was a quite unimportant valve and exhaust duct.

A schematic drawing of the Assembly Room ventilation flow is presented in Fig. 18. It illustrates most of the features discussed in this subsection. The drawing is a bit more than schematic in that elevations and locations of intake and exhaust features are approximately correct relative to one another. Still, these features are not precisely to scale. The drawing suggests that fresh air would enter the room and flow east before it was swept downward and back west for exhaust.

Not many dimensional details are provided for this Assembly Room ventilation system because very little equipment constituted any significant neutron reflection or moderation. Furthermore, what little material there was existed several meters away from fissile material during any experiment. An adequate description is that the air intake plenum with its heating and cooling capability was in the southwest corner of the room elevated a few meters above the floor. It was constructed of thin

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<sup>24</sup>The glovebox was used for a few years on the uranium program called “The Coupled Assembly” study; but, even so, no significant contamination is thought to have existed in that area.

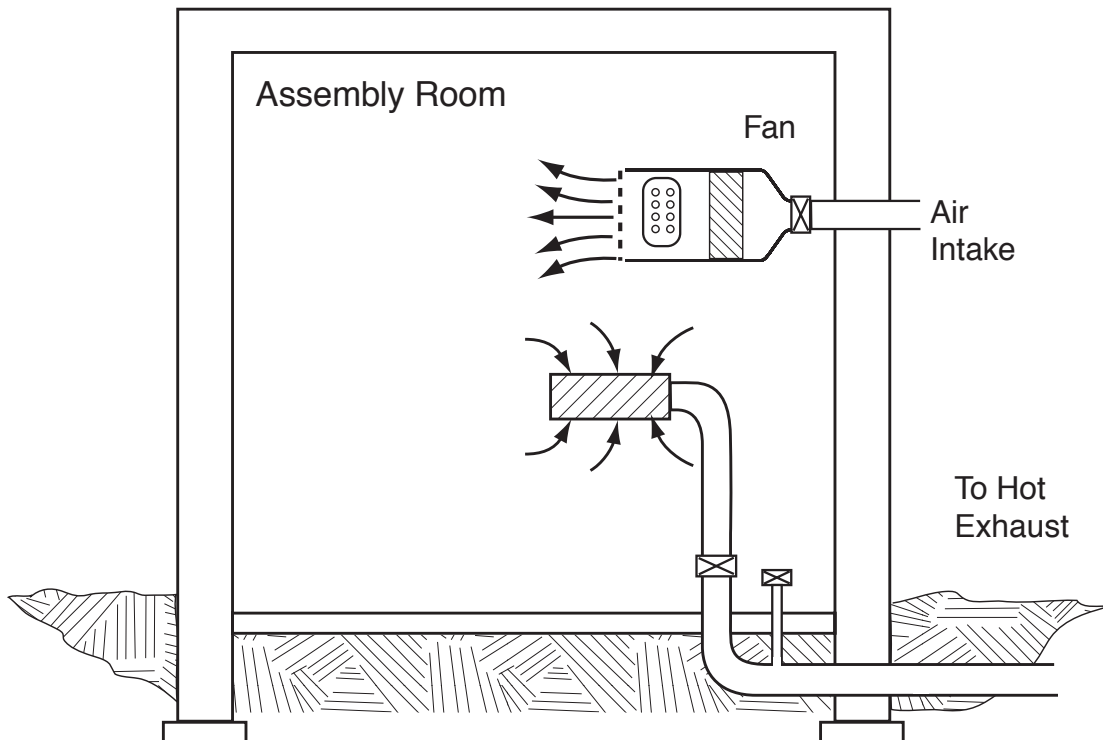


Fig. 18. This section schematic view of the elevation of Room 101 (looking south) shows the ventilation system as it existed through the mid-1980s. Outside air entered the room from the west and was drawn through a filter system (cross hatched) and a heating/cooling chamber (8 circles in an oval) before entering the room several meters above the floor. Room air exhausted through a set of pre-filters (opposite cross hatched) a few meters east of the west wall and about three meters above the floor. It passed down a duct to a Hot Exhaust Plenum discussed later.

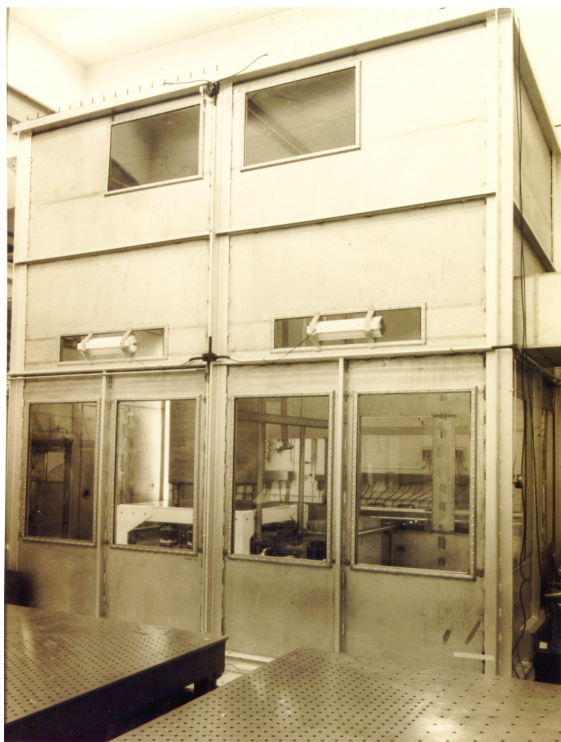
sheet metal and supported on a metal platform. The Hot Exhaust duct exited the room near its northwest corner but not right in the corner. The pre-filters stood about three meters above the floor and a few meters east of the west wall.

On one occasion in the 1980s, a smoke bomb was intentionally released as a means of observing air movement within the room. This was a safety test by persons responsible for radiological safety at Rocky Flats. The test, itself, was quite qualitative. In spite of the lack of hard and clear-cut evidence, the observed slow clearing of the air led to a long, protracted, and expensive modification of the air flow patterns within the room. Details of this modification are not recalled; but, in general, input air was

brought way over to the east side of the Assembly Room near the ceiling; and filtered air evacuated the room itself as well as the interior of the Walk-In Hood, described below. The idea was that air should sweep from the upper east portion of the room down to the lower west before exiting it. This author doubts that air movement was improved at all by this change. No second smoke bomb test was ever conducted to prove the point one way or the other. Dates of this modification are not recalled; but it is doubtful that more than a couple of experimental programs ever “benefitted” from this modification. Whether or not the air flow in the Assembly Room was ever adequate has never been determined or measured.

### Walk-In Hood

The walk-in Assembly Room Hood was also built as part of the initial 1964 construction. The clean and uncluttered status is easily seen in Fig. 19. Solution experiments and those involving bare plutonium were to have been performed there. The hood was a stainless steel room built for additional contamination control during certain kinds of experiments. First intentions were that uranium solution experiments would be performed in the south half of this hood; and plutonium



*Fig. 19. This photograph of the walk-in Assembly Room Hood was taken in early 1965 before any fissile material had been admitted into the CML. The Solution Base can be seen as white through the middle two of the lower four windows. The Vertical Split Table was located behind the right hand window but does not show well in this photograph. A small portion of the Horizontal Split Table can be seen in the lower foreground.*

experiments would be performed in the north half.<sup>25</sup> The Solution Base, described elsewhere, was about centered in the south half. The never-used Vertical Split Table, originally intended for bare plutonium metal experiments, was similarly situated in the north half. It, too, is described later.

This hood was situated within the west half of the Assembly Room. It was 3.0 m wide by 4.9 m long (north/south) and stood 5.7 m tall. The long dimension of the hood stood parallel to the west wall. The southwest corner of this hood was 1.6 m east of this west wall and 3.3 m north of the south wall. It was constructed of 11 gauge stainless steel (3 mm thick); but about 19% of the four walls contained 13-mm-thick plastic windows for viewing. In addition, four small windows (0.5% of the wall area) were composed of safety glass. The hood had a stainless steel floor coved into the walls to provide complete containment of a fissile solution spill should one occur. The coved design permitted easy washing and decontamination following a spill. Walls were stiffened on the outside by stainless steel structural members as can be seen in the figure; but these are not described here. If these details should ever be needed, they may be obtained from the As-Built drawings 14832-01, -02, and -03 mentioned above. These drawings can be found at the LANL Archives.

The ceiling of the walk-in hood was also stainless steel. It was made such that either or both halves could be removed.

<sup>25</sup>The 1964 notion that two different nuclear fuels might be used in opposite ends of the relatively small walk-in hood was really quite naive. Every contamination incident, however small, would have to be assumed to be plutonium. Decontamination of even the smallest problem would be difficult, expensive, and labor intensive. Decades of experience suggest that plutonium solutions should be handled in one building and enriched uranium solution in another. The two should never be co-mingled in the same walk-in hood. Furthermore, wastes generated would tend to mix these two elements.



Each lid was slightly rectangular with a perimeter frame having a square cross section; and the flat sheet material was stiffened with X-shaped braces along diagonals of the rectangle. The perimeter frame was padded with a rubber cushion that formed a good seal whenever the lid was lowered onto the top of the hood.

### *Elevated Platform*

This was a concrete-floored mezzanine constructed in the southeast corner of the Assembly room. It was not part of the initial 1964 construction but was added during the late 1970s. The platform stood just above the pair of blast doors in that corner. It was composed of concrete and structural steel shapes. The platform remained at that location throughout the remaining history of the CML. The purpose of this mezzanine was an attempt to increase floor space available to all future programs at the CML.

The platform measured 3.04 m by 4.88 m; and the top of its concrete floor stood 3.35 m above the floor of the Assembly Room. The entire unit consisted of the concrete-and-structural-steel floor supported by a horizontal open mesh framework underneath with this, in turn, supported by four sturdy legs. The platform floor was composed of eight rectangular panels. Each panel was ordinary concrete poured into a heavy steel channel frame. A heavy-duty superstructure supported these eight panels, holding them in contact with one another in a 2x4 array.

### *— Floor Panels —*

Each of the eight panels measured 1.22 m by 1.52 m and was 203 mm thick. To make each, steel channel stock was welded into a rectangle of those dimensions. The commercial stock is referred to

as “C8 x 11.5.” It measures 203 mm across the wide face and weighs 17.1 kg/m. Channel flanges faced inward forming a smooth outside vertical surface. Corners were mitered to 45° and welded. At this point, the frame of the panel looked like a very thick picture frame.

These floor panels contained rebar embedded in the concrete for added strength. The elevated platform might be called upon to support heavy loads in some applications. All rebar was commercial ribbed steel in the 19 mm size. It was laid out in a rectangular mesh with the plane of the rebar about 50 mm above the bottom of the finished slab. Four 1.4-m-long rebars were equally spaced parallel to the long dimension of the frame; and five shorter lengths (1.2 m) passed at right angles, also, equally spaced. They were tied together with wire at intersections.

A better connection between concrete and frame was ensured by welding 14 short lengths of the same 19 mm rebar to the inside web of the channel frame. The 14 were about equally spaced around the perimeter at the mid-plane. Each weld stud was 127 mm long. These are sometimes called “Nelson Weld Studs.”

Each floor panel had three holes passing through it. These would be used to pass fissile solution lines, cables, and other experimental equipment from below the floor to the working surface. The location of these holes is not described here because that detail is considered unimportant. They were, however, in a triangular pattern spaced to provide a convenient selection. Each was lined with a 197 mm length of nominal 50-mm-diameter stainless steel Schedule 10 pipe. The only other steel in a finished floor panel included four heavy-duty lifting anchors embedded at corners. These were used to lift floor sections into place on its support superstructure.

The eight frames were weighed prior to pouring concrete. The total weight of steel in each one averaged  $122 \pm 1.4$  kg. The concrete was poured on April 10, 1980. The mix contained:

Portland Type II Cement	1194 kg	(15%)
Moist Sand	2957 kg	(37%)
Moist Rock (20 mm average size)	3316 kg	(42%)
Tap Water	473 kg	(6%)

The concrete supplier measured the water content of their moist sand that day. They reported 5%, in agreement with a simple procedure performed at Rocky Flats. There, a can of their stored sand was weighed as found, dried on a hotplate, and weighed again. This simple test found the sand contained 5% water, too. At Rocky Flats, the moisture content of the aggregate was found by the same simple method to be 1.7%.

These panels were cast horizontally and upside down. One surface of each form was covered with plywood to yield at least one smooth surface on each panel. That one surface became the working surface (top) when the floor was in place. The other side (bottom) was simply hand-finished by workmen.

— *Support Structure* —

These eight floor panels were supported by a horizontal open-grid superstructure formed of heavy steel “Wide-Flange I-Beams.” All beams had their webs vertical for best load support. Even though beams of two sizes were used, all beams were laid out such that their top surfaces were co-planar. This construction yielded a flat top plane to support the eight panels. The outside dimensions (to beam centers) of this complicated superstructure were 2.54 m by 4.37 m. This was large enough to allow the 2×4 array of concrete-and-steel

floor panels to overhang about equally on all sides.

Horizontally, beams of two sizes were used. One long east/west stringer was a “W10x45” I-beam. It was 254 mm tall and weighed 67 kg/m and formed the north stringer. Five I-beams, orthogonal to the north one were equally spaced in the north/south direction. These were “W8x31” I-beams measuring 203 mm high and weighing 46 kg/m. Four short W8x31 I-beams were bolted between the five north/south ones; and these formed the south longitudinal stringer. Finally, four more W8x31 I-beams were bolted midway between the north and south stringers forming a central support beam for the concrete-and-steel floor panels. Under this construction, each edge of the eight floor panels was supported by steel I-beams.

Even though wide-flange I-beams of two heights (254 mm and 203 mm) were used, they were laid out such that all top flange surfaces were co-planar. Joints were carefully cut to fit other beams whether they were the same size or not. Short lengths of angle iron were bolted to both webs at these joints to fasten them together. The total weight of these 13 pieces of wide-flange I-beam stock of two sizes was 1167 kg. All this was contained in a thick plane whose top surface stood 3.15 m above the Assembly Room floor.

Some document, possibly an engineering drawing, claims that the “twist-mode” for this otherwise all-rectangular parallel-piped construction was to be restricted by diagonal bracing. Supposedly, angle iron stock, 50 mm on a side by 6.4 mm thick, was to have been welded to the bottom of the W8x31 I-beams wherever they touched along both diagonals. This bracing, however, is *not* substantiated by photographs of the underside of the Elevated Platform spanning several years. Furthermore, this

author does not recall seeing any such bracing. This bracing is reported here only because some document said they would be there. They probably were never installed. One rationale for omitting them might have been the observation that the south and east walls or the room would prevent any twisting.

— Legs —

The horizontal superstructure and the eight floor panels above it were supported by four sturdy legs. These were also the same (W8×31) wide-flange I-beam stock. The cross section of this structural steel looks very much like the letter “H”; but it is different from a true H-beam. Three of the legs were located under corners of the superstructure; but the fourth leg (in the southeast corner) would have restricted the

opening of the eastern-most door under the mezzanine. It was relocated a little to accommodate the door. Each leg was welded at the bottom to a 356 mm square pad of 13-mm-thick steel. This pad distributed weight to the floor over a larger area. South legs supported the W8×31 beams of the superstructure; but north legs supported the W10×45 beams. Because of this, their lengths differed by the difference between the two I-beams (51 mm). Two diagonal braces of W8×31 I-beam stiffened each leg in orthogonal directions. A photograph of the underside of the concrete-and-steel platform, a portion of its steel structural support (the west half), and the top part of bracing for both west legs is shown in Fig. 20.



*Fig. 20. The concrete Elevated Platform consisted of eight panels supported by a steel superstructure, supported, in turn, by steel legs. All of this except the poured concrete was made of structural steel shapes. A portion of one leg and diagonal bracing for two legs is seen at the right in this underside view of the Elevated Platform. Solution lines passed through holes precast into the slabs. Several radiation detectors can be seen connected to coaxial electrical cables.*

— Superstructure —

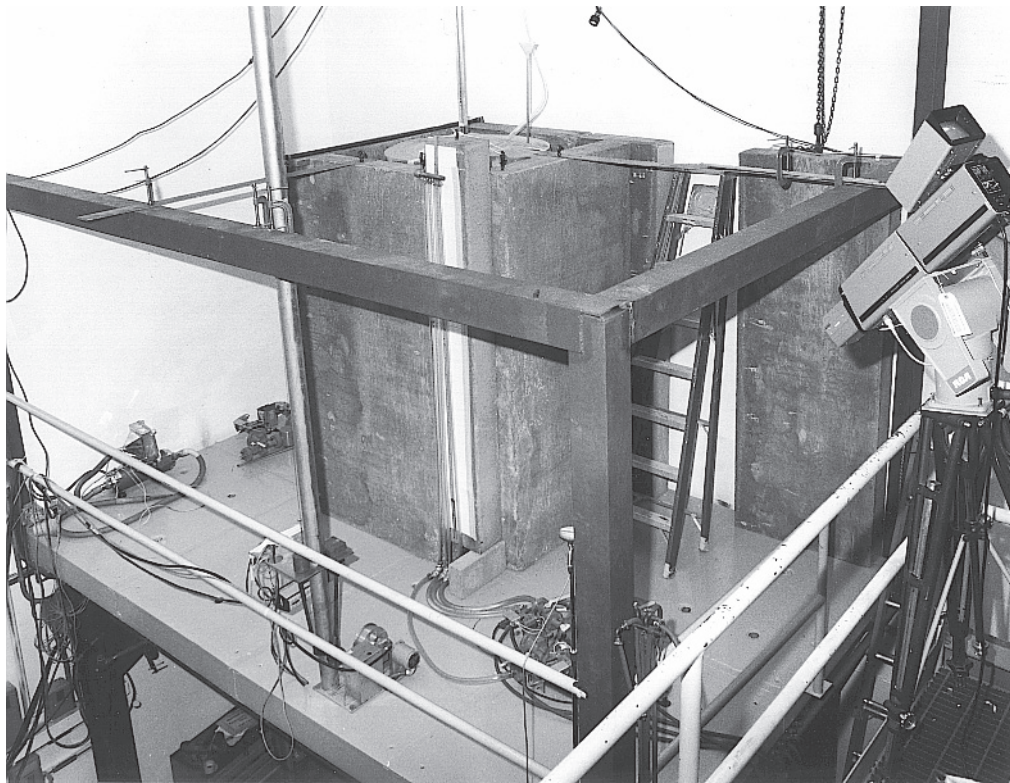
Above the mezzanine, a small amount of structural steel was used to facilitate stabilization of concrete reflector walls. East and south walls of the Assembly Room would prevent these walls from falling; but the other two directions needed some kind of “fence” to which concrete wall panels could be tied. Three posts of 152 mm angle stock (13 mm thick) rose at all corners except the southeast one. These were tied together with two horizontal lengths of the same stock. Almost all of this construction can also be seen in Fig. 21. Only the northeast vertical post is cut off at the left of the picture and the television camera hides the southeast post. The two horizontal members, clearly seen, were 2.46 m above the floor of the mezzanine and just about co-planar with the tops

of the nested annular tanks and reflector wall sections. Any of these experimental items could be tied to either of these horizontal angle members for seismic stability.

Finally, a pair of yellow-painted pipes formed a safety railing to prevent personnel from falling off the platform. These were about 50-mm-diameter light-weight steel pipes bolted to the superstructure. They spanned the full length of the north side, also visible in the figure, of the platform and half the width of the west edge.

*Miscellaneous Items*

An elevated Air Handling Deck existed near the southwest corner of the Assembly Room. This deck supported the room’s separate heating and cooling apparatus; but that apparatus consisted of thin sheet metal



*Fig. 21. The superstructure above the Elevated Platform helped stabilize sometimes heavy experimental components. Light-colored railings to the lower left prevented falls. One experimental apparatus (the first Annular Tank study) is seen in the center of the photograph surrounded by cast concrete wall panels.*

and can probably be ignored with respect to any influence on neutron movement. The bottom of this deck was 4.5 m above the Assembly Room floor. The air handling unit could be described as two adjacent, thin, sheet-metal boxes. One was 2.5 m long by 2.0 m square; the other, 1.7 m long by 1.4 m wide and 1.0 m high. The larger contained a set of HEPA filters. The unit could receive outside air through the pipe seen half way up the west wall in Fig. 16 (top). The air handling unit was required to be isolated from outside air during every

experiment. This was done for environmental safety reasons. No photograph of the deck could be found; but it is not very significant anyhow.

Another large item in this room was the heavy equipment traveling crane built into the room for general use. Although constructed of heavy structural steel shapes, this crane was sufficiently far away from experimental apparatus and so close to the ceiling as to be ignored as a potential neutron reflector. The crane had a capacity of about 4,500 kg. Figure 22, repeated later



*Fig. 22. The overhead traveling crane appears in the upper half of this photograph. It was far enough away from any experiment as to have negligible influence on any critical configuration. The crane's lifting capacity was rated at about 4,500 kg.*

to illustrate another feature, shows the south quarter of this crane moving some experimental component.

No part of any experiment was closer than three meters from any part of the crane. It was so insignificant, that the location of this crane during experiments was never recorded. The bridge of the crane traveled east/west; the trolley from which the hook hung, north/south.

For many years, the crane was controlled by a lengthy and heavy pendant which hung down to working level near the floor. This pendant had control buttons for control of the crane. It and its long heavy cable tended to get in the way of objects being moved. This problem was solved by a clever scheme designed by the Building's technician, Doug Payne. He modified the crane for radio control; so it could be manipulated from anywhere within the room. His clever invention even went one step further. He devised an antenna system such that the radio signals could be sent from the Control Room and cause crane movement in the Assembly Room. This useful feature was used to move the external neutron source both out and in during experiments involving uranium.

Finally, the Assembly Room contained other smaller pieces of equipment; but these are considered far too small and too far away to be worth description. Large portable tool boxes and normal clutter found around any productive laboratory are included in this list.

## The "Four Reactors"

Four machines had been conceived and built as part of the initial construction of the CML. The purpose of each was to provide a remotely-controlled method of adding reactivity to any of a wide range of possible critical-approach experiments.

This reactivity could be added in many ways. One would add reactivity by simply increasing fissile fuel loading. Others would accomplish that feat by increasing neutron interactions between two previously assembled fissile loads. A fourth would increase neutron reflection and moderation as a means of adding reactivity. These four were by no means the only possible designs capable of accomplishing the goal; but they were the ones employed at Rocky Flats. Had any other design been needed for some unforeseen project, it could easily have been designed, built, and used. A review of the 1700 experiments performed at this CML shows that no other design ever did prove necessary.

Any machine designed to achieve criticality for the purpose of understanding the physics parameters associated with that condition can do so with essentially no power generated. They should be understood to be simply "critical assemblies" with no reference to *power*. These experimental assemblies differ markedly from any power reactor design intended to supply the endless energy requirements of machine-conscious human beings. Power reactors create megawatts of power. The whole concept of "power" seems hardly pertinent when considering critical experiments. The machines at Rocky Flats—and any other Critical Mass Laboratory throughout the United States—were conceived as "Reactivity Addition Devices" by early designers. At their most eloquent, they may have been described as "Zero-Power Reactors." In spite of these arguments, DOE Orders—specifically DOE Order 5480.6—pertaining to the ownership, management, and regulation of reactors did not clearly recognize the physical differences just discussed. Consequently, the four machines at the Rocky Flats CML became saddled with the questionable designation of "Reactor."

Admittedly, those DOE orders do distinguish between “Category A” and “Category B” reactors. The dividing line is a huge 50,000 Watts! Even low-power reactors falling into the lower category demand some attention be paid to the dissipation of heat whereas the entire concept is almost always moot and irrelevant with respect to “critical assemblies.” Nonetheless, the four machines at Rocky Flats fell under the purview of a Category B Reactor. That was a most distressing state of affairs and led to undue expenditure of time, money, and brain power over the life of the laboratory.

The point is relevant at a couple of levels—both political and physical. Politically, some misconception might arise in the mind of an uninformed public who believed that Rocky Flats served a very different role in the nation’s nuclear industry. They might blanch when told that 1700 “nuclear reactors” had been built at Rocky Flats during three decades late in the century. Physically, addressing the requirements of DOE Order 5480.6 demanded attention be paid to the removal of non-existent heat. The Order also called for a measurement of the instantaneous power level; and this was a very difficult task when that power was zero.

The next several pages describe the construction, composition, and operation of each of the four Reactivity Addition Devices sadly defined to be Category B reactors.

### ***Vertical Split Table***

The Walk-In Hood in Room 101 contained two of the four Reactivity Addition Devices. The machine in the north half was the Vertical Split Table. It’s light-weight and open, “airy,” construction contained very little stainless steel tubular stock and only thin horizontal membranes of metal. The entire table is considered not to con-

tribute any significant neutron reflection to any experiment. Its low mass and distance from any other apparatus renders it irrelevant from a neutron’s point of view. Furthermore, the machine was never used for any experimental program. Consequently, no other discussion will be afforded this totally insignificant and unused object.

### ***Solution Base***

The other half, to the south, was occupied by another Reactivity Addition Device called the Solution Base. This table was an integral part of almost every experiment involving enriched uranyl nitrate solution. It was used in a dozen or more experimental programs over the productive life of the CML. Only the so-called Coupled Assembly study and the follow-up Uncoupled Coupled Assembly program did not use this Solution Base.

The Solution Base, inside the Walk-In Hood in Room 101, was a heavy-duty square table described later in considerable detail. One stainless steel line connected it to the set of uranium solution storage tanks in the Room 103. During an experiment, fissile solution could be pumped through that line from storage into whatever apparatus had been assembled at the other end atop the Solution Base. A wide range of flow rates were necessary because solution could safely be added very fast at the beginning of an experiment; but, at some point, that fill rate would add reactivity too fast for safety.<sup>26</sup> At the end of the experiment, the solution would be returned to storage through the same line. Valving in both the Assembly Room and the Mixing Room allowed this option. The line, itself,

<sup>26</sup>Discussion of the storage tanks and the means of producing various pumping rates is deferred to the section of this chapter describing the Mixing Room (Room 103).

was Schedule 40 stainless steel pipe 33.4 mm in inside diameter (42.6 mm outside). It was commonly referred to as the “Fill/Return” line. That single line did branch at one point in the Assembly Room,

between the Walk-In Hood and the west wall, into four short vertical paths which then reformed a single line. This is shown in the top portion of Fig. 23. The “FILL” option proceeded from left to right in the

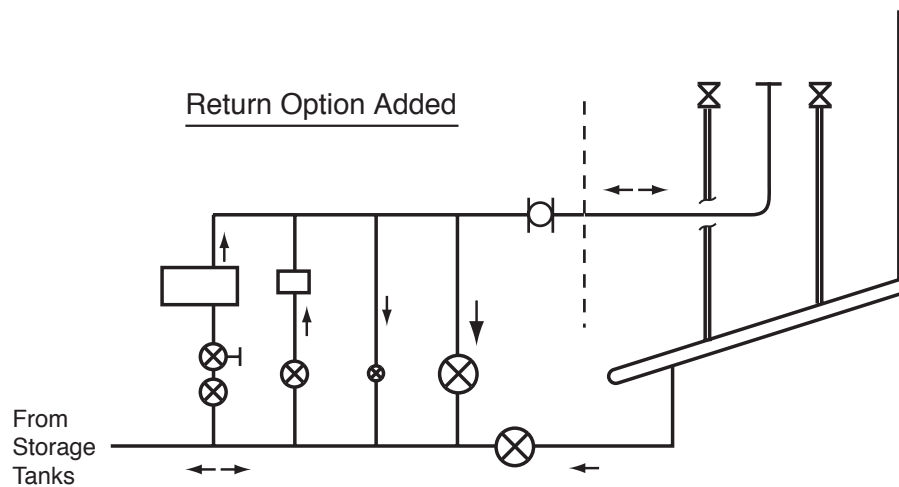
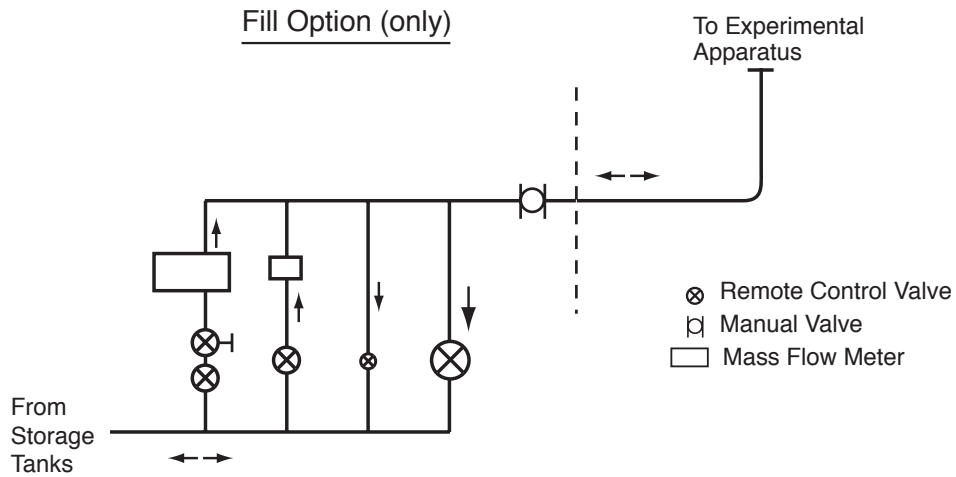


Fig. 23. The top half features the solution fill option. Fissile solution moved from the storage tanks (out of view to the left) toward the experimental apparatus (right) via a single line which broke into four parallel branches in the Assembly Room. The four branches are, from left to right: FAST fill, either slower pump, “tic” drain, and normal return. The remote control valve with the “T” on its side is a Throttling Valve used to vary solution flow rate through that pump. Rectangles represent devices which record the amount of solution passing through it. The dashed line divides the Assembly Room (left) from the Walk-In Hood (right). The bottom half adds solution return options including the safety SCRAM. The sloped tank was called the SCRAM tank; its vent is to the far right of it. X-shaped hour-glass symbols represent the two SCRAM valves.



figure; “RETURN,” the opposite. That explains why arrowheads point in both directions in the figure. During filling, the left vertical branch provided a solution path when the FAST pump<sup>27</sup> was used. The remotely controlled valve with the “T” on its side was a “throttling valve” used to vary the delivery rate for this pump. The rectangle represents a commercial Mass Flow Meter.<sup>28</sup> The next branch to the right provided the path whenever either the MEDIUM or SLOW pump was used. The smaller rectangle represents a smaller version of a Mass Flow Meter. The third branch from the left consisted of a very small diameter stainless steel tube and a correspondingly small valve. This small-tubing route would be used when only a few grams of solution were to be removed from an experiment. This process was described by the colorful words: “Tic Drain.”<sup>29</sup> This was needed to make very small adjustments right close to criticality. The last branch (to the right) was the normal return route used at the conclusion of an experiment. Fissile solution was simply allowed to flow swiftly back to storage tanks.

The four optional branches rejoined another horizontal header, above the lower one, that led through a little-used manual valve into the Walk-In Hood. Once inside, one branch of a T-connection (not shown in the figure for clarity) led through a manual valve to the Site Gauge. The Site Gauge was a vertical length of clear plastic tubing in the southwest corner of the hood. This gauge was one way of determining the solution height in an experiment because the clear tubing could be viewed by closed circuit television in the Control Room. The other branch of the “T” led to the experimental apparatus. This connection to whatever tank had been designed for the experiment was via a kind of flanged fitting called a “Marmon Connection.” One end of the Marmon fitting was welded to the FILL line; and a mating fitting was welded to the experimental tank. Then, a clamp secured a seal between the two.

At the end of an experiment, solution needed to be returned to storage; and these options are shown in the bottom portion of the figure. The usual procedure was to open the valve in the right-hand-most vertical leg (shown in both portions).

<sup>27</sup>Pumps and other solution storage features are described later in this chapter.

<sup>28</sup>Mass Flow Meters warrant description. These were built by a small commercial firm close to Rocky Flats. Mass Flow Meters, as the name implies, measured the mass of solution passing through them. If reset to zero with solution just about to enter the tank, the device would record the mass of solution pumped into the tank. Solution density equals the delivered mass divided by the volume of that solution—the cross sectional area times the height. Since both density of the solution and cross sectional area of an experimental tank could be known very precisely, these meters then provided an independent measure of the solution height within the tank. These clever instruments employed the Coriolis force in an interesting way. A “U”-shaped tube was set onto mechanical vibration similar to a tuning fork. The flow of solution through the tube produced a twist in the tube because of its mass via this force. The twist was restored by an opposed magnetic force; and the current needed to nullify the twist was a measure of the solution mass passing through the device.

<sup>29</sup>Tic Drains also warrant discussion. Critical heights were often very sensitive to the exact amount of solution present. A few milliliters often made a quite noticeable difference in reactor period. This drain mode allowed the removal of *very small* quantities of solution significantly lessening the reactivity of the experiment. This, in turn, permitted bracketing precise criticality and allowed interpolation of critical heights. This was the only portion of the entire solution handling system to employ any hardware different in size than Schedule 40 stainless steel pipe 42.6 mm in outside diameter.

Naturally, all critical experiments also required two independent SCRAM mechanisms. Each had to remove reactivity faster than the greatest possible reactivity addition rate. In this case, uranium solution had to flow *out* of the experimental tank faster through one valve than it could possibly be *added* by the FAST pump at its greatest delivery rate. This was tested on a number of occasions. The SCRAM removal rate was so much greater than the fastest fill rate that the truth of this condition was accepted without daily verification. Two such devices were required because one could possibly fail to function; the second provided redundancy. The term “independent” means that each SCRAM mechanism must be *physically* independent of the other, although they need not be *fundamentally* different. Thus, in this case, two identical but independent valves could be used as SCRAM mechanisms. If fundamentally different devices had been required, one could have been such a valve and the other, an overhead bucket of boron compound that would be released in response to a SCRAM signal. One device would remove fuel; the other would add a neutron absorber.

The bottom portion of Figure 23 repeats the top but now includes the two SCRAM valves, the associated collection tank, and related plumbing. The vent line to the far right was the source of one of the anomalous events discussed in another chapter.

Everything below the plane defined by the tops of the two SCRAM valves all the way back to the storage tank farm essentially remained unchanged throughout the lifetime of the CML. On the other hand, apparatus above that plane varied markedly from program to program. The scope of this book is to describe all aspects of the CML facility up to—but specifically

*excluding*—details about each and every experimental program. Those important details can be found in the many journal articles published following experimental programs; they are not repeated here.

The SCRAM valves used at the CML were non-commercial units specifically designed for this application. Even in 1963, they cost \$15,000 each. They were constructed of stainless steel pipe, 76.2 mm inside diameter. Each came in two sections bolted together top to bottom. The top end of the top section, which connected to whatever experimental tank might be employed, was welded to a commercial stainless steel fitting called a “Marmon Coupling”—similar to but larger than the Marmon Coupling already discussed. Couplings for the two SCRAM valves plus the normal fill/return couplings were coplanar about 25 mm above the top of the Solution Base. The three matched similar couplings welded to whatever experimental apparatus was to be used. Figure 24 shows these couplings on the underside of some small-diameter experimental tank. Springy clamps with a U-shaped cross section squeezed both halves together under a bolting action forming a leak-tight seal. The diameter of each valve’s opening exposed to solution was 50.8 mm. A plunger could move up and down through a centered guide shaft. When “up,” O-rings sealed the valve closed preventing solution flow. When “down,” over 2500 mm<sup>2</sup> was available for rapid solution removal. A cross section of the top half of this valve is shown in Fig. 25. The figure stops short of the bolted-on bottom of the valve. Once installed, these valves were almost never disassembled; but the April 1982, photograph of Fig. 26 illustrates the exception. A review of written requests for servicing reveals such requests in April and May of 1977 and March of 1981, although this



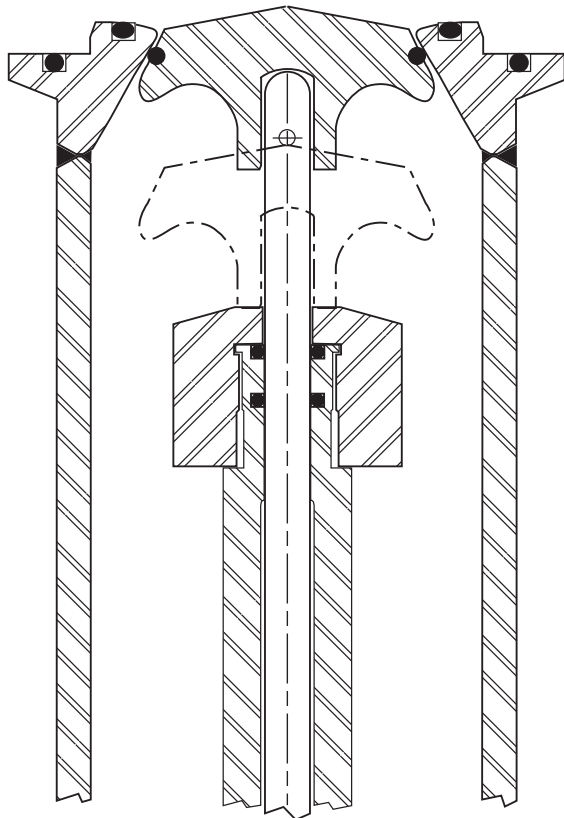
*Fig. 24. The smaller Marmon coupling connected the experimental tank to the FILL/RETURN line. The two larger-diameter couplings similarly connected to the pair of SCRAM valves. This is the underside of some small-diameter experimental tank.*

author recalls a number of other times these somewhat sensitive valves required attention. These valves and their sensitivity to hydrostatic pressure have been discussed elsewhere in this book.

The two SCRAM valves guided solution directly into the SCRAM Tank located below the table. Often the more colorful word “Dump” replaced the term “SCRAM” in reference to uranium solution experiments. Regardless of the tank’s name, solution would be retained there after the SCRAM had occurred for safety reasons. Had an actual criticality excursion precipitated the SCRAM signal, the fissile solution would have been replete with

highly radioactive fission fragments. Trapped in the SCRAM tank, the entire consequences of such an accident would be safely contained within the Assembly Room only. In the more likely case that no accident had happened,<sup>30</sup> solution could be released for return to the storage tanks. Confirming that a nuclear accident had not occurred was easily done by simply observing the ambient radiation level in the Assembly Room following a SCRAM.

<sup>30</sup>No such nuclear criticality accident ever happened at Rocky Flats. That enviable record spans between 800 and 1000 experiments using the uranium solution. It also spans fourteen separate programs.



*Fig. 25. SCRAM valves for uranium solution experiments were non-commercial units made from stainless steel pipe and topped with commercial “Marmon Couplings” as shown in this cross section view. Only the top half is shown. The central plunger was held closed by an electric solenoid hanging from the bottom of the valve. Phantom lines show the plunger in its SCRAM location.*

When proven safe, the remote-control valve at the output end of the SCRAM Tank would be opened; and solution could return to storage.

Each SCRAM valve was held closed by its own powerful electromagnetic solenoid. This drove the plunger upward and sealed its O-ring against a mating surface. The “hum” of closed valves was quite audible through the audio communication between the Assembly Room and the Control Room. One force (the solenoid) closed the valves; but three forces tended to work

against it, trying to open the valve. This design was intentional and contributed to safety. The solenoid armature and the valve’s long shaft were quite heavy; therefore, gravity tried to open the valve. A fairly hefty spring also pulled against the solenoid’s armature. Finally, the hydrostatic pressure of whatever solution rose above this seal tended to open the valve, too. This design proved to be quite satisfactory for most programs at the CML. Only during the last few uranium solution programs, such as the Annular Tank and Shielded Annular Tank studies, did the limits of the SCRAM valve design get pushed. These programs took place on the Elevated Platform in the southwest corner of the Assembly Room. Solution close to the top of one of the taller experiments stood over four meters above the SCRAM valve seals. High concentration solution had a density in excess of  $1.5 \text{ mg/mm}^3$ ; so the hydrostatic pressure on the valve heads was quite high. The difference could be heard in the sound of the solenoids trying to hold the valves closed. In fact, on more than a few occasions, seals were sufficiently tested to permit small quantities of solution to leak past them. This did not happen all the time because sometimes valves sealed better than others. Whenever a sufficient, although still small, amount of solution leaked past these seals into the Dump Tank, a liquid sensing probe fixed at the low point of the tank would initiate a SCRAM of the entire experiment. This sensitive probe was there for safety reasons to ensure that adequate SCRAM volume capacity always existed. A dump into an already full—or even partially full—safety tank might not shut down a criticality accident. During the 1980s, perhaps 10 to 20% of solution experiments suffered this annoying fate of leaking valve seals. A couple of hours may have been spent on



*Fig. 26. The SCRAM valves were almost never disassembled; but this 1982 photograph shows the exception. The flanged joint is the mid-height of the valve. The centered guide tube for the operating plunger rises above the joint.*

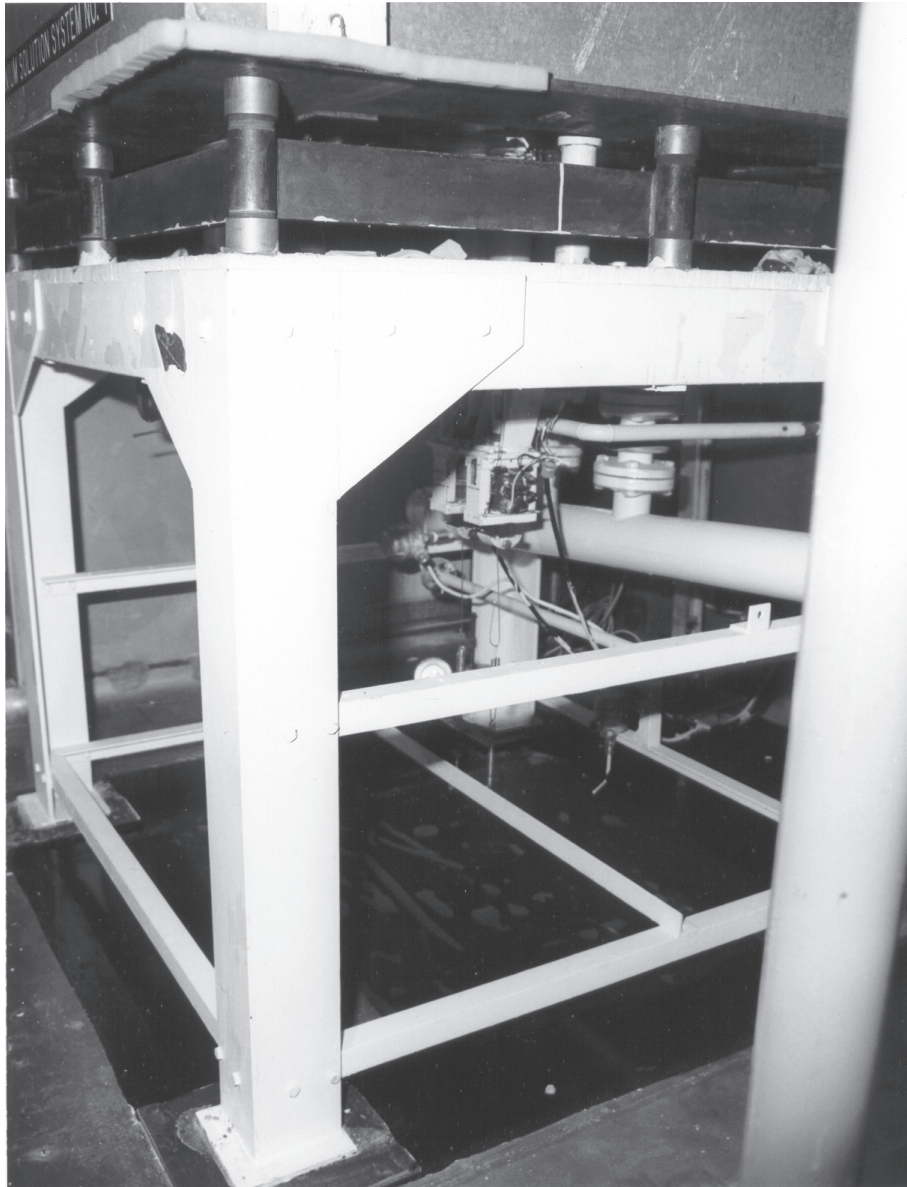
the approach toward criticality only to have the shut down terminate the experiment before any useful information could be gleaned. After a few attempts to rebuild the valves as shown in Figure 26, a budget request for new replacement SCRAM valves was made. This first appeared in the budget about the time of the last experi-

ment at the CML; and no further action was taken.

The Solution Base remained essentially unmodified from program to program over thirty years while the apparatus erected upon it varied markedly for each program ever studied. The Solution Base consisted of a thick steel square table surface sup-

ported by a heavy-duty framework welded together of structural steel shapes. Figure 27 shows one view of this massive table. The table appears white; darker components near the top of the photograph are apparatus belonging to some experiment. The framework stood about as high as the table top was square. Framework was

constructed principally of 152 mm × 152 mm × 11 mm thick steel angle iron stock welded together. The top was framed into an open square, 1.50 m on a side. The four corners were supported by legs of the same material. Thick steel pads (203 mm square by 9 mm thick) were welded to the bottom of these legs to reduce the point loading on



*Fig. 27. The Solution Base appears white in this 1985 photograph. Equipment on the table's surface near the top belongs to one of many experimental programs performed on this table. Dark-colored pads below the white ones at the foot of each leg were added years earlier to distribute floor loading better. One SCRAM valve solenoid and the Dump Tank are seen under the table top.*

the concrete floor. The figure shows these pads as white; but sometime prior to 1985, other larger pads were placed under these to decrease the floor point loading even further. The 25-mm-thick steel table top merely rested on this table frame. The height of the top surface of the table top stood about 1.38 m above the floor. The table top had one triangular hole cut near its center. This space allowed the two SCRAM valves and the solution fill/return line to pass from below the Base to whatever apparatus had been constructed above. Triangular gussets welded the legs to the table's top frame for strength. The combined material of these eight gussets (two per corner) was about 0.25 m<sup>2</sup> of 9-mm-thick mild steel plate. The only other steel was about 6 m of 50 mm x 50 mm x 6 mm thick angle iron stock welded horizontally to the legs near the bottom. This smaller angle and the gussets can be seen in the figure.

The spacious underside of the Solution Base supported a few components related to experiments. The largest was the pair of SCRAM valves (discussed above) which led to a critically safe SCRAM tank, sometimes called the Dump Tank. This tank was schedule 10 pipe with an outside diameter of 141 mm. It was 1.83 m long and slightly sloped to facilitate drainage. It averaged about 0.9 m below the experimental tank's bottom. The SCRAM tank vented via a very tall 67.0-mm-diameter schedule 10 pipe adjacent to the outside edge of the Solution Base. Other items under the table were associated with the fissile solution delivery and recovery.

The SCRAM tank originally designed for the facility was too small for some experiments. This has been mentioned elsewhere. The size of the SCRAM capacity was increased significantly, in stages, throughout the life of the laboratory. At its largest, the SCRAM capacity consisted of

the original pencil tank plus two stainless steel tanks<sup>31</sup> plus two large-sized plastic tanks. The total capacity of all five SCRAM tanks added to almost 1000 liters. The pencil tank was critically safe due to its small diameter; the other four were Raschig ring filled.

Both SCRAM valves, the SCRAM tank(s), as well as its vent line contained no solution during the experiment. This is important information because the possible presence of fissile solution in various lines close to a critical configuration might be important when computationally evaluating a critical experiment. Other items under the table which did contain fissile solution during an experiment included:

- (1) The single stainless steel solution "fill pipe," described above, passed solution into the tank during an experiment and formed one optional route for solution return after the experiment. It projected downward about 0.5 m below the tank before a 90° bend near the center of the table led to a long horizontal run away from the table.
- (2) The design of the Marmon Couplings for the SCRAM valves left small pockets of solution just above each valve head. Each pocket was 50 mm in diameter by about 20 mm deep and produced small perturbations to the otherwise flat surface formed by the bottom of the experimental tank. This solution remained as long as these valves were closed electrically, forming a very small perturbation to the

<sup>31</sup>of these was the never-used tank from the would-be plutonium solution storage farm in Room 103 (described later). Both of them had been used in an abortive solution storage system contained in Room 101 (also discussed later).

otherwise flat surface of the experimental tank.

- (3) Some experiments (but not all) had another small-diameter line from the bottom of the tank leading to some form of sight gauge used to observe solution height. This was only 12.7 mm in diameter when the line existed at all.

Two different electrical devices were under the table; but neither of them contained fissile solution during an experiment. The two SCRAM valves, themselves, were a complex geometry; but each could be approximated by 0.5 m of commercial schedule 40 pipe, 88.9 mm in diameter, extending below the tank. A heavy electric solenoid hung below each valve about 0.6 m below the tank's bottom. Secondly, an electronic device mounted with its liquid-sensitive probe a few millimeters above the stainless steel floor was clamped to one of the smaller angles. Its purpose was to detect solution leaks if one were to occur and advise experimenters of that condition.

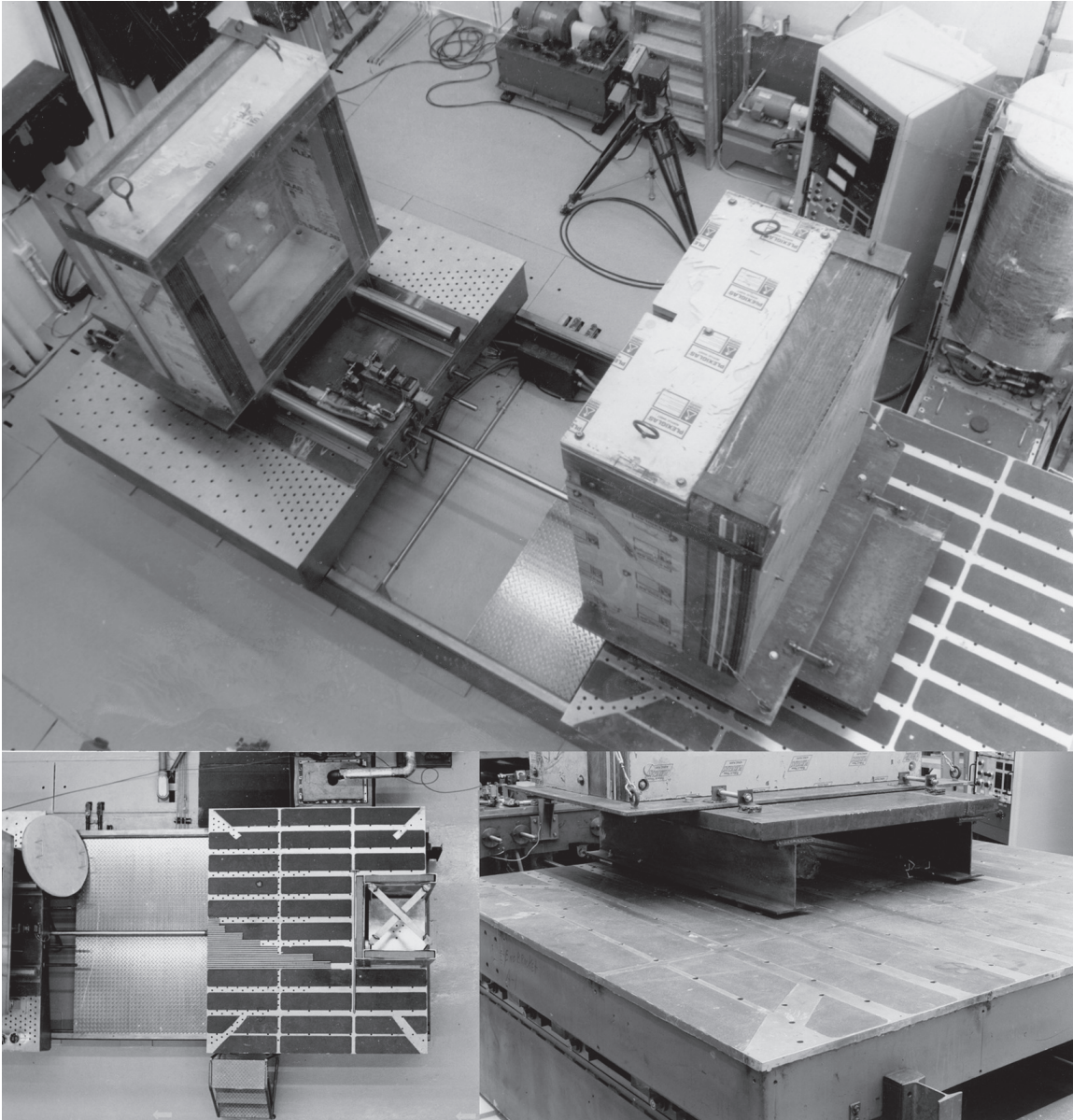
### ***Horizontal Split Table***

The next large item within the Assembly Room itself was the Horizontal Split Table. This is another one of the four Reactivity Addition Devices defined by DOE Orders. The table was obtained used from Brookhaven National Laboratory (BNL) on Long Island, New York, in 1964. Exactly when or how this massive machine was moved into the CML is not recalled; but it sat installed and fully operational the first day of occupancy. It was small enough to fit through the pair of Blast Doors in the southeast corner before the central mullion had been installed.

As received, the massive table consisted of a fixed north half and a moveable south table. The south table moved on rollers which rolled over a pair of polished rails. The rails were attached to opposite sides of a long, rigid, rectangular extension south of the north half. The height of the moveable south table plus the rigid framework under the rollers equaled the height of the north table. When quiescent, the overall split table resembled two tables of equal height with a space between them. A pair of tall, thin, vertical channels, as far apart as the width of the table, seemingly connected the two. The three photographs of Fig. 28 illustrate the table's complicated geometry.

The Horizontal Split Table functioned as a Reactivity Addition Device in the following manner. Both the experimental apparatus and the nuclear fuel would be loaded about equally on each half of the table. The physics parameter which prevented criticality during assembly was the relatively large spacing between table halves. That is, neutron interactions between fuel on both tables was too small to provide significant reactivity. The experiment began when the subcritical, but fully loaded, south table was remotely drawn closer to the subcritical, but fully loaded, north table. The closing mechanism was a polished piston attached to the south table's underside and drawn hydraulically toward the waiting north table. The speed of closure was most rapid at this time; the south table moved northward at the rate of several millimeters per minute. Naturally, carefully placed radiation detection instrumentation monitored each moment of the table's closure because the neutron counting rate increased as neutron interactions did.





*Fig. 28. The top photograph shows an overhead angled view of the Horizontal Split Table being used for an experimental program. The north table (left) is fixed and contains a “second SCRAM” mechanism on top of it. The south table (with tread) has a table on top of it to level with the north table’s second SCRAM. This south table moved north in response to a pull by the shiny piston in the middle. Both side channels show light-grey rails upon which the south table rolled. The lower left photograph is an overhead of the south table as used for another purpose at another time. Empty space between halves has been filled in with a metal plate that appears shiny. The lower right photograph shows details: the thick plate on I-beams which elevated the south half to the same elevation as the second SCRAM table on the north, the outside edges of rollers (lower left), and two protruding screws on the visible edge of the north table (far left). These remotely controlled screws delicately controlled table closure during the last several millimeters. Four protruding rod-like devices, are seen in the top photograph, are discussed in the text.*

When the south table approached to within 250 mm of the other, further closure stopped because the table contacted a large-diameter screw of that length extending south from the north table. This was called the “Power Screw.” Four other protrusions—in addition to the shiny piston—can be seen on the south side of the north table in the top photograph (three look dark and are hard to see, the other, shiny); and the Power Screw is the second from the bottom. Once made, contact could never be broken; otherwise, a table SCRAM would occur. That Power Screw could be turned remotely from the Control Room and withdrawn very slowly back into the north table. As it did, the polished piston continued to pull on the south table, drawing the two halves ever closer together. In effect, the piston was pulling the table toward closure; but the extended screw prevented closure except as allowed by the retreating screw. The rate of closure of the table in response to the closing Power Screw was considered the “middle” closure speed, only about a millimeter or two per minute.

In time, the table closed to a point that even this quite slow “middle” closure speed added reactivity too fast. Large planar faces of fissile material could experience significant increases in neutron interaction with almost imperceptible decreases in separation. At this point, the rotation of the Power Screw could be reduced a final factor of ten. Table closure was then extremely slow. In addition to that, “jogging” the spring-loaded closure push button to achieve time-averaged slower closures occasionally became necessary to keep the indicated neutron flux growth rate within allowed guidelines.

The table had been used at Brookhaven National Laboratories (BNL) for subcritical experiments up until the early 1960s. It had

only a single SCRAM capability—the rapid opening of the south table away from the north. Operational philosophy at Rocky Flats required that any experiment taken to criticality have *two* independent SCRAM capabilities. This “second SCRAM” was designed by G. Tuck and installed for the life of the machine at Rocky Flats. It may be seen clearly on the north table in the top photograph of Fig. 28. A second movable table was added to the top of the fixed north table. This smaller table rolled on the round bars shown shiny in the top figure. In use, it would be driven hydraulically toward the south end and latched. Large springs—similar to those found on garage door openers—pulled against this latch. The second SCRAM table would be closed and latched first in the experiment, before any closure of the south table began. If at any time during an experiment a SCRAM signal should occur for any reason, the latch would release allowing the large springs to withdraw the smaller table away from the center of reactivity.

The SCRAM mechanisms, then, for the Horizontal Split Table consisted of two table movements. First, the south table rapidly returned south to its initial position. This motion was fast, clearly visible to the eye; but the actual time for table movement, although recorded a number of times, is not now recalled. Its capability was touted to begin at 150 mm per second even when the table was loaded to 20,000 kg. The table was never loaded that heavily. The initial opening rate slowed down significantly as the fully-open condition was approached. Secondly, the smaller table on top of the north table was jerked north under the tension of garage door springs. This movement, too, was clearly visible, occasionally recorded, but no longer recalled.

Nuclear materials on each side had to be assembled following usual manual assembly procedures. Each side had to be treated like an *In Situ* experiment and was limited to assembly only to a multiplication limit of ten. With hundreds of critical experiments performed using this table, that multiplication limit never served as a limiting factor. The great preponderance of reactivity would be added through the act of closing the two tables one upon the other.

This Horizontal Split Table measured about 5.4 m long by about 2.2 m wide; and it rose about 0.7 m above the concrete floor. The mild steel weighed about 5000 kg. These parameters pertain to the original split table as received from BNL; they do not include anything associated with the second SCRAM. Although the table had a fairly complicated geometry of honeycombed steel webbing, structural steel channel, and flat steel plate, a reasonable approximation to its steel content, suitable for computer modeling, would be a 25-mm-thick vertical rectangular cylindrical perimeter 5.4 m by 2.2 m by 0.7 m high supporting two co-planar, horizontal, 1.9-m-long by 2.2-m-wide table tops. One of these table tops would be at each end of the rectangle leaving an open space between. These table tops would be 50 mm thick.

The length of this table (north/south) was parallel to the long dimension of the Assembly Room Hood; and the west edge was about 1.9 m east of it. The northeast corner of the Horizontal Split Table was 2.4 m west of the east wall and 1.1 m south of the north wall.

The working surface of the south table needed to be raised to bring it level with the north table plus its second SCRAM. A thick steel slab mounted on I-beams accomplished this as shown in the lower

right photograph of Fig 28. Dimensions of this small table were not recorded but may be estimated from the figure. The lower right photograph indicates that this additional table spanned just about five of the eleven safety tread rectangles glued to the south table. Knowing the 2.2 m width of the table, the overhead view of the figure (lower left) permits this estimate with little parallax. The covered five treads span about 45% of the width, or, 1.0 m wide. Using the same technique, the top photo suggests the added table spanned about 1.8 lengths of the three treads covering the table half north to south. That comes to about 60%. The original table was 1.9 m in that direction; so the second SCRAM table would be about 1.14 m north/south. The table appears to be about 50 mm thick. This estimate comes from comparing it to the 12.7 mm thickness of the plate resting on it (lower right photo). The size of the I-beam was also not recorded; but the same kind of detective work suggests they were 203 mm tall I-beams.

### ***Liquid Reflector Apparatus***

This was the fourth and final Reactivity Addition Device defined as a reactor per DOE orders. It was the only device that did not exist at the time initial building construction was completed; but it followed shortly thereafter. It was built in time for the very first experimental program at the CML beginning September 1965. It earned its name because of the way reactivity would be added to an experimental assembly. Some construction of solid fissile material would be fixed in place within its open-topped tank. The tank was situated directly above a large reservoir containing a non-fissile liquid of choice. Remotely, additions of reactivity would result from the introduction of that non-fissile liquid as

it flowed below, around, between, and above the solid fissile fuel components. Reactivity would increase because of improved moderation of fission neutrons as well as the increased reflection of neutrons back into the fuel region. In contrast, split table machines added reactivity by increasing neutron interaction between two separated regions of fuel, while solution experiments added reactivity most directly: more fissile material simply congregated in a small region of space.

The non-fissile liquid of this apparatus had to be compatible with whatever fuel was used. When either enriched uranium metal or “bare” (not contained) plutonium metal was involved, the non-fissile liquid was an hydrogenous oil selected to provide both neutron reflection and moderation. Oil would be noncorrosive with both fissile metals whereas water would not. In fact, oil seemed to coat each metal (especially plutonium) and protect it against unwanted attack by possibly humid air. Water in any form is known to be very incompatible with plutonium, especially. Plutonium metal is also pyrophoric when exposed to ordinary air; and the oil apparently protected the metal to some degree.

The oil was manufactured by a popular American distributor of automotive fuels<sup>32</sup> (Texaco) and carried their designation #522. The same oil is still sold as their Texaco product #00522 Canopus 19. It is a dry, pure, hydrocarbon fluid with a density of 0.889 mg/mm<sup>3</sup>. The carbon-to-hydrogen mass ratio claimed by the manufacturer is 6.8. Its hydrogen number density is  $0.0699 \times 10^{21}$  atoms/mm<sup>3</sup>; and that for carbon,  $0.0386 \times 10^{21}$  atoms/mm<sup>3</sup>; therefore, the number density ratio of hydrogen

to carbon is 1.81 to 1. The number density of hydrogen to oxygen in water is, of course, 2.0. This oil resembled water in many respects. It was only a little more viscous than water and had similar affects on neutron movement. Hydrogen is, of course, the most important neutron moderator and is only “diluted” in either liquid by either carbon or oxygen. Carbon is a better moderator than oxygen; so, even though oil has a smaller hydrogen content, it is considered a better moderator than water. Because oil and water were so similar, oil-based data could be applied directly to many plant problems involving water around fissile metal. If better analysis were required, various techniques could be used to “adjust” the oil data for the slight differences in atomic ratios.

The Liquid Reflector Apparatus consisted of the oil reservoir and experimental tank attached to it. The entire assembly was one construction and could be (and sometimes was) lifted with the crane and moved about the Assembly Room. At the onset of an experiment, fissile metal would be rigidly fixed in place within the experimental tank. Then, oil would be pumped remotely from the Control Room between the reservoir and the tank. The oil would surround whatever fuel had been installed, reflecting and moderating fission neutrons.

The oil distribution system connecting tank and reservoir was constructed mostly of copper tubing and brass valves. The pump used to move the oil was an inexpensive submersible one resting on the bottom of the reservoir. Control valves directing the flow of oil were actuated by electric solenoids. The pump operated continuously during an experiment; but oil did not move unless one or more of three valves were opened. These valves allowed oil to flow at different rates. Four different flow rates were available; the one used depended on

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<sup>32</sup>Equilon Enterprises, LLC, “*Shell and Texaco Working Together*”, P.O. Box 4427, Houston, TX 77210-4427.

proximity to criticality. The fill line between the reservoir and the tank branched into a number of parallel lines for this purpose. The fastest rate simply fed the output of the pump directly to the tank through unencumbered copper tubing. Two lesser rates were established by having two other branches each fitted with an orifice of a different size. The larger hole posed less resistance resulting in a greater flow. A quite-small-diameter orifice in the third branch yielded the slowest flow rate. Even slower average oil addition rates were possible by “cycling” the spring-loaded switch controlling the pump. A fourth speed, second greatest, was possible by opening both valves allowing oil to flow through both orifices simultaneously.

A fourth parallel branch allowed oil to flow *away* from the experimental tank back to storage. When used, the pump would be off; and opening a valve allowed oil to flow backwards through the pump. The type pump used permitted this reverse flow. This branch had no orifice in the oil’s path and would be used to remove small amounts of reactivity without a full system SCRAM. A simplified schematic drawing of the plumbing system is shown in Fig. 29; and a photograph of the apparatus showing the four branches in the fill line to the lower right is presented in Fig. 30 (to the left of the white-faced gauge).

Two larger remotely-controlled, electrically-operated, valves served as SCRAM valves on this apparatus. Both were screwed directly to the bottom of the tank; this assured that any experiment could accurately be described as having no oil columns, other than the small-diameter fill line, projecting below the bottom surface of a tank. Steel pipe (not copper tubing) connected these valves to the reservoir. Each allowed oil to plunge away from the

region of reactivity and flow unhindered back to the reservoir. Both SCRAM valves opened automatically in response to a safety shutdown signal; but each could also be functioned independently and on demand in response to their own spring-loaded switch. This option added some flexibility to experiments as any volume of oil could be drained back to storage without initiating a full-blown SCRAM.

Curiously, both SCRAM lines also had a manual valve in series with the remotely-controlled one. This design should probably not have been permitted lest one of these safety shutdown valves have been

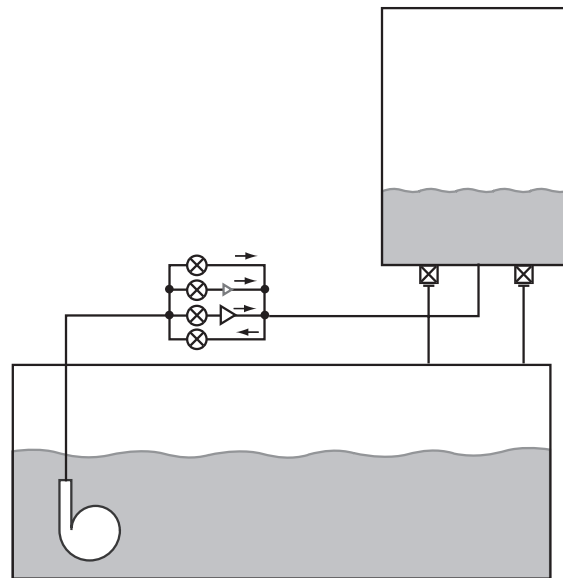
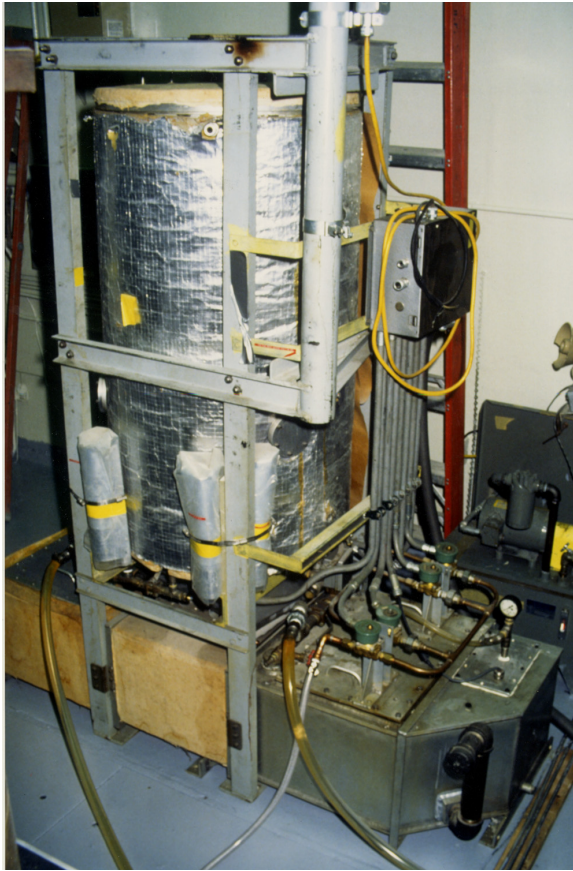


Fig. 29. This schematic elevation drawing of the Liquid Reflector Apparatus shows the reservoir below an experimental tank. Oil in each is shown shaded. The four branches of the plumbing flow-rate-control system are shown rotated 90° for clarity; otherwise, the drawing is a true elevation. Different sized triangles in two branches represent orifices of different sizes producing two lower delivery rates. The top three branches provide four fill rates as discussed in text. The bottom route is the normal (not SCRAM) return. Two SCRAM valves led directly to the reservoir.



*Fig. 30. The rectangular reservoir for the Liquid Reflector Apparatus appears near the bottom; and the four branches in the oil fill line are to the right just left of the white-faced gauge. Three radiation detectors are strapped to supports for the experimental tank near its bottom. The tank has been wrapped in a shiny heat-insulating blanket; and this is discussed in the text.*

inadvertently left closed. The design would be inconsistent with modern safety policies. Proper functioning of these important valves, however, was ensured administratively. The daily pre-experiment checkout required verification that both manual valves were open.

The operation of the oil plumbing for the Liquid Reflector Apparatus was very similar to that for the uranium solution system described above. Copper pipe and brass valves replaced stainless steel; and

sizes of items varied as well. Neither oil fill rates nor the SCRAM rate for oil return is recalled; but the overall design proved to be quite satisfactory over decades of service. The fastest fill rate did not require too much time to reach the point where significant reactivity was about to be added; and the slowest practical rate provided more than adequate control over critical approaches. The SCRAM rate always proved adequate too. The requirement that a single SCRAM must remove reactivity faster than the fastest possible addition rate was verified each day.

Experiments with uranium or canned plutonium metal were performed in this “tank and reservoir” apparatus. Experiments with bare plutonium were a little different. Oil in direct contact with plutonium metal could become contaminated. Consequently, these experiments employed an additional “inner tank”; and the complete apparatus may be viewed as a “tank within a tank atop a reservoir.” Both tanks were necessary on any experiment with bare plutonium metal because a smaller volume of contaminated oil would result; and yet the smaller tank was not large enough to provide effectively infinite oil reflection. This two-tank arrangement provided full oil reflection but kept most of that oil free of plutonium contamination. Each tank actually consisted of three parts: an oil storage reservoir, a pumping system, and a cylindrical container. The introduction of oil added reactivity in the approach toward criticality.

— Outer System —

The reservoir for the larger system was almost a rectangular parallelepiped. It was 1.88 m long by 0.66 m wide. The top surface was level; but the bottom was sloped to provide drainage. One end was 0.381 m high, the other, 0.356 m.

The capacity of the reservoir was about 430 liters. It was constructed of 4.76-mm-thick Type 6061-T6 aluminum plate except for the top which was thicker (12.7 mm) to support the weight of a person. The reservoir was externally braced at the thick end with aluminum angle stock about 25 mm on a side. Similar bracing was found at one-third and two-thirds the length; but the shallower end had no such stiffener. The reservoir was elevated above the floor by aluminum angle stock at both ends. The thicker end had a 51 mm by 51 mm angle (9.5 mm thick); the other was 76 mm by 51 mm angle, also 9.5 mm thick. This difference matched the sloped bottom. The top surface was fitted with two rectangular access plates; and a submersible pump would later be placed at the deeper end. Two nominally 25-mm-diameter threaded pipes welded into the top surface would later be connected to the SCRAM lines; and a coupling welded into this top was used to connect the pump to the distribution manifold.

The bottom of the attached experimental tank was centered 0.3 m above the top surface of the reservoir and also centered along its length and width. An aluminum channel framework outside the experimental tank provided this support. The fact that some reflector oil remained inside the reservoir when criticality was attained must be recognized because that oil provided additional bottom reflection to the assembly under study. The higher the critical height happened to be, the less significant this problem became because the reservoir contained less oil and it was further away.

Reflector heights were indicated outside the tank by a simple U-tube sight gauge. This 12.7-mm-diameter clear plastic tube from a fitting at the bottom of the tank was clamped vertically to the tank. Oil heights were read remotely from an adja-

cent calibrated linear scale by a closed circuit television camera. The camera was mounted on a vertical shaft and could move up and down with the oil level. Viewing the oil height this way—always from the same relative perspective—eliminated inaccuracies due to parallax resulting from a fixed-height camera merely rotating vertically.

The outer experimental tank, itself, was a right circular cylindrical shell 711 mm in outside diameter. The shell was formed by rolling 6.4-mm-thick Type 6061-T651 aluminum plate and welding that along the vertical side seam. The tank stood 1.31-m tall (inside dimension) from the upper surface of the bottom plate to the top of the stiffening ring welded to the rolled plate. It had a flat bottom but was open at the top. The annular width of the stiffening ring was 25 mm; and its inside diameter was 673 mm. The ring was 32 mm high but heavily chamfered at both top edges and the bottom inside edge. This chamfer facilitated movement of hardware into and out of the tank.

The bottom had the same thickness and composition as the rolled side. Both SCRAM connections were welded there as pipe couplings diametrically opposed from one another but near the outside of the tank. The fill connection coupling was midway between the two and also welded near the outer edge. The only other hole in the bottom was a welded coupling for the reflector height measurement. It, too, was near the outer edge but rotated 15° from one of the SCRAM valves.

Three ports were welded to the side 0.43 m above the bottom. These were *originally* intended to receive (after loading the metal) radiation detectors projecting radially inside the tank; but this design was never used. The presence of detectors would have excluded oil which would have

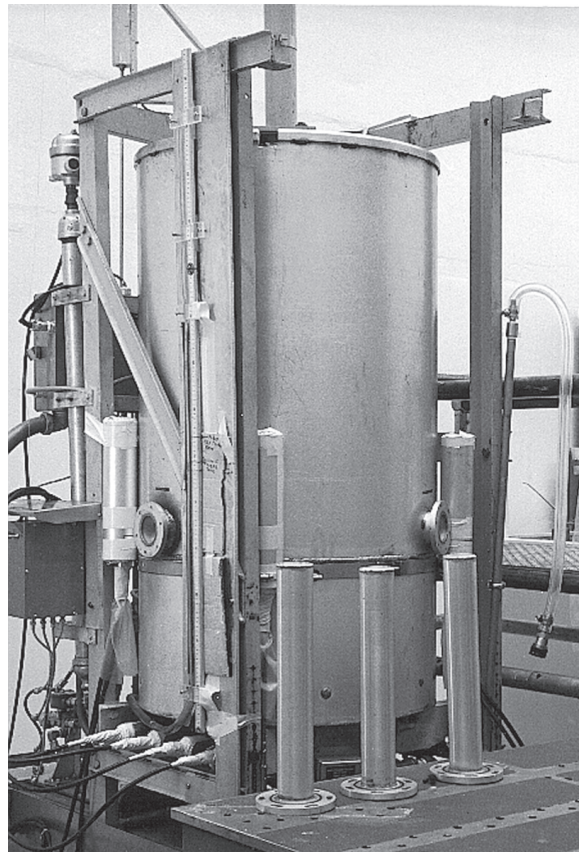
altered the moderation of the assembly under study. Still, the three ports, on 120° centers, formed small “pockets” of oil outside the smooth boundary of the right circular cylinder. Each pocket was a circular cylinder about 64 mm in diameter projecting 38 mm out from the side.

Most features described above are clearly evident in Figs. 31 and 32. In the first, the reservoir is hidden by the Horizontal Split Table in the foreground. The never-used radiation detector tubes rest on that table; and one of the resultant “pockets” can be seen left of center. Seven radiation detectors can be found in various locations, four below the tank and three strapped to the side. The sight gauge is to the left of tank center. The second of these figures permits a view from above into the outer tank. This is the region that would later receive either the inner tank (for bare plutonium) or the uranium metal assembly. In this 1974 photograph, the tank has been wrapped in a thermal insulation blanket in anticipation of still another experimental program. The insulated piping and hardware to the right of the tank and reservoir were never used.

— Inner System —

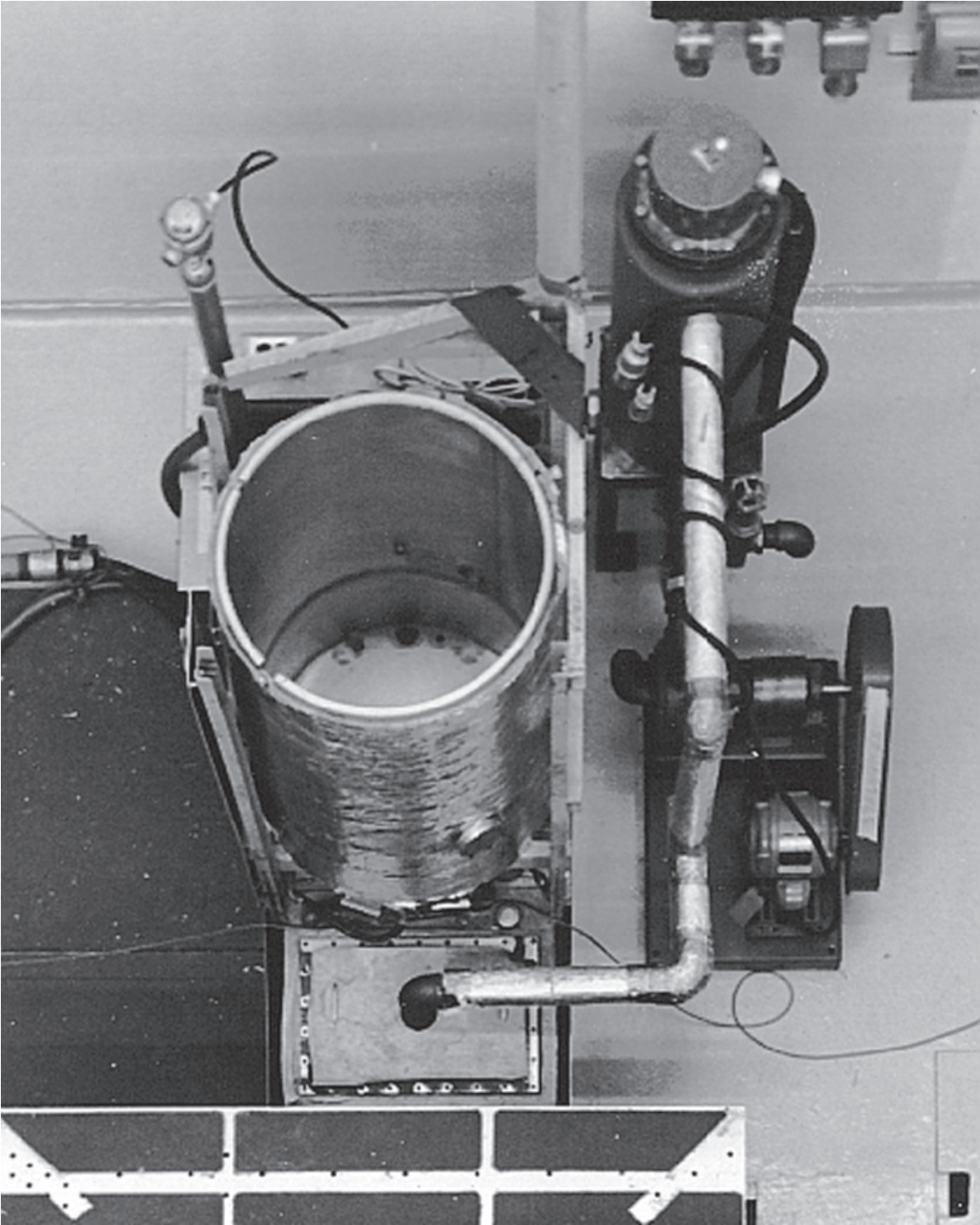
The inner tank would be used only for experiments with bare plutonium metal. This was a means of limiting the volume of oil contaminated with plutonium. The entire inner system was essentially axially symmetric. Its reservoir was cylindrical except for a small section cut away to support the pump. Inside dimensions were 570 mm in diameter by 250 mm high. Top and bottom were 9.5 mm thick; but the cylindrical wall was only 3.18 mm thick. The capacity of this reservoir was about 56 liters, allowing for the 18% (approximately) of the reservoir truncated to make room for the pump. It was constructed of Type 6061-T6 aluminum plate.

The inner experimental tank, like the outer, was also a right circular cylindrical shell; but it was only 364 mm in outside diameter. The shell was formed by rolling 3.2-mm-thick Type 6061-T651 aluminum plate and welding that along the vertical side seam. The tank stood 0.73-m tall (inside) over its top stiffening ring welded to the rolled plate. It had a flat bottom but was open at the top. The bottom was



*Fig. 31. The experimental tank stands above its own reservoir, hidden by the Horizontal Split Table in the foreground. Three re-entrant tubes, originally intended to hold radiation detectors, rest on the table but were never used because they excluded oil from regions too close to the unit under study. Seven radiation detectors can be seen: four horizontal and under the tank and three vertical and attached to support posts. The Sight Gauge tube used to measure oil height can be seen to the left alongside a pair of wooden meter sticks. The top of this open-topped tank was stiffened by a metal ring.*





*Fig. 32. The 711-mm-diameter opened-top container shown in this bird's eye view received an inner container only when bare plutonium experiments were conducted. Most experiments conducted here did not use an inner tank. Insulation wrapped around the tank and equipment to the right was related to an aborted experimental program that would have used heated oil.*

9.5-mm thick but had the same composition as the rolled side.

The stiffening ring at the top differed markedly from the larger tank. It was 12.7-mm thick and also Type 6061-T6 aluminum. Its inside radius equaled that of the inner tank; the outside radius was several millimeters larger than the stiffening ring atop the larger tank. This design allowed the inner tank to “hang” from the top flange of the outer tank. Finally, a 12.7-mm-thick by 457-mm-diameter Type 6061-T6 aluminum disk covered the top opening of the inner tank. It was gasketed and bolted in place to contain contamination. The mounting fixture for

supporting the actual fissile metal assembly load hung from this disk.

The bottom of the associated experimental tank was centered 300 mm above the top surface of its reservoir and coaxial with it. The interconnecting piping between the two held them apart. This separation was probably adequate to always provide essentially infinite reflection to the bottom of an assembly; but the fact that some air space remained inside the reservoir when criticality was attained might be useful in a detailed calculation. That air reduced neutron reflection due to oil in the reservoir. The greatly simplified sketch of

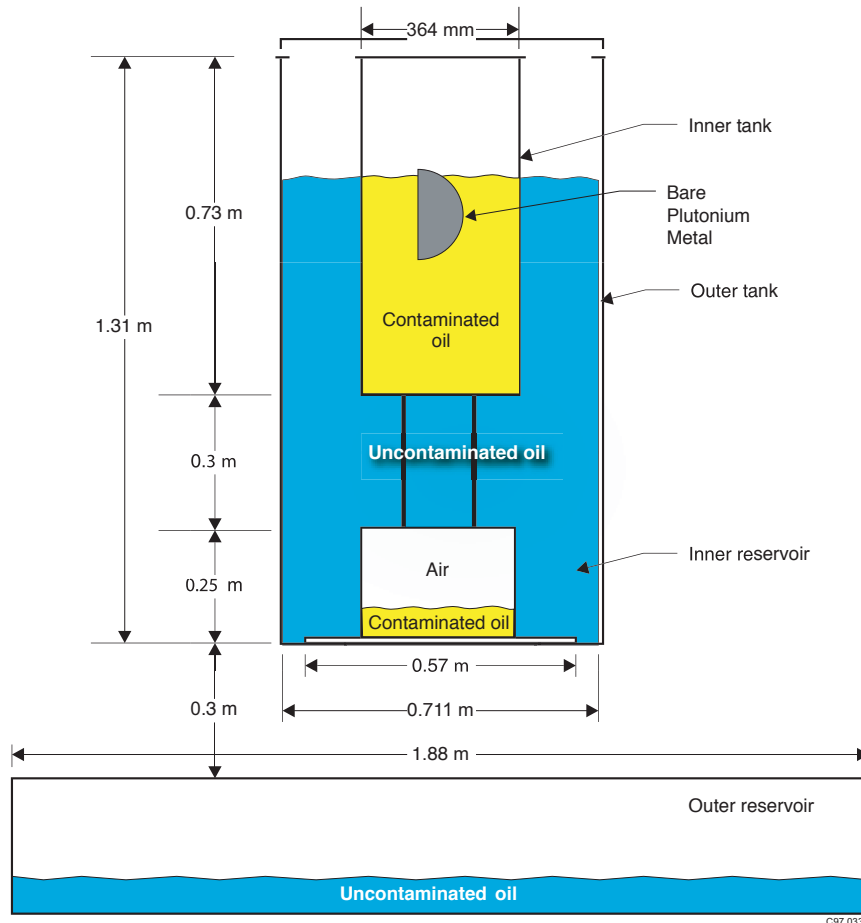


Fig. 33. Relative positions of inner and outer tanks and their associated reservoirs are shown. Regions of contaminated and uncontaminated oil, approximately 56 liters and 430 liters, respectively, are represented by two degrees of shading. They are shown at an arbitrary point of an arbitrary experiment. Regions of air (unshaded) exist above both. The black hemisphere illustrates one program performed with this equipment.

Fig. 33 (not to scale) illustrates this probably insignificant caution.

The oil distribution system connecting tank and reservoir was constructed mostly of galvanized pipe and brass valves. The pump used to move the oil was an inexpensive submersible one resting on a ledge by the reservoir. Control valves were actuated by electric solenoids. The pump operated continuously during an experiment; but oil did not move unless one or more of three valves were open. Different rates were available on this system just as on the larger. Both SCRAM valves were screwed directly to the bottom of the tank. This assured that any experiment could accurately be described as having no oil columns projecting below the bottom surface of a tank.

Reflector heights within the inner system were transmitted outside the outer tank for readout via a "capacitance probe." The probe projected down a vertical clear plastic tube adjacent to but a short distance from the inner tank itself. This tube was connected to the tank near its top and bottom but had a tee-connection at the top to receive the probe. As oil filled the plastic tube, the capacitance between the probe and its surroundings changed. This changing capacitance was read out in terms of changing oil height. This probe could be calibrated by filling the inner tank with oil apart from the larger tank and without fissile material. During such calibration, both the electronic readout and the visual height in the clear plastic could be compared to produce that calibration. The accuracy of this device may not have been very great putting some question on oil heights determined by it.

Most features described above are clearly evident in the photograph of Fig. 34, shown at the loading station just below the wing of the plutonium-handling

glovebox in Room 103. The flexible plastic bag can be seen at the top of the figure. The capacitance probe's tube is to the right and the pump can be seen on its indentation in the reservoir.

— Larger Experimental Tank —

The apparatus described above, with or without added insulation, worked satisfactorily for most experimental programs. Almost every one, however, might have benefitted had the diameter of the tank been just a little larger. Sometimes, one

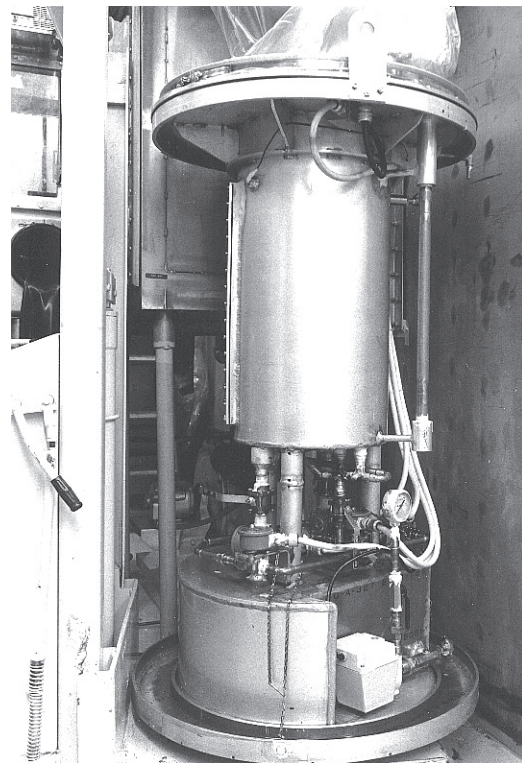


Fig. 34. The inner system housed contaminated oil in direct contact with bare plutonium. The reservoir (below) is separated from the inner tank (above) by its plumbing. The tank, shown here at the plutonium handling facility in the Mixing Room, received assembled plutonium configurations through the plastic bag shown at the very top of the photograph before that bag was sealed and the whole container moved to the Assembly Room for insertion into the outer tank.

wondered if outside corners of fuel assemblies had enough oil around them to be “effectively infinite.” The last program, performed in the early 1980s, using the canned plutonium cylinders needed a much larger tank. There, the array to be studied was a  $3 \times 3 \times 3$  configuration of 3 kg canned plutonium metal cylinders. These 81 kg of plutonium were to be reflected and moderated with hydrogenous fluid.<sup>33</sup> The spacing between units was a little more than 130 mm; and the each unit was about 76 mm in diameter. The diagonal of one horizontal plane of such an array would be 690 mm. This was only a little smaller than the 698 mm inside diameter of the aluminum tank. Thus, that tank would be too small.

A larger tank was needed; so the original tank/reservoir assembly was set to one side and hydrogenous liquid from the original reservoir pumped into a larger, special, tank designed for this one study only. The replacement tank sat a distance away from the reservoir and its still-attached (but unused) tank. Plastic tubing coupled the two together providing fill, return, and SCRAM paths for the liquid. This plastic tubing simply rested on the floor between the reservoir and the new tank. That new tank was made of thick-walled plastic, nearly cubical (711 mm<sup>34</sup> inside dimensions), and measured about 910 mm on a side by 1016 mm tall overall. Walls were 102 mm thick, and the tank was open at the top. The floor was 19.1-mm-thick aluminum alloy plate. The whole new tank rested on a 889-mm-square steel framework which elevated the tank 762 mm above the floor. The steel framework was relatively lightweight steel angle

stock. A photograph of this larger tank is shown in Fig. 35. This tank was much better suited to its task. A 490-mm-square array would have a little over 100 mm of liquid as reflector as the minimum reflector to the 27-unit plutonium array. That liquid plus the plastic would constitute the total reflector. Thick plastic walls merely reduced the volume of liquid needing to be pumped.

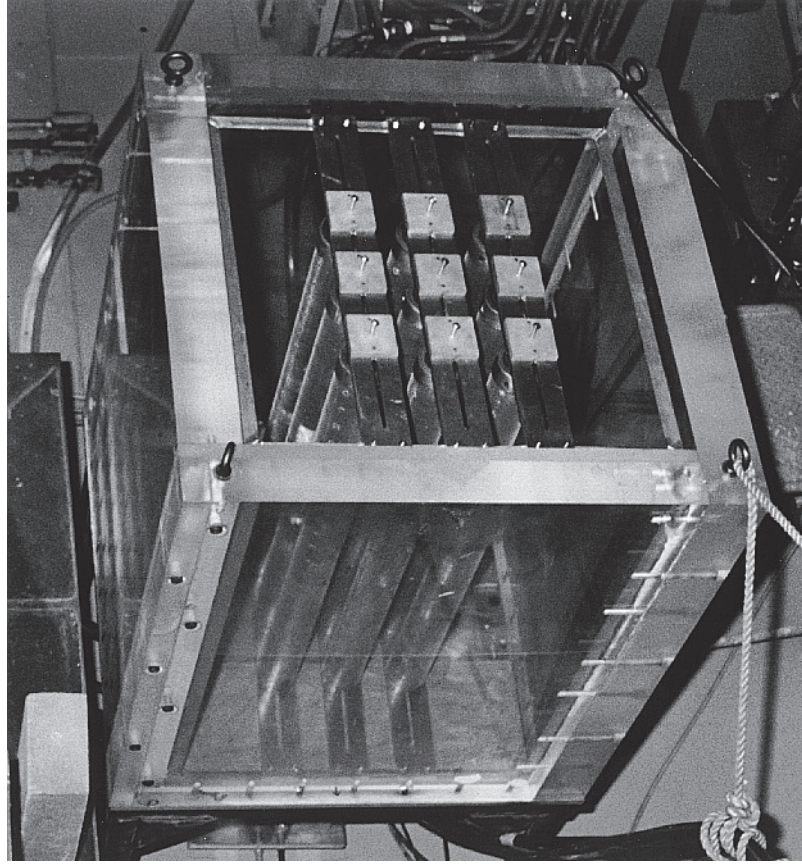
Water was used instead of oil because the plutonium was doubly contained and, therefore, completely protected from contact with whatever liquid was used. Water would dry from the cylinders overnight; and it had other advantages. Old oil was completely cleaned from the reservoir and plumbing before being replaced by water in the reservoir. Under this design, water in and around the plutonium would constitute the bulk of neutron moderation and reflection; but the thick, plastic walls would supply the final additional reflection to provide an effectively infinite reflector. Water and plastic are a little different neutronically; but the difference was negligible that far into the reflector.

The decision to use water instead of oil had an unexpected “down side” however. This plastic tank was the one involved in the plutonium contamination incident of 1982/83. Water vapor had leaked through the two layers of containment and attacked the bare plutonium metal. This problem is discussed in considerable detail in another chapter. Fortunately, no water ever became contaminated, and the reservoir and Assembly Room floor both avoided contamination. All contamination was contained within the open-top plastic tank. The tank and all apparatus inside it had to be discarded.

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<sup>33</sup>Such a large amount of plutonium in a small space far exceeded normal plant Criticality Limits; and flooding with an hydrogenous liquid makes the experiment even more remarkable.

<sup>34</sup>That the inside dimension of the thick-walled plastic tank should be identical to the inside diameter of the outer tank (711 mm) is purely coincidental.



*Fig. 35. A thick-walled plastic tank was used in place of the cylindrical one for the last program using the Liquid Reflector Apparatus. Over 81 kg of plutonium metal in a fairly compact array would be flooded with water. This experiment took place in the early 1980s.*

## **Vault Room (Room 102)**

Room 102 was a well-shielded room always intended for the storage of solid fissile fuels. Liquids were to be excluded altogether; and this would permit the approval of larger fissile masses to be stored there. If liquid moderators and reflectors had been present in the room, criticality limits for fissile metals would have been smaller. The floor plan was simple. A rectangular room would have light-weight metal shelving all around with peninsular shelving leaving narrow aisles for access.

### *Initial Construction*

Original construction produced a simple rectangular room 4.72 m wide and

6.91 m deep (east/west) on the inside. The wall to the south was the 1.52-m-thick north wall of the Assembly Room. The wall to the north was also fairly stout. It was 0.41 m thick to provide additional shielding for the Cold Area of the building. This “shadow shield” wall, as it was sometimes called, protected personnel in the Control Room from intrinsic radiation from the fissile metal stored there as well as additional protection from the radiation burst from a hypothetical criticality accident in Room 101. The east wall was back-filled cinder block, typical of the rest of the building. Radiation shielding was not needed to the east because personnel were excluded from that area during experiments by fencing. The possibility of a criticality accident in that room at other times and

with people possibly working just east of the room was, apparently, not deemed credible. The wall between the room and the Hallway (Room 108) was 0.61 m thick. This thick wall would provide some minimal shielding for personnel in the hallway or Room 103 in the event of a nuclear excursion in Room 102.

Two doors originally accessed this room. A pair of light weight steel doors filled an opening 2.03 m wide by 2.13 m high and opened onto the Hallway. The extra-wide opening permitted easy movement of fissile materials into and out of the room. Interestingly (in light of later nuclear materials safeguards concerns), another pair of light weight steel doors opened directly onto the *out-of-doors* along the east wall! Those doors were 1.52 m wide by the same 2.13 m high. These doors were intended for the occasional receipt of solid fissile materials from other plant buildings as they might be needed for future experiments at the CML. That a room containing a very large inventory of solid fissile materials, presumed quite attractive to potential terrorists, was so readily accessed from the out-of-doors is quite surprising to current thinking. Suggesting such a design in later decades would seem quite naive.

### *Room Modifications*

In the early 1970s, the vulnerability of the room to fissile material diversion because of these exterior doors was recognized. Access to the outside was eliminated by removing the doors and filling in the opening to form a single solid wall facing east. This was done in 1971. It was a tricky feat to do, especially as the last cinder block was installed supposedly containing mortar all the way around it as well as backfilling its holes. The filled-in door opening had to have similar rebar construc-

tion to bring it to the strength of the existing wall. One no-longer-recalled point is whether or not the new wall section was tied into the existing wall by any rebar construction ties.

Interior doors were not even locked during the last half of the 1960s even though several hundred kilograms of fissile materials were comfortably stored there. No one worried about that much material being stored in an unlocked room which also had light-weight doors to the outside. Sometime in the early 1970s, however, combination locks were added to interior doors. Apparently, someone worried just a little. This author recalls arguing that door locks were totally unnecessary and hindered rapid access if ever needed. Considering later security embellishments, this author was also quite naive.

The original roof of this room was equally naive with respect to nuclear materials safeguards. It was the same sheet metal pan-type roof found over the entire Cold Area. The sheet metal was overlaid with tar and gravel laid with the metal pan supported by periodic trusses. Access to this room for nefarious purposes would have been quite simple during those first years. Fortunately, plant security officers were never called upon to defend the room or the building against attack.

The interior of Room 102 was furnished with four U-shaped bays of shelving. Shelving was made of light-weight sheet metal strengthened by steel angle stock. These shelves were used to store various forms of solid fissile nuclear materials in specially-designed storage containers. Each bay consisted of two wings and a back stand of shelves as shown in Fig. 36. Wings of the U stood three levels high; the backs, four. Three sets of these shelves were bolted together forming the four bays. Wings of one U were bolted

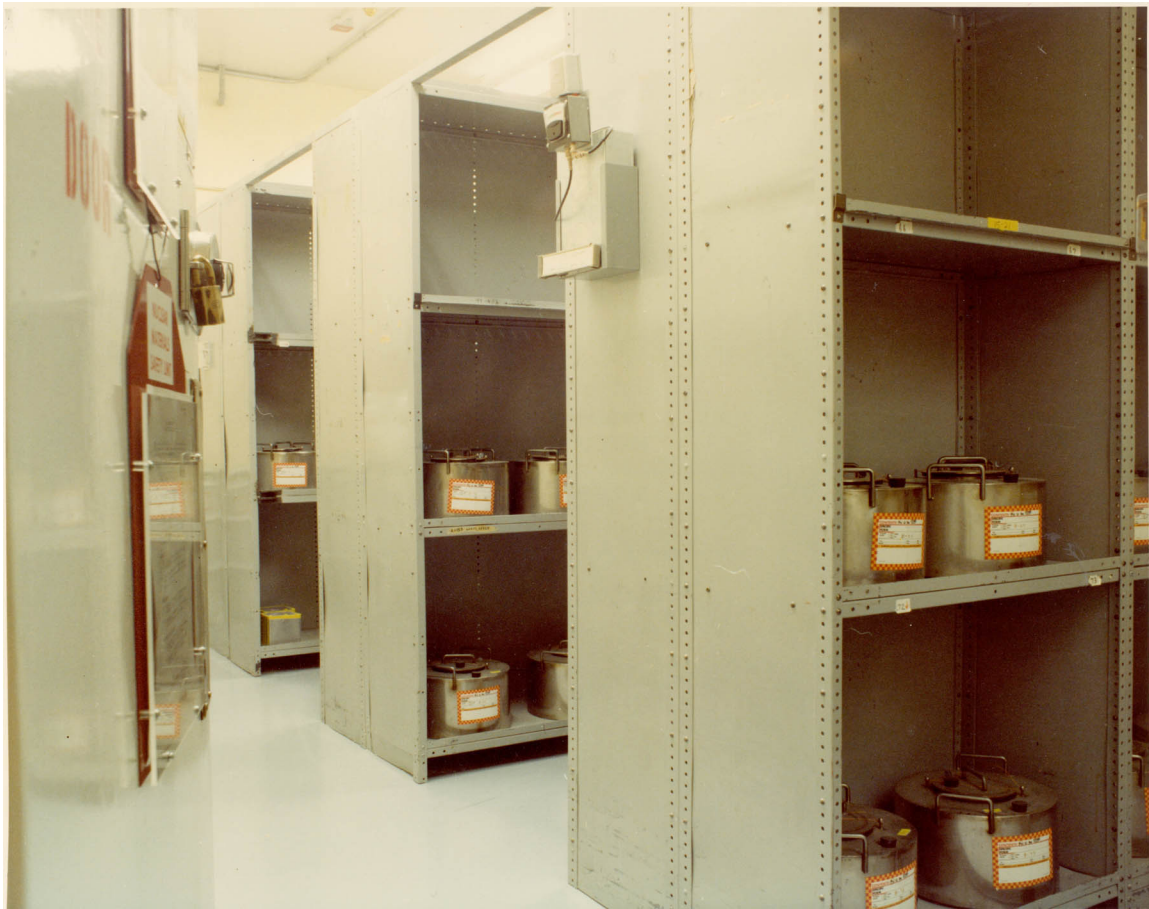


*Fig. 36. Room 102 was used to store containers of solid fissile material on several sets of shelves similar to this U-shaped bay. The water-filled stainless steel containers seen here housed one doubly-canned plutonium machined metal cylinder each. Other shelves housed machined enriched uranium metal hemispherical shells in modified commercial pressure cooker pots as well as cubical cans of low-enriched compacted uranium oxide. Neither the pressure cookers nor the oxide cans are shown in this figure.*

to the wings of the next U as shown in Fig. 37 except for end wings which stood against concrete walls at the east and west ends of the room. A single row of shelves, four compartments high, formed by the backs of the U's stood against the south wall of the room. In all, about 100 storage compartments existed in the room.

Each compartment was limited to the amount and kind of fissile material it could contain. These limitations were the Criticality Safety Limits for fuel storage. Certain containers for each fuel form had been designed; and safety limits for each

compartment specified the number of containers allowed per compartment shelf. Containers for the machined enriched uranium metal hemispherical shells, two allowed per compartment, were further restricted on the total mass allowed per container (10.5 kg). Containers for canned plutonium machined cylinders were limited to one cylinder (slightly more than 3 kg) per container with two containers allowed per compartment. The low-enriched uranium oxide was limited to six cubical cans (greater than 15 kg each) per compartment; and these cans were not contained in any



*Fig. 37. Four U-shaped bays in Room 102 were bolted together across the length of the room forming about 100 storage compartments. Several containers for plutonium metal can be seen; but two cans of the low-enriched uranium oxide appear on the bottom shelf of the furthest visible shelf. The unit hanging from the face of shelves nearest the camera is a radiation detector to survey hands for possible alpha contamination. The access door from the Hallway is seen to the far left with holders for Criticality Limits attached to it.*



additional containers. As stated earlier, these large mass limits could not have been allowed if liquids had been allowed indiscriminately within the room. This exclusion of liquids was only superseded occasionally and then within approved Criticality Limits. Those exceptions allowed a few four-liter bottles of fissile solution to be stored on these shelves for one experimental program.

This room contained a very large amount of fissile material over its lifetime. At its maximum, it housed about 280 kg of high-enriched uranium metal hemishells plus about 375 kg of plutonium metal in the form of doubly-canned machined metal cylinders plus approximately 2100 kg of low-enriched uranium oxide compacted into briquettes and tightly packaged into cubical aluminum cans. All this material remained in this room for many years during the 1970s and 1980s. In addition, this room housed a number of small encapsulated radiation sources. These included  $^{210}\text{Po}/\text{Be}$  neutron sources in the early days,  $^{252}\text{Cf}$  neutron sources after about 1970, and  $^{60}\text{Co}$  gamma ray sources. It also included a small number of plastic vials containing uranium and plutonium liquid radiation sources which were secondary “standards” for a gamma-ray well-crystal spectrometer, used for analytical purposes. That so much material was handled in this room over so many years without any kind of negative incident is a testimony to the management skills of those persons responsible for these materials (G. Tuck and D. C. Hunt) as well as those who composed and issued the Criticality Safety Limits (the Criticality Engineering group). Essentially no contamination was ever found in this room on either floor or shelving. That accomplishment deserves commendation and warrants pride.

### *Enlargement*

Photographic records through late 1979 reveal the room changed little over the first 15 years or so; but two factors contributed to a major change to Room 102 soon thereafter. World-wide tensions over the Cold War increased fears about terrorist attacks; so enhanced safeguards against unauthorized diversion of Special Nuclear Materials (SNM) seemed prudent. Secondly, the original room was proving marginally too small. Maneuvering rolling carts into tight bays was difficult. Some storage containers were heavy; and lifting them to higher shelves was not easy. A larger room with shelving around the walls and a fairly open central area would prove much better. More shelving meant higher shelves need not be used.

Enlargement of Room 102 was authorized a few years either side of 1980, although the exact year is no longer recalled. Humorously, any recollection of the approximate year exists only because the shelving was repainted at the time! Blue was selected because the new contractor at Rocky Flats, Rockwell International, had that as their emblematic color. The room was about doubled in size. The width remained unchanged; but the east wall was extended considerably in that direction. The new room measured the same 4.72 m wide but was now 12.09 m deep. A thick concrete roof was installed at the same time as a deterrent to possible terrorist attack. The exact thickness of this new roof is not recalled confidently; but it probably was about 300 mm thick. The extended walls as well as the replacement roof had two layers of rebar embedded for both mechanical strength and “hardening” against potential attack by outside interventionists. The hardened room could not easily be accessed using explosives or by

ramming walls with a heavy military vehicle.

A small corner of the new room was needed for a new door. The door was much more secure and significantly enhanced materials safeguards. The door and the new depth of the room can be seen in Fig. 38 as well as Fig. 39. The first looks east; the second, west. The replacement door resembled a bank's vault door. For that reason, Room 102 was also called the "Vault Room". The door was inset within

the room; and the inset took up about 2.13 m of the full 4.72-m width. The inset reduced the full length of the room by 1.22 m.

The new room had its freshly painted blue shelves distributed around the perimeter. Shelves were three and four levels high. More than sufficient shelving existed for the fissile material stored; so upper shelves were seldom needed. This arrangement allowed ample space in the center for several experimental purposes. Routine



*Fig. 38. Room 102 was about doubled in size during the first half of the 1980s; and a bank-vault-like door installed for materials safeguards measures. The shelving was rearranged around the walls of the room for better access to fissile materials. This configuration also left room in the center for waste drums and other equipment.*



*Fig. 39. The enlarged Room 102 was used to collect drums of possibly contaminated waste during the building's decommissioning. This 1994 photograph shows a number of these drums. The door (rear, right of center) was similar to a bank's vault door giving rise to the nickname "Vault Room" for Room 102. The door was in an inset into the room at the room's west end.*

maintenance, such as occasionally cleaning the uranium hemishells, could be performed in that space comfortably. Ample space existed for the mandatory periodic accountability of solid fissile material. Storage included "soft" and "hard" waste drums, described below, as well as the "source pig". The pig was a 30-gallon size drum filled with paraffin. The drum, itself, was wrapped in a layer of cadmium sheet. The purpose behind this design was to

minimize radiation from this pig. Paraffin slowed neutrons down to thermal energies; and the cadmium sheet absorbed them. A number of vertical metal tubes were embedded in the paraffin; and these housed several neutron sources. A small lead cylinder housed a wand with a  $^{60}\text{Co}$  source sealed in its tip, was also stored there. The lead was thick enough to attenuate the gamma rays. This pig is shown in Fig. 40. When the impetus for greater

*Fig. 40. The “source pig” was a small drum filled with paraffin to moderate neutrons and wrapped with cadmium sheet to absorb them. Four neutron sources exist at the ends of the wires shown emerging from the pig. The lead cylinder at about 5:00 o’clock housed a gamma ray source. Square paper tags contained information about each source. The pig was on wheels for easy movement but normally remained in Room 102.*



security developed, a pair of hinged bars were installed. These pivoted on one side and were locked with a padlock on the other as seen in the figure.

The enlarged Vault Room served its multiple purposes very nicely for many years. Fissile material was always readily attainable, routine maintenance on solid fissile fuels was easily done, and, in the decommissioning phase of the 1990s, the room provided a collection place for waste drums collected during shutdown operations.

### **Mixing Room (Room 103)**

The Mixing Room<sup>34</sup> was across the hall from the Vault Room just described. Its name derived from the room’s principal function as perceived in the 1960s—a place to blend and store fissile liquids to any

<sup>34</sup>The discussion of this room covers many pages. Two reasons justify this extraordinary length. First, the equipment contained therein was the most prone to evolution, additions, and modifications of any portion of the CML. Second, this author was assigned responsibility for the uranyl nitrate solution and its handling; so possibly less important details seem quite important to him.

desired fissile concentration. The chemical form of that solution was always and only uranyl nitrate salt<sup>35</sup> dissolved in dilute nitric acid. Originally, this storage was to have included *both* enriched uranium solution as well as solutions formed from weapons-grade plutonium; but, soon after construction, the folly of handling both elements in the same general area was realized. The valid argument was made that any contamination found would have to be regarded as belonging to the more hazardous element (plutonium) until proven otherwise by a laboratory pulse-height spectral analysis.

Plutonium solutions were, therefore, never stored in this room at any time in its history. However, a very brief resurgence of the notion of introducing plutonium solutions did resurface in the early 1970s. CML staff traveled to Hanford, Washington, to study their methods of storing and handling plutonium solutions. A modicum of consideration was given to the notion along with some engineering effort. The notion, however, quickly faded and died. The use of plutonium solutions in Building 886 was never again seriously considered.

Half the room was intended to store fissile solutions in Raschig-ring-filled tank farms situated in a depressed pit area. The other half was to be a laboratory area for performing analytic laboratory measurements associated with the chemical properties of fissile solutions. This upper area appeared a little larger than needed; so, when some floor space was needed for another purpose, that area was used. That new feature was a “Down Draft Room” coupled to a small glovebox. This facility would house and handle bare plutonium metal. This was added in the early 1970s.

Ignoring the wisdom of separating elements, this facility was designed to store and handle bare machined plutonium metal hemishells. Somewhat surprisingly, the sharing of space between the two elements was successful over the decades the plutonium complex existed in spite of early speculations. True, the two existed on different levels; and the plutonium was not in solution form. The complex facility, itself, still remains in that room, although the bare plutonium metal had been removed many years ago. No floor or surface contamination in the room has ever been traced to this complex.

### *Initial Construction*

The Mixing Room was essentially a rectangle measuring 11.29 m north/south by 7.68 m the other direction. The original floor plan is shown in Fig. 41. Departures from the rectangular shape existed at both eastern corners. A rectangular notch out of the northeast provided additional room for the Airlock (Room 104). Dimensions of that notch inside Room 103 were 2.64 m (north/south) by 1.52 m. A second rectangular notch out of the southeast corner was really part of the Labyrinth in the Hallway (Room 108). This notch was 2.35 m (north/south) by 3.30 m but had a truncated corner. Interestingly, none of the construction drawings specified precisely the size of the truncation. No reason for this omission is known. A reasonable guess would be that this truncation preserved the wall thickness (1.52 m) at the very corner of the L-shaped bend in the Labyrinth. Ordinarily, construction drawings are not to be scaled; but this questionable technique appears to substantiate the assumption. Assuming that then, simple trigonometry dictates that the face of the truncation would have been 1.26 m across. That is, a triangular portion

<sup>35</sup>Uranyl nitrate hexahydrate:  $[\text{UO}_2(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}]$ .

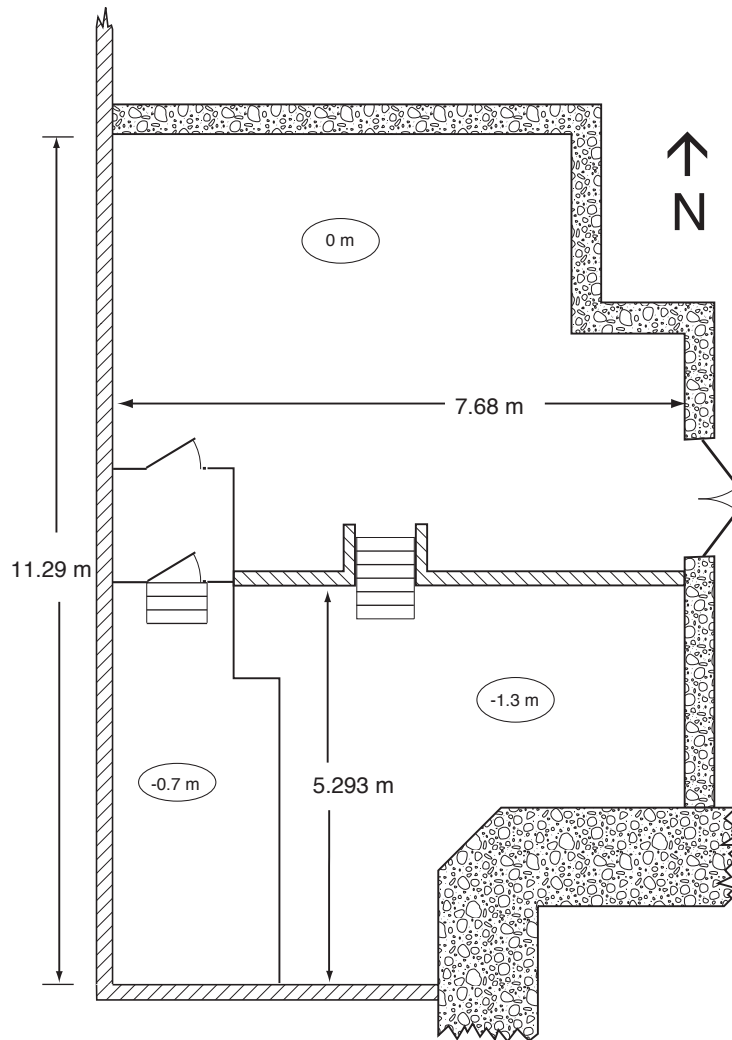


Fig. 41. The north half of the Mixing Room (Room 103) was at the same level as the office area; but the tank farm storage area, south of a 150-mm-high “dam” (reverse cross hatch) was depressed 1.3 m over most of its floor area but only 0.7 m over the area to the southwest. Walls to the north and east were poured concrete (darker shading) while those to the west and south were back-filled cinder block (cross hatched). Uranium solution was confined to the south half of the room while the upper level contained an L-shaped laboratory area and the airlock to the would-be “plutonium solution tank farm” along the west wall to the south. The airlock led down three steps to the stainless-steel-lined tank room. Just to the east of that was the associated “plutonium solution” glovebox.

0.89 m on a side was missing from the northwest corner of the southeast rectangle.

Walls to the north and east were poured concrete; those to the west and south (both outside) were back-filled cinder block strengthened with rebar characteristic of the rest of the building. Thicknesses varied

significantly all around the room. The first 4.25 m south along the west wall from the north end was 254 mm thick; but the remainder was slightly thinner (203 mm). Cinder block was 203 mm thick but thicker sections resulted from an added layer of insulation and plaster inside the cinder

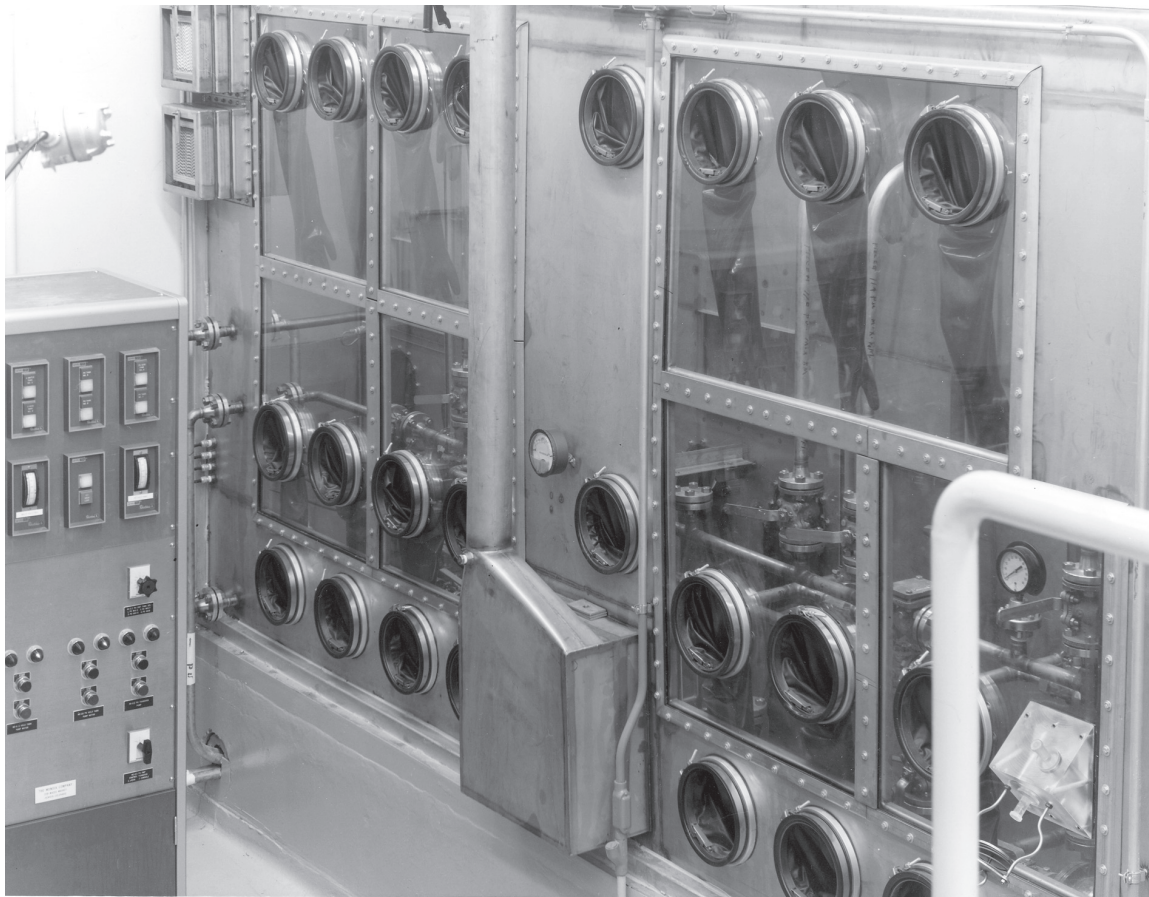
block. The south wall, west of the labyrinth, was the same 203 mm thick except for the east-most 1.98 m where the thickness again became 254 mm. Walls to the north and east were 406 mm thick and simply provided additional shielding between offices and other fuel-handling portions of the building. Some modicum of shielding would provide a little protection in case an accident ever happened in either storage room. The only interruption in this shielding was a 1.8-m-wide thin sheet metal doors in the east wall used for access into Room 103. Labyrinth walls to the southeast of the room were 1.52 m thick and included the truncated corner discussed in the preceding paragraph. This provided radiation shielding at least equal to that which surrounded the Assembly Room. A criticality accident would be most likely to occur in that room; so protection from radiation was most important there.

### ***Uranium Solution Handling System***

The north half of the room was at the same elevation as the office area; but the south half had depressed floors standing at two different lower elevations. Floor elevations relative to “ground zero” are shown in the figure enclosed in ovals. The minus sign indicates a depression. Both depressions were designed to locate the top surfaces of Raschig-ring-filled storage tanks as low as possible relative to the apparatus used in the Assembly Room for critical experiments. The lowest depression (–1.3 m) would house the uranium solution tank farm; the lesser depression (–0.7 m) would house the plutonium solution tank farm and its associated glovebox. That never-used glovebox, raised on a concrete slab above the lowest elevation, is shown in Fig. 42 as it existed in May of 1965.

The floor was 152-mm-thick poured concrete with a single layer of embedded rebar. Floor joints between concrete and metal pipes and conduit of various purposes were never leak tight from the very beginning. Groundwater from heavy spring rains often seeped onto the depressed floor of the pit area containing the tank farm. This floor was well below outside grade level and an underground river appeared to flow southwest just to the west side of the building. Most of the time, puddles on the floor caused little problems. They were easily cleaned up and could be avoided by walking around them before cleanup. Some ground water was present, however, at the time of the May 1969, leak of fissile solution onto the floor of the Mixing Room. This leak is discussed in another chapter. Nonetheless, persons dismantling Building 886 in the spring of 2002 were cautious about the possible presence of at least some uranium contamination beneath the concrete floor of the pit area of Room 103.

The ceiling in this room was the same as that over the entire office area of the building—a simple tar-and-gravel surface over a sheet metal pan surface. The metal was stiffened by folds and creases. Welded trusses supported the sheet metal. This simple surface remained the sole deterrent against unauthorized access through the roof throughout all of the productive years the Mixing Room housed its huge inventory of fissile materials. Only during the super cautious and politically tense years of the early to mid-1990s was any kind of surreptitious threat against these materials perceived. Then, the roof area above this room was covered with coils of razor ribbon wire.



*Fig. 42. The glovebox for the plutonium solution system appeared ready for service in May of 1965; but it was never called upon for its intended service. Four identical tanks were housed in the stainless steel room (enclosure) just behind the glovebox. (May 1965)*

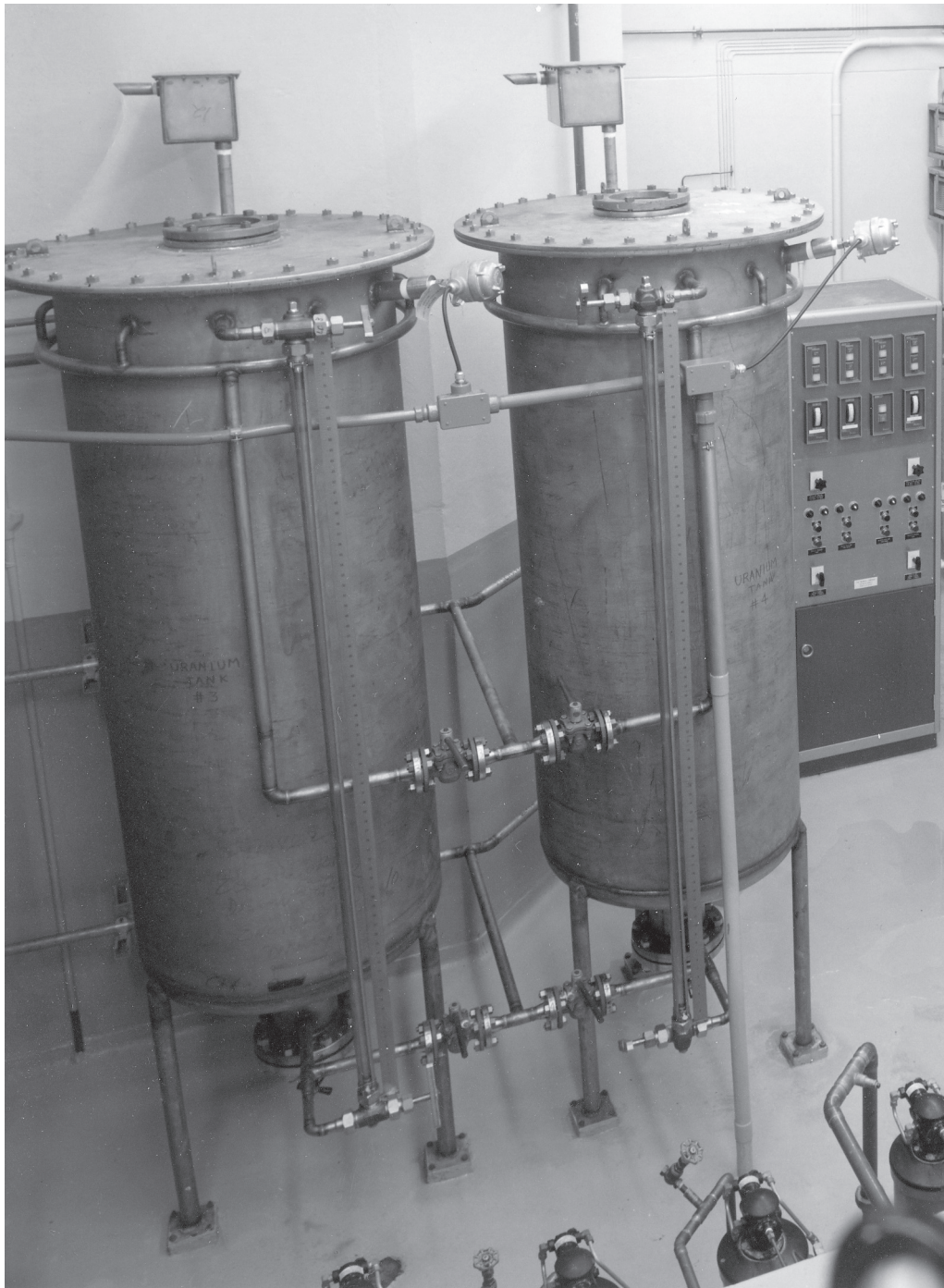
#### *Fissile Solution Tank Farm (1964)*

In 1964, only four tanks were installed on the lowest level for the uranium solution system; and they were identical to one another. Humorously, original drawings identify these four as “U Mix Tanks #1 and #2,” a “Water Tank,” and an “Acid Tank.” That one would or could store a tank of water and another tank of acid without contaminating either while serving two tanks containing uranium solution is really quite naive. Even as the building was under construction, the original intent was to treat all four tanks equally; all would be contaminated with uranium solution. Two of these original four are seen in Fig. 43.

Details showing the fill manifold (top), the drain nozzle and manifold (bottom), tank legs and support pads, and the bottom portion of the Site Gauges are shown in Fig. 44.

Another set of four tanks were installed in the stainless steel enclosure along the west wall; and these were to have served similar roles for the later-aborted plutonium solution system. They, too, were identical to one another but much smaller than the uranium tanks. As already stated, they were never used and, so, will not be discussed further except for two points. One of these tanks was used years later as an auxiliary SCRAM tank (in January 1980) because the small pencil tank under





*Fig. 43. Two of four identical uranium solution storage tanks installed during initial construction reveal all of the features described in detail in the text. The horizontal Fill Line Header appears just below the middle of the tank's height. The Drain Header is located near the bottom of the tanks. Sight Gauges appear at the front of each tank. Liquid level sensors project into the tank near its top; and the tank vents rise out of the tank cover. (May 1965)*



*Fig. 44. Tanks were filled through the header at the top of the photograph and drained via the header near the bottom. Other details, such as Sight Gauge and valving, are discussed in the text and clearly illustrated here. (May 1965)*

the Solution Base was recognized to be inadequately sized for a particular program. For that study, the SCRAM capacity was increased significantly. This will be discussed later; but one of these tanks was part of that.

The second reason to mention these tanks concerns their Raschig ring packing. Glass rings were divided into two perforated baskets which, together, would occupy the full height of the tank. Both baskets were 432 mm in diameter. The top basket was 584 mm high while the bottom one was about 635 mm high. The bottom height is difficult to estimate because the basket was dished to match the tank's

bottom geometry. In an attempt to increase ring packing fraction (more boron per unit volume), Raschig rings were “hand-packed” inside each bottom basket. Hand packing attempted to place cylindrical axes vertical and parallel but was hard to do because of the dished shape. Top baskets were filled randomly except that the baskets were shaken as rings were added to encourage settling. Top baskets for the four tanks received 1240, 1174, 1233, and 1244 rings, respectively. Bottom baskets held 1380, 1400, 1373, and 1409 rings in the same order. These 1965 data might have caused some concern under latter-day thinking. The top basket of the second

example seems unusually low compared to the other three. Hand packing rings seemed to produce a higher packing fraction than random packing while agitating but not nearly as much as might be expected. Packing fractions increased between 2.4 and 4.2% except for the anomalous second example which appeared to be 9.7%. Perhaps the rings added to the top basket were miscounted.

The four “plutonium solution” tanks are shown in Fig. 45 looking into the stainless steel enclosure. The picture is dated May of 1965. The top basket of the nearest tank is about to be installed. The wisdom of these baskets might be questioned. The perforated metal baskets took up volume and excluded some neutron-absorbing glass. The question seems mute, however, since the tanks were never used for their intended purpose.

Returning to the uranium tanks, all four were 762 mm in outside diameter and stood about 2.2 m tall, although their dished bottoms makes a precise height difficult to specify. Tanks were rolled from 6.35-mm-thick stainless steel plate. They had flat tops all co-planar with one another. The distance from the floor to this top plane was 2.58 m. The top cover was 984 mm in diameter and 12.7 mm thick. The cover bolted to a top flange welded to the tank’s wall. This flange was also 12.7 mm thick and 984 mm in diameter. The cover had four lifting lugs in case it ever needed to be removed, although that never happened during the productive life of the tanks. The top cover also featured a centered viewing port used to see inside the tank and gain limited access inside it. This port opening is recalled to have been about 200 mm in diameter and covered with a thick glass port cover held in place by a flanged ring; but this diameter is not recalled exactly. The tops of two of the

tanks as they appeared in 1974 is shown in Fig. 46. The dished bottom was a commercial industrial standard fitting identified as a “30” × 1/4” ASME F&D Head.” The tank stood on three pipe legs welded to the perimeter of the tank near its bottom. Legs were made of commercial stainless steel Schedule 40 pipe and measured 48 mm in diameter. These were merely bolted to the floor during their entire useful life; and no other bracing existed.<sup>36</sup> All these features and more to follow can be seen in the figure.

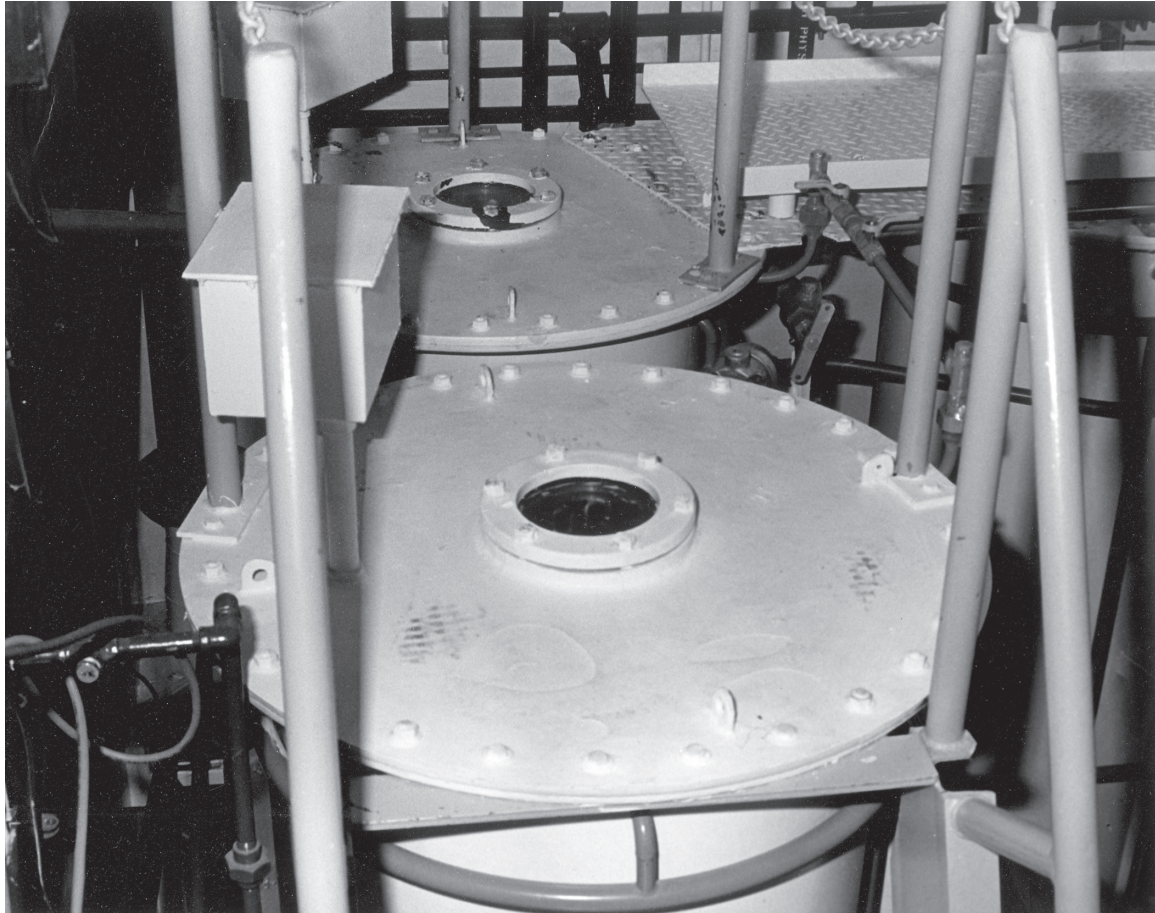
Each tank was equipped with a novel device near the top. This was called a “Spray Ring”; and it caused the solution to enter the top of the tank through six equally spaced nozzles rather than a single entry line. The purpose behind this Spray Ring was to improve homogenization of liquids being pumped into a tank by forcing the liquid to take several paths through the glass Raschig rings (see below) rather than just one. Experience had taught that solution entering a tank filled with randomly oriented Raschig rings tended to follow a path of least resistance through the bed of glass. This was called “channeling”; and the effects of channeling were minimized by offering six orifices for solution flow.

Each tank was filled with borosilicate glass Raschig rings for criticality safety. These glass rings are discussed in another chapter but one important point should be mentioned. Prior to 1964, several sizes and thicknesses of borosilicate glass had been tried industry wide as candidates for a “standard” Raschig ring. Designs evolved and improved such that the rings selected for these tanks ultimately proved to

<sup>36</sup>Concern over seismic stability only blossomed during the early 1990s—long after the tanks had served their intended purpose—at which time engineered stabilizers were fit to each tank of the entire farm.



*Fig. 45. The top basket of randomly oriented Raschig Rings are about to be added to the near tank in the stainless steel enclosure. These tanks were to have housed plutonium solutions; but that never happened. (May 1965)*

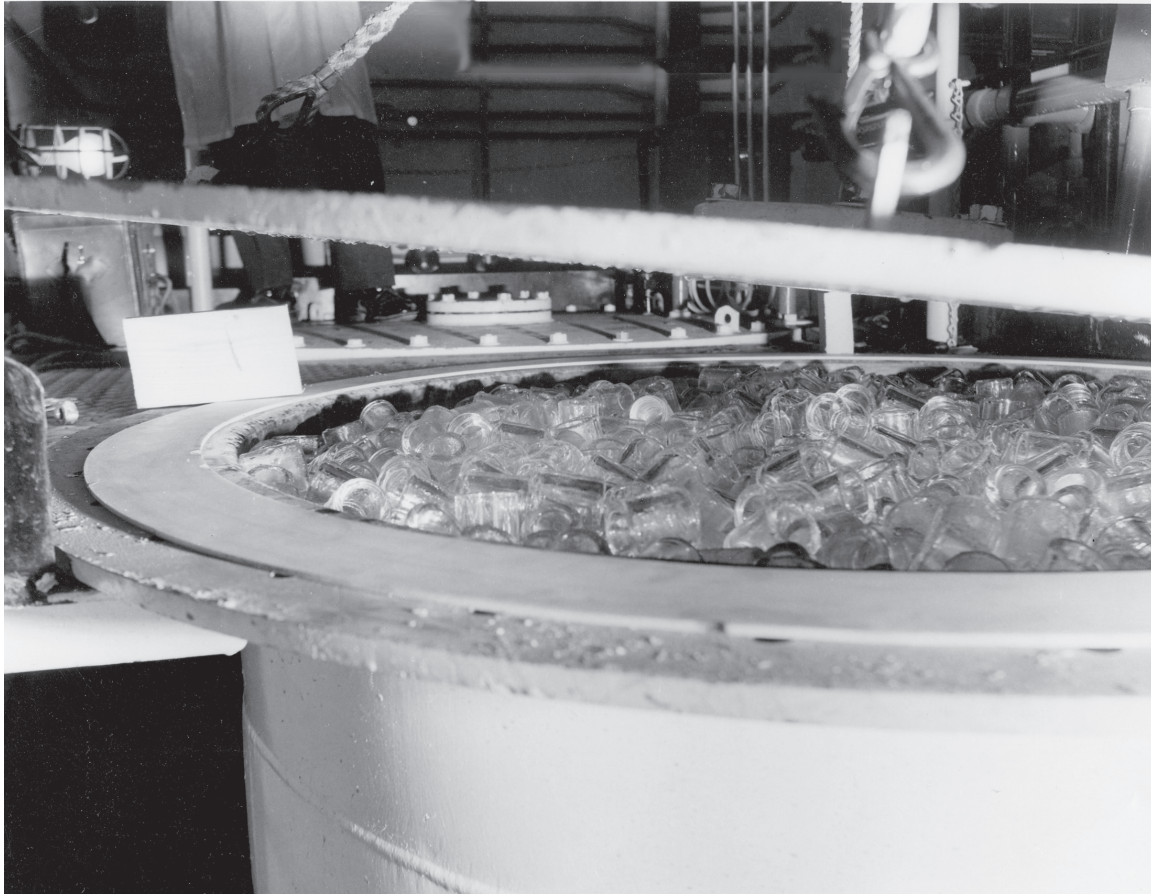


*Fig. 46. The tops of two of the original tanks, pictured in 1974, show their glass inspection ports, tank filter housings, and four small lifting lugs. Scuff marks suggest a paint job is in the near future. (May 1974)*

become the industry's standard. They were hardened, stress-relieved, and fire-polished glass. These right circular cylindrical shells were nominally 38.1 mm in diameter with a 6.3-mm-thick wall; and they were about 44.5 mm long over the fire polish. These first four tanks were filled to the brim with 12,840, 12,670, 12,670, and 12,660 Raschig rings. Figure 47 illustrates this condition clearly. Rings occupied about one-third the tank's capacity leaving the remainder to house uranium solution. Later, these tanks would be filled almost<sup>37</sup> to the top with 484 liters of solution each.

Each tank's fill line entered the Spray Ring via a vertical leg that connected to a horizontal "Fill Manifold." This manifold was about half way up the height of a tank; so solution had to be pumped upward into a tank. A manual valve isolated the tank from the header. Solution passed out of each tank through a second horizontal connection—also isolated from the horizontal "Drain Manifold" by a manual valve—located *near* the very bottom of the tank. This lower connection was welded to a cylindrical nozzle concentric to the tank at its bottom; but it entered about 80 mm *above* the bottom-most flange. This design,

<sup>37</sup>This fill line actually entered the tank about 100 mm below the top flange of the tank. Tanks were never *intentionally* filled above that 484 liter level.



*Fig. 47. Borosilicate glass Raschig rings filled each tank to the brim. (April 1976)*

unfortunately, left a fraction of a liter in the very bottom of this nozzle which could not leave the tank even when the tank was thought to be drained completely. Sediment could collect there; and another concentration would be compromised by this residual amount of the previous concentration. This design flaw was rectified in the fall of 1978. Cylindrical nozzles were removed; and the drain line made to connect to the very lowest point of the tank. This improvement can be seen in later photographs presented for other purposes.

Each tank also had a vertical Sight Gauge mounted externally. Solution height within the tank was read via this Sight Gauge. The gauge connected to the drain

header at the bottom and to the tank itself near the top of the tank. Both tops and bottom Sight Gauge connections were valved so the gauge could be isolated from the tank. Later, the top design was changed and some tanks may not have had a valve at the top of the tank. The gauge, itself, was made of a clear plastic tubing called Tygon®. This material worked well provided the Sight Gauge was changed every few years. Otherwise, the acid tended to leach plasticizer out of the plastic. This was the source of one of the problems discussed in another chapter. Another problem was that long vertical lengths of free-standing flexible tubing would be susceptible to accidental damage unless protected.

Vertical metal shields were installed on opposite sides of the tubing to reduce this possibility. Within a very few years, however, even this design was replaced by lengths of more-rigid stainless steel angle with the tubing securely tucked between two pieces of angle stock.

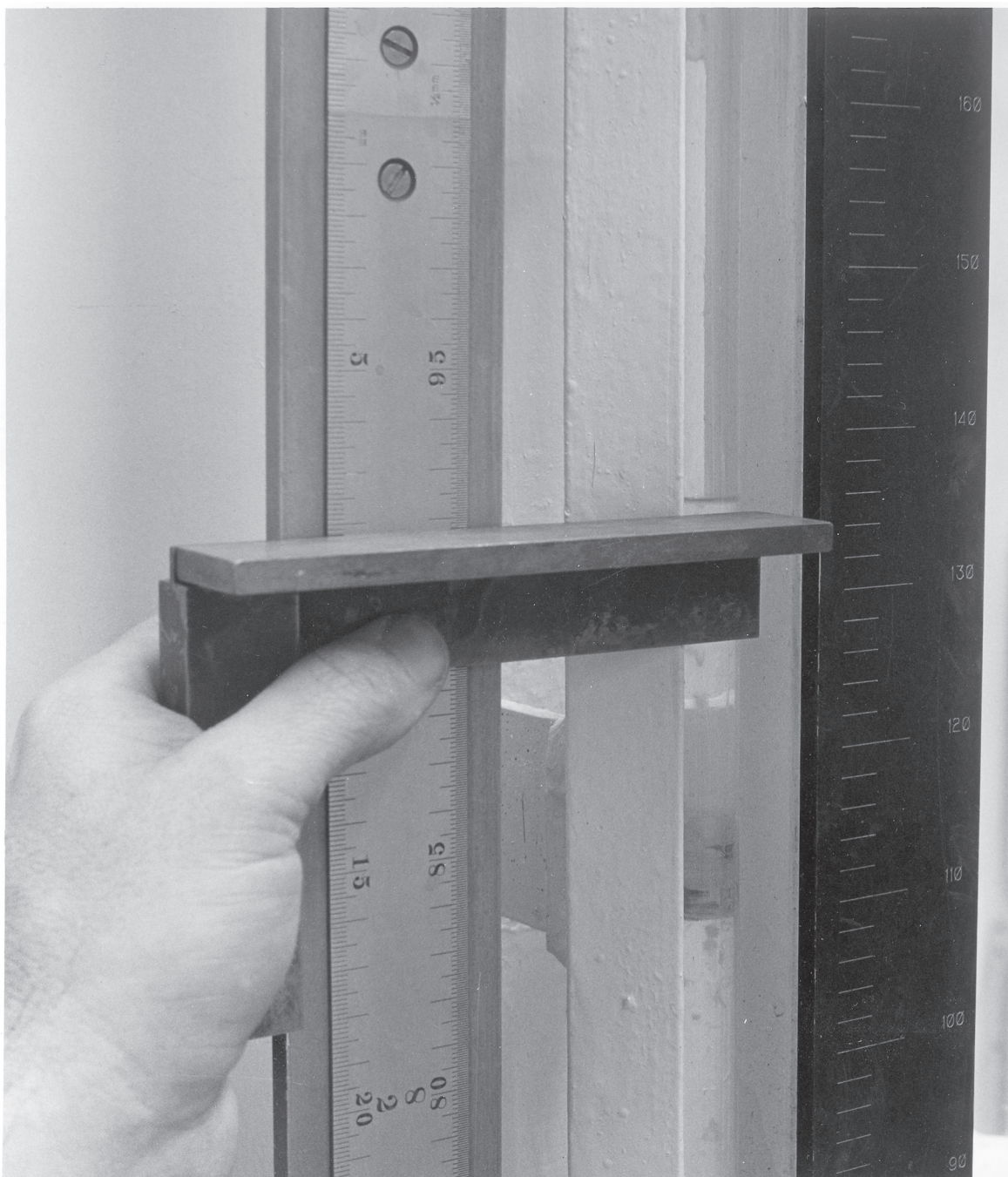
Accurate readings of solution heights inside tanks were important. Good inventory of uranium mass depended upon it as did mixing and blending to achieve a new concentration. Even one method of determining critical solution heights delivered to an experimental configuration depended on measuring the solution removed from storage tanks. The method of determining the height in a tank was to observe the liquid/air interface (the meniscus) in the Sight Gauge and somehow transfer this height to a vertical calibrated scale<sup>38</sup> about 10 to 15 mm to one side of the plastic tube. A machinist's square helped this transfer; but parallax became a problem. Different people would read different heights because of the elevation of their eyes relative to the square. That problem was solved by attaching a horizontal metal plane to the blade of the square such that the meniscus could be viewed just skimming over the surface of this plane. This procedure is illustrated in Fig. 48.

<sup>38</sup>Initially, this scale consisted of engraved "meter sticks" placed end-to-end over the linear portion of the 2-1/2-m-tall tank. These can be seen in Figs. 43 and 44 showing two unpainted tanks. Sometime later, this was replaced with a calibrated scale reading out directly in liters of solution stored. This data was obviously very tank-specific; and the information to generate them was obtained from the periodic volume-calibration of tanks as discussed elsewhere. Calibrated scales (yellow) are shown in Fig. 59. They only contain volume measures over the nominally linear portion of a tank; the dished bottom is clearly not linear. Nonetheless, the lowest volume included all solution in the tank up to that point.

A couple of cautions seem pertinent here. The meniscus is obviously curved within the tube. Where that meniscus is measured is not as important as measuring the meniscus at the same relative location every time. Density differentials between solution within the tank and that in the gauge also can introduce errors. For example, solution might evaporate at different rates in the two regions; so naively measuring a long-time stagnant tank could be in error. For this reason, accurate measurements were always taken just after circulating the solution to ensure that the solution in the gauge represented that within the tank. The physics of Sight Gauge measurements is not at all simple whenever a precision better than 1% is desired.

The original four tanks had Inspection Ports on the top of the tanks; and the three used tanks came with that feature already in place. The used tanks also had similar ports on the sides of the tanks but near the bottom; but the first four initially did not. These ports would serve as Inspection Ports as well as ring Removal Ports if a change in the Raschig ring loading ever became necessary. They seemed so valuable that similar lower ports were added to each of the original tanks. A frontal view of one such port is seen clearly near the bottom of the tank to the right in Fig. 49 of January 1969. All Inspection Ports were thick, hardened, clear glass disks (25 mm thick by about 200 mm in diameter) clamped to the body of the tank by a bolted flanged ring. Several Inspection Port rings are shown painted in the figure, although some of the upper ones appear scuffed and chipped.

A second kind of "port" was a different design and served a different purpose. The unpainted ports in Figure 49 are of this design. Three can be seen, although every tank had this potentially useful feature.



*Fig. 48. A machinist's square was used to transfer the meniscus bottom to the tank's calibrated scale. The scale to the right is the one calibrated in contained liters of solution and fixed directly to the tank. The scale to the left is portable and measures the height above the floor in millimeters. Both scales were necessary when setting the fixed scale relative to the floor based on tank calibration data. The photograph is taken from slightly above the plane attached to the square; so the meniscus appears a little above the blade. (February 1973)*





*Fig. 49. The original four tanks (flat tops) were increased to seven by the addition of used tanks from another building by the time of this January 1969 photograph. The three are the rightmost and the two short tanks in the foreground. The view looks just east of straight south from the upper level into the pit area. Used tanks have dished tops as well as bottoms. Many features of the tanks are discussed in the text. Safety Limits posted on the tank to the right reveal the rather informal format permitted in 1969.*

Two of the three are to the right of center near the bottom of the figure. Only a part of the third is seen to the far left, also near the bottom. This feature was added in the fall of 1978. These ports served as “Raschig Ring Inspection Ports.” Short collars of 108-mm (inside diameter) stainless steel tubing were welded to a flange and to the tank’s body after being covered to match the curvature. At this point, no access to the interior of the tank existed; but, after welding in place, 13-mm-diameter holes were drilled into the tank – one

near the top of the new port; the other at the bottom. The flange assembly projected 76 mm from the side of the tank. Once a cover flange was bolted in place, fissile solution could flow freely into and out of the port whenever solution passed through the tank. That same solution would flow over and around a captive set of five Raschig rings contained therein. The purpose behind this scheme was that the five rings could be cleaned and weighed periodically to detect long term effects on the glass—even over decades of use.

Alternatively, identifying five specific rings from within the tank and among many thousands of nearly identical rings would be nearly impossible; and measuring very small weight losses over any random selection of five rings would be statistically unsound. These Ring Inspection Ports were a good idea.<sup>39</sup> Unfortunately, their merit was not recognized by management; and much less reliable tests (even senseless ones) were carried out in the attempt to determine the same result.

Initially, each tank vented to room atmosphere directly through its own filter box housing. This was located just a short distance above the tank's top lid; and these can be seen in various photographs, including the January 1969 one. Fortunately, these filter housings were relatively small. One incident in May of 1969 put these filters to test as one tank was unintentionally overfilled. Had the filter housings been very much larger, a criticality accident might have happened as high concentration solution found its way into the paper media of the filter. Tank ventilation will be discussed later in much greater detail.

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<sup>39</sup>A variation on ring inspection capability was designed and installed in 1967 in some other tanks (but not all). Again, this worthwhile idea was never allowed to be tested. The idea was to bury a perforated tube vertically right in the bed of randomly placed rings during initial packing. The tube's diameter would be only a little more than the diameter of a Raschig ring. A set of Raschig rings were to be strung through by a stainless steel flexible cable. Those rings would be lowered into the tube to experience day-to-day service from the bottom of the tank to its top. Inspection of specific rings could be accomplished by removing the entire stringer, cleaning them, testing them, and returning the set for more exposure.

### *Evolution of the Uranium Solution Tank Farm*

Almost right away, the adequacy of only four tanks to handle about 1200 liters of solution was called into question. Each tank had a capacity of 484 liters; so three of the four tanks were required just to store the liquid. If any mixing, blending of new concentrations, or other routine maintenance operations were performed, this would require additional storage capacity. About the same time this need became clear, Rocky Flats lost the nation's uranium processing contract to Oak Ridge National Laboratory (late 1960s); and a number of uranium-contaminated tanks became surplus. Several of these tanks were claimed; and three of them were actually installed in Room 103 in the late summer of 1965, only months after the uranium solution had been delivered.

One of the new tanks was about as tall as the original four but larger in diameter (914 mm). It could hold 530 liters, almost 10% more than the original ones. The other two were the same diameter as the first four but almost exactly half the height. Their liquid capacity was 242 liters compared to 484 liters. All three had dished bottoms like the first set; but, unlike the four, they also had dished tops. The three new tanks show prominently in Figure 49. Spray rings were added to the used tanks because the technique had proved so useful. Sight Gauges for all three were tapped right into the side of the tanks and were valved top and bottom. The figure shows these Sight Gauges, their angle stock protection, and the manual valves very clearly.

Seven storage tanks served CML needs quite nicely for a couple of years. When more storage capacity was needed, however, floor space became a problem.

The only unused space was that currently taken up by the never-used “plutonium solution storage tanks.” One of these four small-diameter tanks had been removed for other purposes, as discussed elsewhere; and that left just enough floor space to crowd in two additional uranium solution storage tanks. The two new tanks had to share cramped quarters with the three remaining, but disconnected and unused, small-diameter tanks. Evidence of this situation is clear in the December 1970, photograph shown in Fig. 50.

Details about these tanks is not recalled. They *probably* were used tanks (not new). Dimensions are not known except to note that the maximum readable capacity in

the Sight Glass was 311<sup>40</sup> liters. Both were flat topped with dished bottoms. Their top plane was co-planar with the other seven tanks of the farm. They were stainless steel, filled with Raschig rings, had spray rings, inspection ports, sight gauges, and all the many features of other tanks. One extra feature became necessary because of their location behind an opaque wall; each tanks had a second Sight Gauge installed where it could be seen by those working on the other seven tanks.

<sup>40</sup>The original four tanks contained 484ℓ; the larger of the next three, 530ℓ; the pair of shorter tanks, 242ℓ; and these two latest tanks held 311ℓ each. Adding these, the capacity of the uranium solution tank farm in Room 103 was almost 3600ℓ.

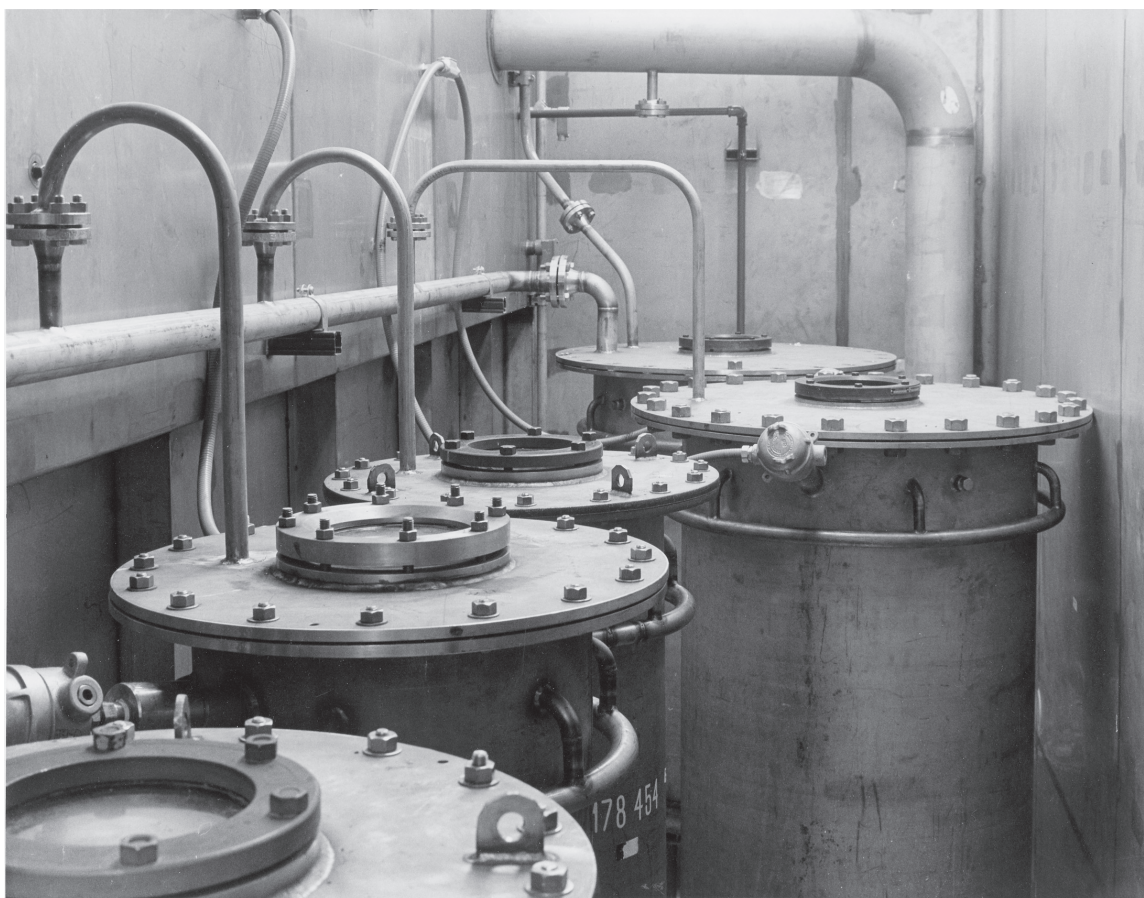


Fig. 50. Two larger tanks (rear) were installed within the would-be plutonium solution enclosure as part of the uranyl nitrate solution storage tank farm about 1970. Three tanks in the foreground were never used and eventually discarded.

Crowded conditions in the enclosed room were tolerated for awhile; but at some unrecalled time, the three superfluous small-diameter tanks were simply removed and discarded. In summary then, these nine tanks in Room 103 represented the maximum capacity (almost 3600 liters) available for the storage and handling of uranium solution in the CML over its three-and-a-half decades of productive life. Seven of the nine tanks rested on the lowest level; and the last two tanks stood on a concrete surface 0.6 m higher.

Nine tanks served the CML well for decades. Toward the late 1980s, some experiments (looking ahead to the 1990s) were projected which would have used two different concentrations in different experi-

mental tanks at the same time. These tanks would have been coupled neutronically through their proximity to one another; but the capacity of only two tanks inside the enclosure would have been slightly inadequate for one concentration. With that situation in mind, a tenth tank was being installed at the time of the FBI raid against Rocky Flats. Plant-wide attention to problems surfacing from that investigation demoted continued installation to a lesser importance; and the facility had seen its last experiment before that tank ever was fully installed. That tenth tank would have been identical in size and configuration to the other two tanks within the enclosure.

*These next few paragraphs are a clear digression from the systematic discussion of the Uranium Solution Handling System in Room 103. The reason for this digression is that an extension of that system eventually located in Room 101 needs to be explained briefly. Organizationally, this could not easily have been included earlier when Room 101 was discussed because too much introductory written material would have had to have been presented to allow a clear understanding of the text; and that would have obfuscated the discussion about the Assembly Room. The discussion of the extension of the Mixing Room functions located in Room 101 seemed better located in the section about Room 103 than interrupting the discussion about Room 101. This digression is separated from the body of text about Room 103 by dashed lines.*

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*Uranium Solution Handling System in Room 101*

For all practical purposes, the uranium solution tank farm existing throughout the entire history of the CML can be considered composed of nine tanks in the south half of Room 103. One short program, however, performed way back in the very early 1970s contained an additional small set of tanks. These tanks were installed

right in the Assembly Room (Room 101) close to the plumbing system already described along the west wall of that room. Three tanks were contained in this extension. One was the never-used small-diameter “plutonium solution storage tank.” The other two were short tanks with capacities of about 250 liters each.

Details about these tanks are not well recalled nor were they ever photographed. What is recalled is that they were referred

to as “the Coupled-Assembly Tanks.” Since the Coupled Assembly experimental program was performed outside<sup>41</sup> the Walk-In Hood in the west half of Room 101, logical reasoning suggests that these three tanks probably did not even connect to the plumbing system belonging to the Solution Base. Even that detail is not recalled with any certainty. The three tanks had their own local interconnected plumbing; but no drawings of that can be found these decades later.

The smallest tank has already been described and stood taller than the other two. These other two were nearly identical, made of stainless steel as well, less than a meter in diameter, not much more than a meter in height, had dished tops and bottoms, and rested directly on the floor just to the southwest of the Walk-In Hood. They had their own interconnecting plumbing. Exactly how this plumbing connected to the main solution handling system contained in Room 103 and 101 is not recalled.

The folly of having a storage tank farm in the same room as the experiment and also separated from the main tank farm was soon recognized; and that “Coupled Assembly System” was dismantled. Two of the tanks became additional SCRAM tanks located inside the Walk-In Hood; and this has been discussed elsewhere. The disposition of the third tank is not known. Incidentally, one of these tanks in this satellite storage farm was the source of one of the larger spills of uranyl nitrate solution. That spill led to fissile solution finding its way into the below-grade trenches in Room

<sup>41</sup>These experiments were performed just above a glovebox initially intended to serve as a valve handling complex for critical experiments involving plutonium solutions. These experiments never happened; so this glovebox was never needed. Therefore, it was used for this application.

101 which could have had quite serious consequences.

The Coupled-Assembly experiments were performed between November 1969, and April 1970. The tanks were clearly there then for that study. A year later, in the spring of 1971, a related study—called “the Uncoupled Coupled-Assembly” program—was performed. Logically, this study might have used the same set of storage tanks; but this is not recalled for certain. If so, the three tanks in Room 101 would have remained there at least through the summer of 1971. If not, they could have been removed as much as a year earlier. One document requesting work from the Maintenance Department suggests that the two larger-diameter tanks were stripped out in 1979.

Tanks and plumbing belonging to the Coupled-Assembly system are so poorly recalled as to warrant no further discussion.

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### ***Tank Farm Plumbing***

All piping associated with the uranium solution handling system in both Rooms 103 and 101 was made with schedule 40 stainless steel pipe nominally called in the industry “one-inch” pipe. The actual outside diameter was 33.40 mm; and the inside diameter was 26.64 mm. Rocky Flats tended to use Type 304L stainless steel, although the commercial pipe is manufactured in Type 316 as well. Any deviation from that specific material and size is specified at the point of discussion. The system contained two kinds of valves. Manual valves were operated by hand; but automatic valves were opened or closed remotely. Usually this remote control took place from the Control Room during an experiment. Manual valves were ball type valves flanged and bolted in place in line. Automatic valves were similarly flanged

and bolted in place. They were air operated but electrically controlled. These valves were manufactured by Grinelle-Saunders and are described to have “150 pound” flanges. All automatic valves—except for two—were “normally closed” valves. That is, their non-activated condition (absence of air pressure) found the valve closed to solution flow; air pressure was required to open the valve. This was a safety feature to preclude any movement of uranium solution unless it was an intentional transfer. The two exceptions were the SCRAM valves. These were normally open for the same safety argument. The normal state was for solution to be able to flow *away* from an experiment; willful action would be required to close these two valves.

When the CML was built in 1964, the plant standard gasket material was Teflon®. That worked well for plutonium solutions and was not attacked by the corrosive acids contained. One problem, however, was that the plastic-like material tended to “cold-flow.” That is, over time, the material became less effective as a gasket. Occasionally, leaks would develop with this material; and flange bolts would have to be tightened periodically. The plumbing system in the CML was designed and built with all Teflon gaskets simply because it was the plant norm. The uranium solution, however, was much less acidic. It would not attack many rubber materials; and these materials would be free from cold-flow. For that reason, the decision was made to replace all Teflon gaskets with ones made of a suitable rubber. Fortunately, that change was made before any fissile solution was ever introduced into the building. The particular rubber selected was Viton-A®; and this proved to be a very wise decision. Not one leak of even a small amount of contamination can be traced to the use of this rubber. That impressive

record spans many hundreds of gaskets used continuously for over three decades!

An important operational philosophy built into the entire system from the very beginning was that fissile solution should never be able to drain *into* an experiment under the influence of gravity. Thus, reactivity ought never be able to add to an experiment even if valves should somehow be so aligned to permit that flow. To attain that goal, the tops of all nine tanks just described were installed to remain in a common plane approximately 0.2 m below the SCRAM valves connection to any experimental tank. The lowest point of any experiment had to be higher than that elevation; so the tops of the storage tanks were guaranteed to be considerably lower than the lowest point of any experiment. In theory, then, gravity could never push solution *into* an experimental vessel. Even without that safety provision, such an accidental flow of solution was practically not even possible. Several remotely-controlled valves would have to fail “open” simultaneously; and the SCRAM valves would have to both fail to be open. This combination of events was so inconceivable as to render any concern over wrong-way solution flow negligible.

Still, a fundamental flaw existed in that theory about gravity flow. The flaw is, itself, so minimal that its recognition caused no grave concern. Still, it should be stated for future consideration applicable to any fissile solution handling system. The problem relates to the wide range of densities for uranium solutions at different concentrations. Low concentrations high enough to still remain a criticality concern might have a density only slightly in excess of 1.0 mg/mm<sup>3</sup>. Very high concentrations close to the minimum critical volume concentration might well have a density of about 1.6 mg/mm<sup>3</sup>. The potential flaw

would exist whenever the low-concentration solution might be very close to criticality in an experimental apparatus in Room 101 at the same time that a mistake was made to open a manual valve to a tank containing a much higher concentration. The higher density solution would push ahead of it the nearly critical lower concentration solution because of the difference in densities. A criticality accident would be possible under this rare combination of conditions. No changes to the solution handling system were made in response to this observation.

The combined solution handling system composed of tanks, assorted pumps, both manual and automatic valves, and interconnecting piping had many functions to serve. Solution had to be passed to and returned from experimental assemblies in another room. It had to be moved from tank to tank for blending concentrations, emptying a tank for periodic maintenance purposes, and other reasons. The liquid even had to be pumped out of one tank and returned to that same tank; this “rolling” ensured homogenization of the concentration. Tanks had to be vented to allow air movement as solution filled or vacated a tank. The contents of a tank had to be readable through some kind of Sight Gauge. A way of introducing solution into the system in the first place was needed. Some means of limiting the volume pumped into a tank to prevent overflowing ought to back up general operator care. If different concentrations were ever to be used, some means of draining lines of the last-used concentration before introducing the next was needed; otherwise, one concentration would be compromised by the residual amount of the other. Solution samples had to be taken for inventory (accountability) reasons; and some means

of returning small beaker-sized amounts to the system had to be provided. Tanks needed to be volume-calibrated periodically to assure maximum precision for inventory measurements; and this required movement of solution.

Indeed, this was a complex system. How each of these functions was manifested in the final handling system is described in a paragraph or two below. Many of these functions were recognized from the onset; but some procedures evolved over time. Occasionally, new equipment became available and permitted improved measures of tank farm parameters. Looking back upon three decades, an accurate observation is that the uranium solution handling system attained its highest degree of functioning and was nearly perfect about the end of the 1980s. This becomes a bittersweet observation when the date of the last useful function of the system (1989) is noted.

A schematic representation of the uranium solution handling system is presented in six figures rather than just one. The system would be too complicated to comprehend unless divided into stages. These six figures are in no way intended to be a chronological development of the system. Instead, they present the final configuration—as it existed for most of the decades of the ‘80s and ‘90s—but broken up into purpose-related blocks. The first of these presents the tanks, three pumps, and fill and drain lines only and is Fig. 51. Other features are omitted for clarity and added in stages. Equipment on this figure enabled mixing, homogenization, and pumping solution out to the experimental area. Other important aspects of the Uranium Solution Handling System are added on subsequent evolutions of this figure.

Each tank was connected to a bottom header<sup>42</sup> which allowed solution to flow away from it. That header led to the input to a number of pumps designed to propel the solution wherever the current procedure dictated. This header was called by two names: the Tank Drain Header and the Pump Suction Header.

A second horizontal header ran a little over a meter above the lower one; and this Tank Fill Header allowed solution to flow into any of the tanks in the farm. This header was just above the set of pumps and, so, was also called the Pump Output Header. This header was essentially parallel to the lower one and followed about the same route in plan view. The level of this header was about mid-way up the taller

tanks and close to the bottom of the shorter two; so the final access into a tank was attained by a short vertical riser. This riser can be seen in several figures.

This header was important, of course, for moving solution about within Room 103; but it also connected to the single line leading, in turn, out to the experimental assemblies located in Room 101. That single line served the dual purpose of returning solution to storage after an experiment. A cluster of automatic and manual valves and one check valve set up the solution routes for filling or returning from the experimental apparatus. This complex was situated just inside Room 103 before the line passed through the wall into Room 101. Solution to the experiments passed through the check valve, a manual valve, and an automatic valve. Returning solution dropped down the vertical leg containing two valves.

<sup>42</sup>A "header" is a horizontal run of pipe which connects tanks for a common purpose. In truth, these runs were not truly horizontal but sloped ever so slightly as to allow residual solution to trickle toward some designed "low point."

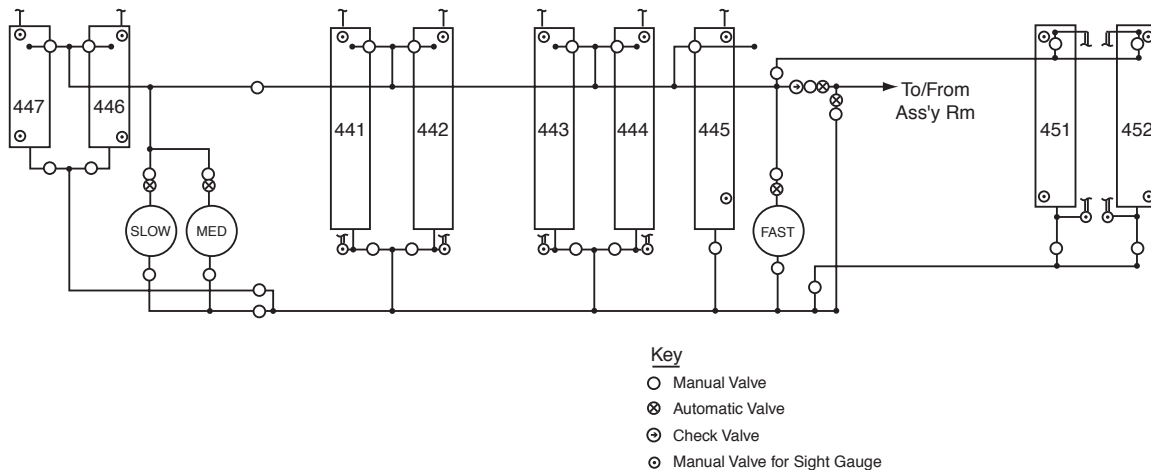


Fig. 51. A schematic drawing of the uranium solution handling system would be overwhelming presented at one time; so it is shown in stages. Here, Tank Fill and Drain headers (top and bottom horizontal lines) connect all nine tanks and three pumps. Tanks are shown as vertical rectangles; pumps, as larger diameter circles. Valve types are shown in the key. Abbreviated tank vent routes are capped with a tilde. One cluster of five valves (right of center) is associated with directing solution to and receiving it from experimental apparatus.



Workers were diligent about not over-filling a tank; but the possibility always existed that some circumstance could lead to an over-filled tank. The risk of that was minimized by fitting each tank with an electronic liquid detection device. Called a Level Tec®, these devices were short metal probes completely covered with a plastic material forming a capacitance between the inner probe and its surroundings. Liquid where it did not belong would change the dielectric constant of the space around the probe and, therefore, the capacitance. The commercial probe was adjusted so that only a few drops of liquid would trip the detector. The probes can be seen as nearly equilateral cylinders in some photographs on the top of some tanks or near the top but on the sides of others.

Readouts for these Level Tec devices as well as other controls were located on the front face of a cabinet situated on the floor of the pit to the east of the “plutonium solution” glovebox. Most of the cabinet can be seen to the far left in the earlier 1964 photograph illustrating that glovebox in its original condition. In addition to these readouts, panels enabled workers to take over local control of the one of the solution pumps for certain functions to be done within the tank farm.

Tanks needed to “breathe”; so some means of allowing air movement was necessary. Initially, tanks vented directly to room atmosphere passing through only a small paper filter in a metal housing. This housing is seen in some figures. By May of 1966, the output from these housings was manifolded together and allowed to vent to room air but directly in front of one of the room’s major room exhaust filters. This manifold was called the Ventilation Header and is the darker and larger diameter stainless steel pipe clearly seen above the tanks in Figure 49, photograph looking at

several tanks. This system was screwed together rather than being welded and is connected to each tank at the filter box. The thought behind this manifold was that any contamination would be quickly swept right into the room’s filtered ventilation system. Still later, the manifold was raised to a great height above the tanks. This increased height was sufficient to prevent cross-contamination due to gravity<sup>43</sup> between tanks of different concentration. This final version of tank ventilation is the subject matter of Fig. 52.

This modification was made after the major contamination incident of May 1969, after some level of paranoia had set in. The worry was that, somehow, solution still might again find its way into the ventilation manifold. Some means of detecting this highly improbable situation and terminating it was sought. This was accomplished by installing a vertical Tank Vent Overflow chamber labeled in the figure simply “Vent Overflow.” The chamber itself was a length of 108-mm-diameter (inside) pipe which would be critically safe by virtue of its slender diameter even if filled with solution. The elevated horizontal manifold emptied into this chamber; and a parallel ventilation line rose again to about the same height forming a “solution trap”. This last riser turned a full half circle and a third vertical line led the now-liquid-free air back down to floor level. This final exposure to room air passed through a filter housing; that air was again swept right into

<sup>43</sup>To illustrate this, two adjacent tanks could contain vastly different concentrations. One could have a density 50% greater than the other. If both manual valves leading to the Tank Drain Header were mistakenly opened at the same time, the hydrostatic head caused by the density differential would push the lower density solution high up the ventilation riser. The elevated manifold was high enough to prevent that errant solution from passing through the vent manifold into any other tank.

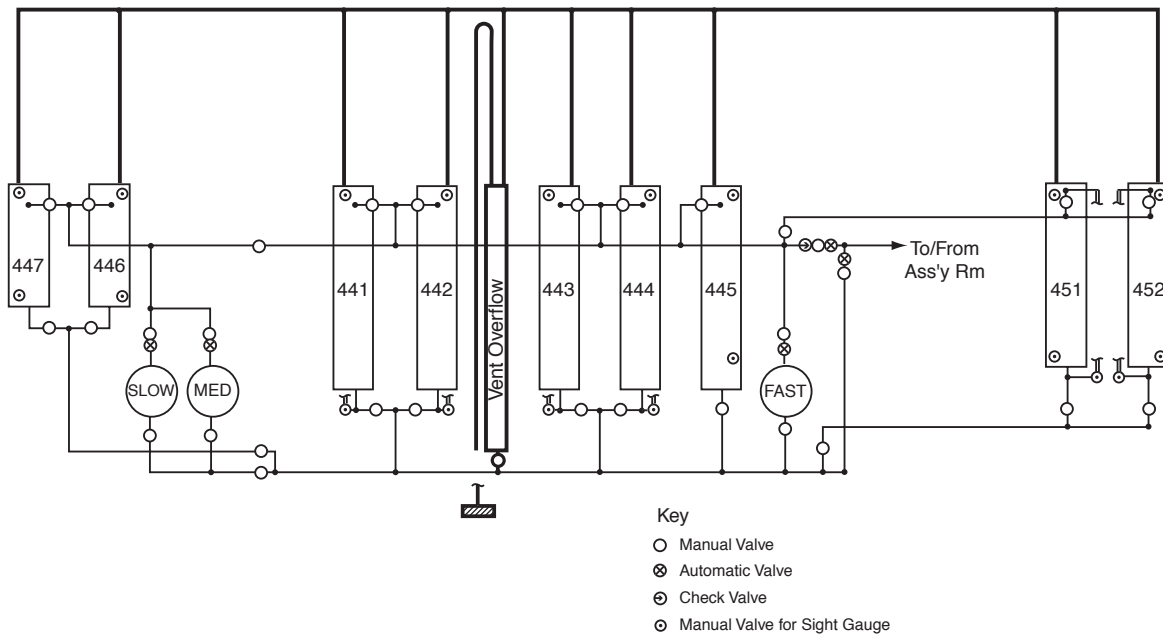


Fig. 52. The tank ventilation portion of the Uranium Solution Handling System is shown in bold superimposed upon the tanks, pumps, and fill/drain plumbing of the previous figure. The elevated manifold precluded cross-contaminating tanks of differing concentrations and the “Vent Overflow” chamber collected any liquids somehow that far off course.

the room’s exhaust system. The bottom of the chamber had a manual valve connecting to the lowest header. This would serve to recover any solution somehow finding its way into the skinny chamber. As expected, this Vent Overflow chamber never saw uranium solution.

The tank farm contained three distinct concentrations of solution throughout most of its lifetime. Changing the system from one concentration to another required many steps. Plumbing lines had to be drained of their held-up solution. This is why horizontal lines were, in reality, sloped toward some low point or some vertical pipe that would allow solution to flow to a lower header. The slope was not readily perceptible, being about 1:100. Furthermore, pumps retaining residual amounts of the last solution had to be drained as well as possible—or lines above them bypassed around the pumps if the pumps had a uni-directional flow working against gravity.

Initially, a simple manual valve was positioned at the very lowest point—at that time—in the very lowest header of the entire system. This small valve was still about 100 mm above the floor, barely leaving enough space for a plastic 250ml beaker to collect solution. The lines in Room 103 usually contained close to 20 liters of solution; so the painstaking draining of the lines was slow, arduous, and wrought with potential for spilling. The problem was resolved by installing a tiny gear pump (the “Drain” Pump) in line with this valve and directing the output from this gear pump up a length of clear plastic tubing into a horizontal plane of small diameter lines and valves that led to every one of the nine tanks. The complete system drainage capability is presented in the third figure in the series: Fig. 53. The vertical tubing was clear plastic as an aid to workers during use. One could tell when the lines had been drained, as well as

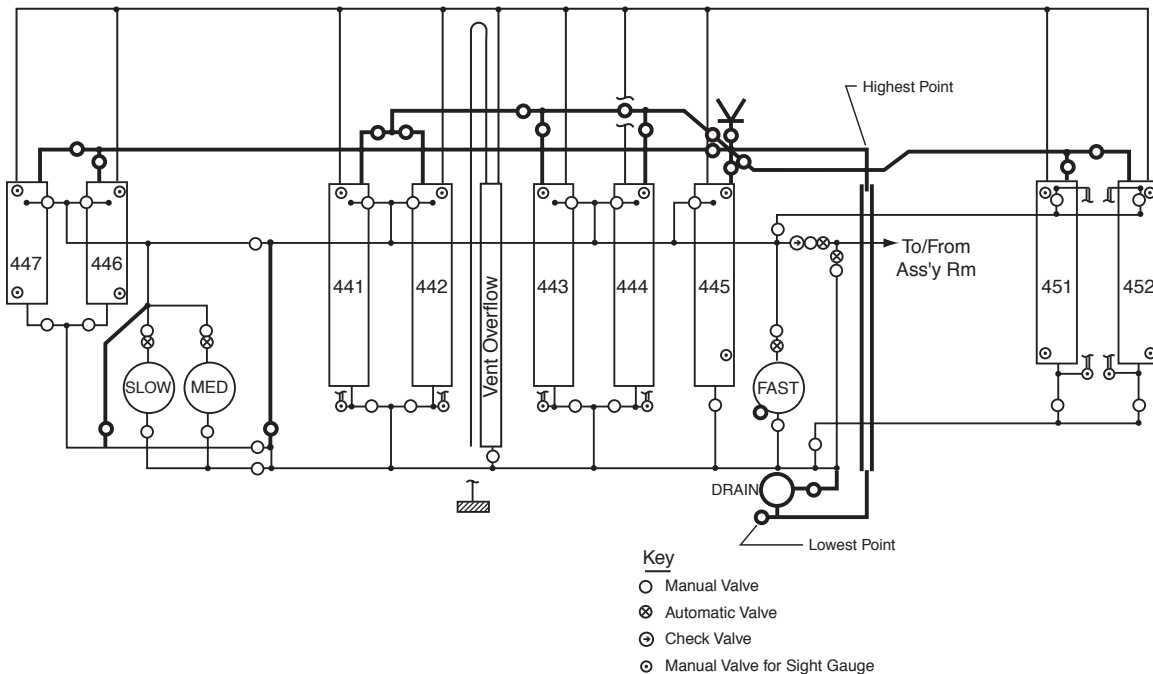


Fig. 53. The Line Drainage system, shown bold, consisted of a small gear pump near the lowest point leading to a vertical rise through a clear plastic tubing (double lines) to a horizontal Line Drainage Header. This header truly lay in a plane even though the schematic drawing suggests otherwise. Closely coupled manual valves allowed selection of solution flow with minimal hold-up down the wrong branch. A small funnel assembly allowed the introduction of small amounts of liquid by hand. Two pumps at the left contained internal check valves that precluded draining through them. The line and valve to their left allowed drainage past them.

possible, by the gear pump. Later, that same tube would show no solution at all as the very lowest drain valve drained the gear pump and the plastic tubing.

The horizontal plane above the tanks, called the Line Drainage Header, was slightly sloped down hill towards each of the tanks. This allowed solution from the highest point of that header to flow downhill into one of the tanks. The highest point and the lowest point are identified in the figure. The Line Drainage Header was designed so that very little solution would hold up in the branch of the header *not* being used to direct solution into a chosen tank. Thus, solution arriving from the highest point to the first decision junction could be allowed into that first tank *or* allowed to pass on to the *rest of the tanks*.

At the next decision point, solution could enter a chosen tank or pass on to *the rest of the tanks*; and so on. Closely coupled orthogonal valves minimized hold-up in the wrong leg. This plane of horizontal drain lines had been installed to the three new tanks in January of 1969 but was extended to the original four in May of that year.

During line draining operations, the gear pump would be able to drain the lines of the previous solution having passed it through the Line Drainage Header into a pre-selected tank within only a few minutes. This stage of the draining was indicated clearly by the yellow liquid in the vertical rise of clear plastic tubing. The liquid head would drop down to within the clear section and bounce up and down in

response to the pulses of the gear pump. At this point, the only solution left to recover was the small amount beyond the gear pump and up the clear tubing. This was drained by hand into a small plastic beaker. That final amount, usually between 100 and 200 ml, was then hand carried carefully to a small funnel welded vertically into the Drainage Header. The funnel had a threaded hole fitted with a commercial pipe plug to keep dust and dirt out of the system when the funnel was not used as shown in Fig. 54. A quart-sized paint can covered the funnel as a further attempt to keep the funnel clean and tidy. The funnel was welded to a large circular trap that served as a drip pan in case any solution leaked

during pouring. This almost never happened; but, if it did, cleanup would be easy. This small funnel construction was used to return any solution obtained from any source back to the system. For example, solution samples taken for material accountability purposes were returned after small amounts had been used for laboratory analyses. These returned samples would be poured into the funnel.

In summary, the line drainage procedure worked well and was not an onerous task. The whole procedure could be accomplished in a couple of hours. This routine helped maintain a distinction between the three concentrations for almost three full decades. No contamination incidents are



*Fig. 54. Small quantities of uranium solution were re-introduced into the tank farm through this funnel assembly located above the tanks and on the Line Drainage Distribution Header. The screwed plug precluded dirt and dust; and the drip pan prevented contamination of the floor far below.*

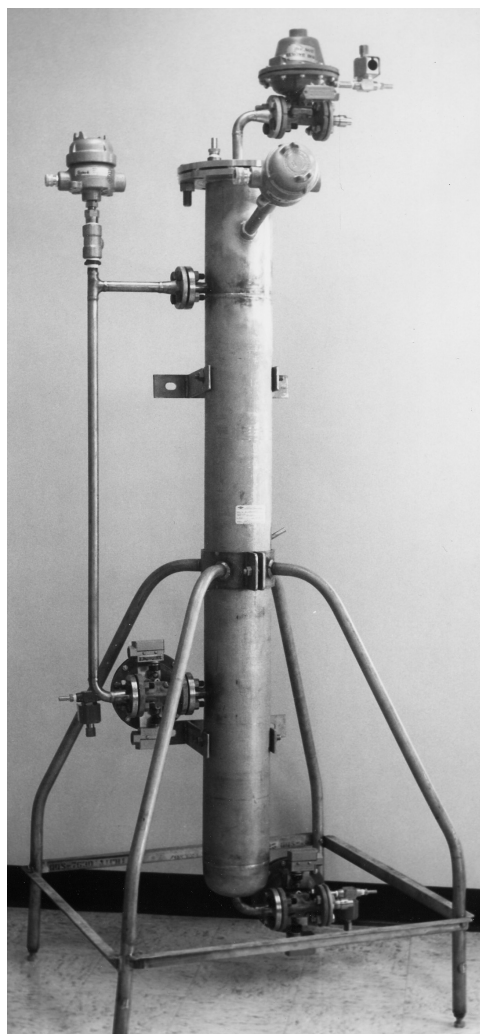
recalled that can be traced back to this procedure. Of course, hand carrying open beakers of uranyl nitrate solution between crowded tanks, up stairs, and past tripping and bumping hazards brought out the greatest attention on the part of the worker—almost always this author.

Government guidelines sensibly required periodic material accountability measurements. These resulted in periodic volume calibrations of the liquid holdings within ring-filled tanks. After all, rings could shift or settle over time rendering an initial calibration useless. Elsewhere on plantsite, tanks were emptied of liquid, calibrated with nitric acid, and that now-contaminated calibration acid treated as liquid waste. It would be processed and the plutonium reclaimed. That procedure would not work at the CML because the building was not connected to the plant's liquid waste processing stream. Everything would have to be done "in house."

This author and the manager of the department in charge of performing tank calibrations plant-wide invented a Tank Calibration Station<sup>44</sup> illustrated in Fig. 55. The vertical pencil tank had an internal sloped plate, a bit below the top, that limited the volume contained to precisely 18.355ℓ. Solution above that amount collected in the vertical leg to the left and above the sloped plate and would become part of the next increment. That precise amount of solution, then, could be delivered to any tank under calibration using the Line Drainage System piping. It was called a "calibration increment."

<sup>44</sup>The wall-mounted Tank Calibration Station was preceded by a floor model version. This was probably invented about 1978 and sat on a portable cradle; but it had to be connected to each tank by temporary lengths of plastic tubing. The later model avoided these contamination risks.

A liquid detection unit ensured that excess solution above the plate was not so large as to compromise the 18.355ℓ calibrated delivery volume. The Station was mounted on the wall and can be seen in a later figure. It tapped into the Line Drainage Header as shown in Fig. 56.



*Fig. 55. The Tank Calibration Station contained precisely 18.355 liters up to a sloped line just at the top horizontal line to the left. After that increment had been delivered, the overflow would become part of the next increment. Electronic liquid detectors ensured the integrity of the increment. The support cradle was not part of the wall mount.*

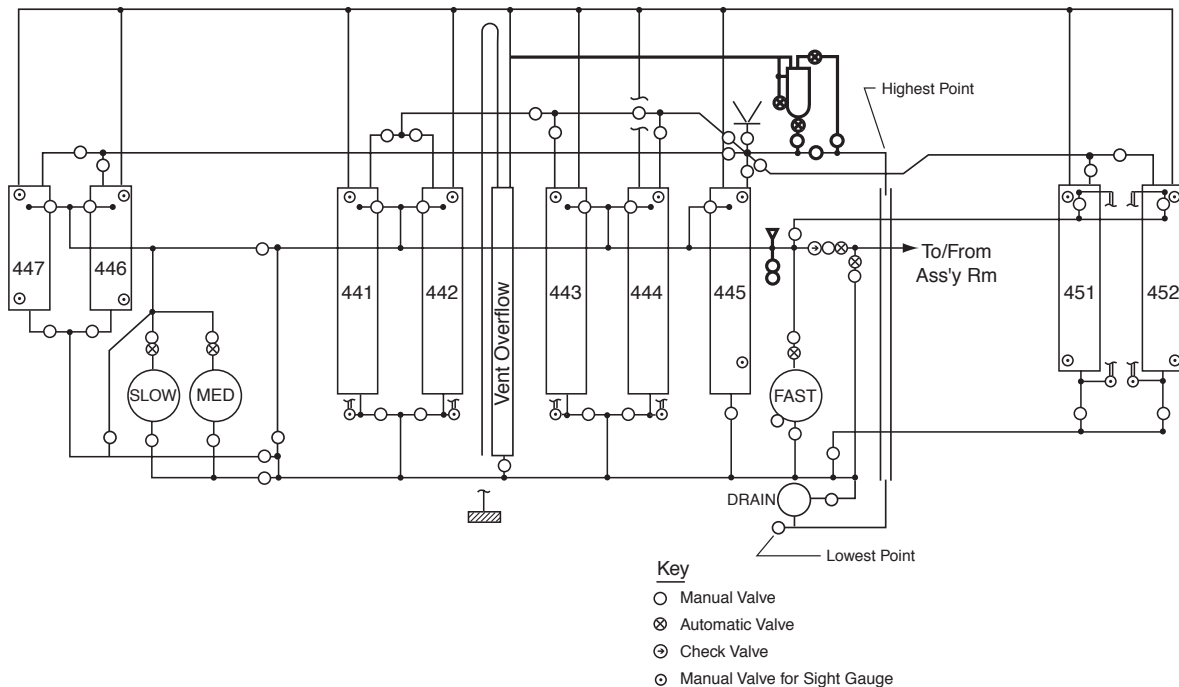


Fig. 56. The Tank Calibration Station tapped into the Line Drainage Header. The U-shaped “prover” contained precisely 18.355 liters of solution which could be used as calibration increments to volume-calibrate a storage tank. Excess solution became part of the next increment. The system vented to the Ventilation Manifold to the left. This figure also shows the Solution Sampling Station represented by two manual valves in series. A pressure indicator gauge (triangle) above the Station help monitor solution flow dynamics. New features are shown bold faced.

The Tank Calibration Station worked very well; and, in fact, produced even more precise calibrations than would be possible using nitric acid as the calibrating medium. Density differentials could not cause a problem because the same solution was used as a medium that had existed in the tank before the calibration. No waste liquids or solids were generated; and no exposure to uranium solution or possible contamination faced workers. Variations on the technique are highly recommended for similar situations elsewhere. Details are published in the literature.<sup>45</sup>

<sup>45</sup>Robert E. Rothe, Louis W. Doher, and A. L. Johnston, “An In-Line Station for Volume Calibration of Raschig-Ring-Filled Storage Tanks for Fissile Solution,” *Nuclear Technology* (28), January 1976.

The figure also includes two Solution Sampling Stations. That is, this fourth figure in the series introduces two new features: the Calibration Station and provisions for obtaining sample vials of solution. These Sample Stations were locations where uranium solution samples were physically removed from the stream of liquid flowing along the Pump Discharge Header. Both Sample Stations consisted of two manual valves in series. The first was a manual on/off valve that could be locked out for security. The second valve was a throttling type valve that could control solution flow to within a fraction of a drop! This last valve led to a pipe plug with a very small diameter (about 1.5 mm) hole in a length of stainless steel tubing forming a “nozzle.” This last valve was so sensitive

that, after closure if a droplet were left hanging from the nozzle, the valve could be “opened” a very small fraction of a turn and this would draw the droplet back into the nozzle. The Sample Port is shown in a later figure illustrating other aspects.

The sampling procedure started with solution flowing at a high rate (about a liter per second) through the upper header. To draw a sample, the first valve was opened after ensuring that the throttling valve was closed. About 100 mL of solution would be passed into a beaker; and this was not used. It might not have been representative of the liquid flowing through the pipe due to residual solution in the two valves. It was collected for eventual return later on. Next, samples of about 125 mL would be collected in small plastic bottles. Samples almost filled the bottle so little room for evaporation remained. Often 16 samples would be selected from each nominal concentration to ensure statistical precision in the eventual analytical results. Between samples, additional unused solution was passed into the beaker. This ensured that successive samples would be independent of one another. When all samples had been drawn, the first manual valve was closed, then the second, and finally a length of stainless steel welding rod was inserted into the nozzle’s snout to keep uranium salt from hardening in the tube. This sampling procedure worked extremely well. Seldom was even one drop of solution spilled although a drip pan was in place for that exception.

One experimental program was conceived about 1980 that would have required very large volumes of *two* concentrations simultaneously existing in closely coupled experimental equipment in Room 101. The existing piping configuration in Room 103 could not accommodate that experiment because lines would be full of

one concentration and not able to handle the second without compromising its concentration. Once the existence of a second line buried in the concrete connecting the Assembly Room to the Mixing Room was recalled, the possibility of performing such a coupled two-solution experiment became a reality. That second line was the one originally intended, in 1964, for plutonium experiments but never used. It coupled the stainless steel enclosure and its associated glovebox in Room 103 with an unused glovebox in Room 101.

The notion was to treat the once-thought-to-be “plutonium solution system” as a *second-concentration* uranium solution system. The tanks and piping in the west half of the storage farm had long ago been converted to a two-tank extension of the seven-tank farm existing about 1970. They were already internally contaminated with uranium solution with all nine tanks considered a single farm. The possibility existed to convert this one farm of nine tanks into two side-by-side uranium solution tank farms consisting of one farm of seven tanks and one farm of two. Those two tanks could be piped to connect to that second line connecting Room 103 to Room 101. All that would be needed was a second set of three pumps to provide the required range of flow rates for a safe experiment. The pumps bought in 1964 for plutonium service would do well here; they were identical to the well-used pumps in the uranium solution system. A second Solution Sampling Station would be needed, too. In summary, then, the full complement of nine tanks could be treated *either* as a single farm of nine tanks *or* two farms of seven and two tanks, respectively. Fig. 57 shows the piping and pumps added to enable this two-concentration capability. It includes a second Sampling Station and an ability to drain the lowest header in the glovebox.

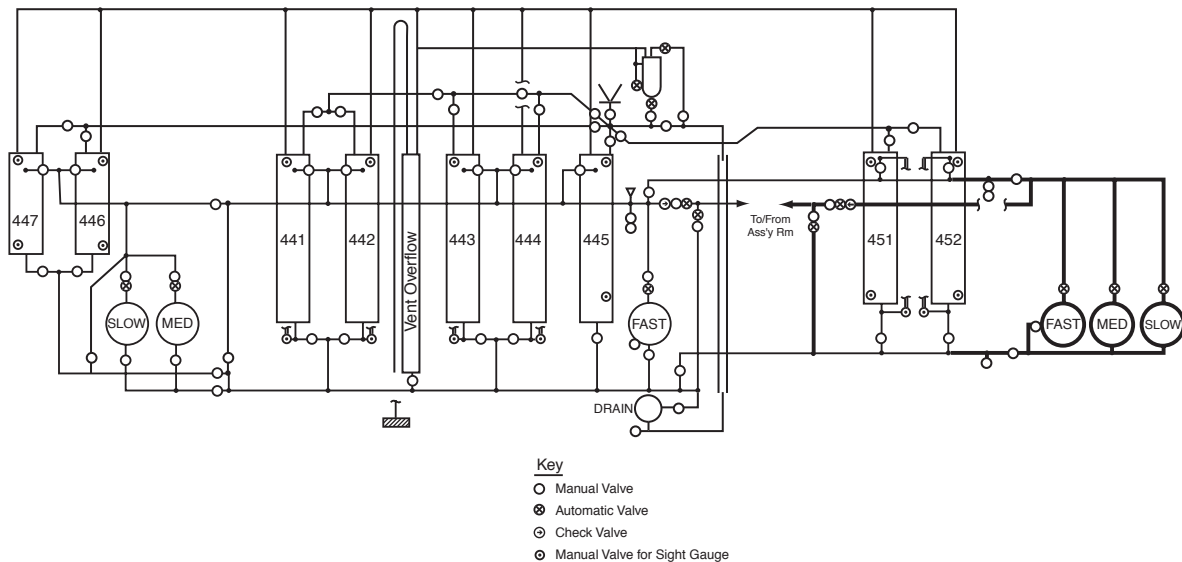


Fig. 57. A second set of three pumps, a second pair of tank fill and drain headers, and a second line out to the Assembly Room were all that was needed to enable experiments using two concentrations of uranium solution simultaneously. Although the capability existed for a number of years, the CML was shut down before an experiment using the capability evolved. New features are shown in bold.

Finally, the ultimate evolution of the Uranium Solution Handling System at the Rocky Flats CML is proudly presented in Fig. 58. The duality of the system is highlighted by the use of another color for one system. The drawing was made in the fall of 1980; so this evolution really only took about 15 years. The system changed very little after that. Only one other improvement was ever made; and that is discussed in detail a bit later. The dual concentration concept was responsible for the attempt to install a third tank inside the stainless steel enclosure (to increase capacity of the second farm); but this tank was only located in place and never actually plumbed into the system. This tank would have been Tank 453. It does not show in any photographs or drawing. The CML fell into disuse before that tank could be fully installed and before the projected experi-

ment to utilize two concentrations in one experiment could come to fruition. This complex of tanks, pumps, valves, and miscellaneous plumbing served a thousand critical experiments over two decades; and a photograph of a good portion of the farm is shown in Fig. 59.

Two original features from 1964 were removed very early in CML history. They may not warrant any discussion at all; but they will be mentioned briefly out of a sense of completeness. Neither appear on any earlier figures. One was a “Distilled Water Tank.” This was a steel container mounted atop the labyrinth wall whose purpose can only be guessed at. Drawings suggest it contained about 750 liters; but this author’s recollection pictures it smaller. Size is not important because the tank was never used. By the fall of 1968, the danger of having a large volume of



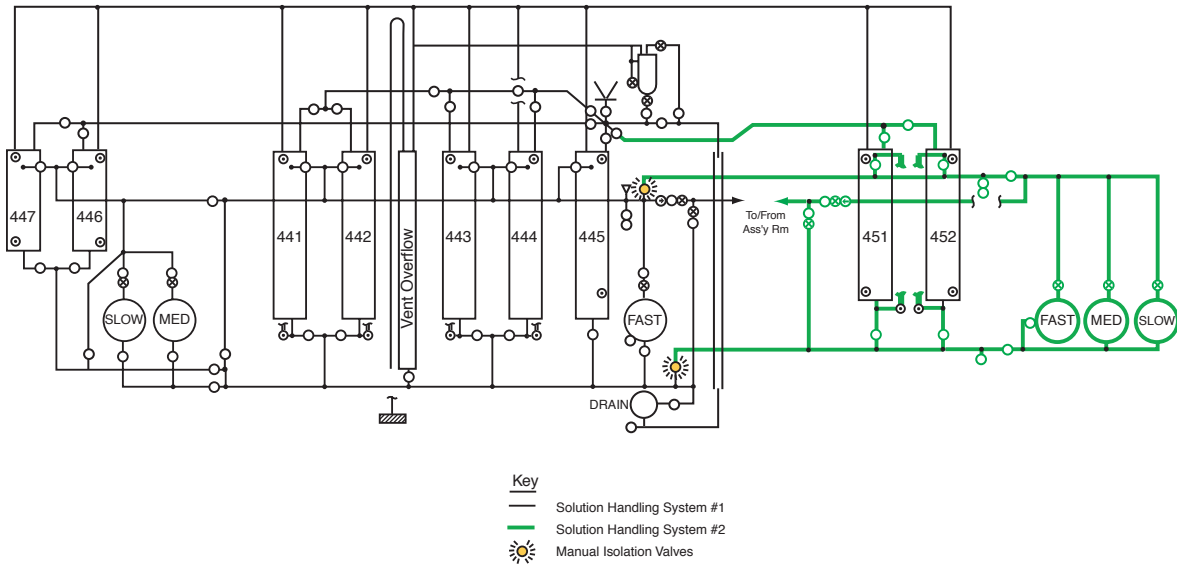


Fig. 58. The completed evolution of the Uranium Solution Handling System in Room 103 fed a thousand critical experiments. The complex plumbing could be treated as a single farm of nine tanks housing never more than three distinct concentrations. In that mode, however, only one concentration at a time could be used. Two manual valves (keyed symbols) could be closed and divide the entire farm into two farms simultaneously handling two distinct concentrations. That portion of the piping which could be isolated into a second concentration or treated as an extension to a nine-tank farm is shown by a special line symbol.

even non-fissile liquid directly coupled to a fissile solution storage system was recognized; so the gravity feed line between this tank and the solution plumbing was separated such that a willful connection would have to be made to connect the two. Even that is irrelevant; the entire tank was discarded in August of 1969 before it was ever used.

The second feature removed early on was called the Loading Station. This was, indeed, the lines through which the several drums of uranyl nitrate solution were first introduced into the CML in the summer of 1965; so they did serve their intended purpose. They were also the same lines, however, that became involved in the first

three spills onto the floor. This happened within the space of about a month that same summer. Perhaps this poor early “track record” prompted the early removal of the Loading Station. It was totally removed in August of 1969. The Loading Station consisted of a couple of meters of piping and two manual valves in the extreme northeast corner of the depressed area containing the four original tanks. The two horizontal headers serving the four tanks were extended into that corner before they rose 0.85 m above the plane of the higher header, made a 90° turn to the north for convenient connection to shipping drums, and were terminated by a manual valve each.

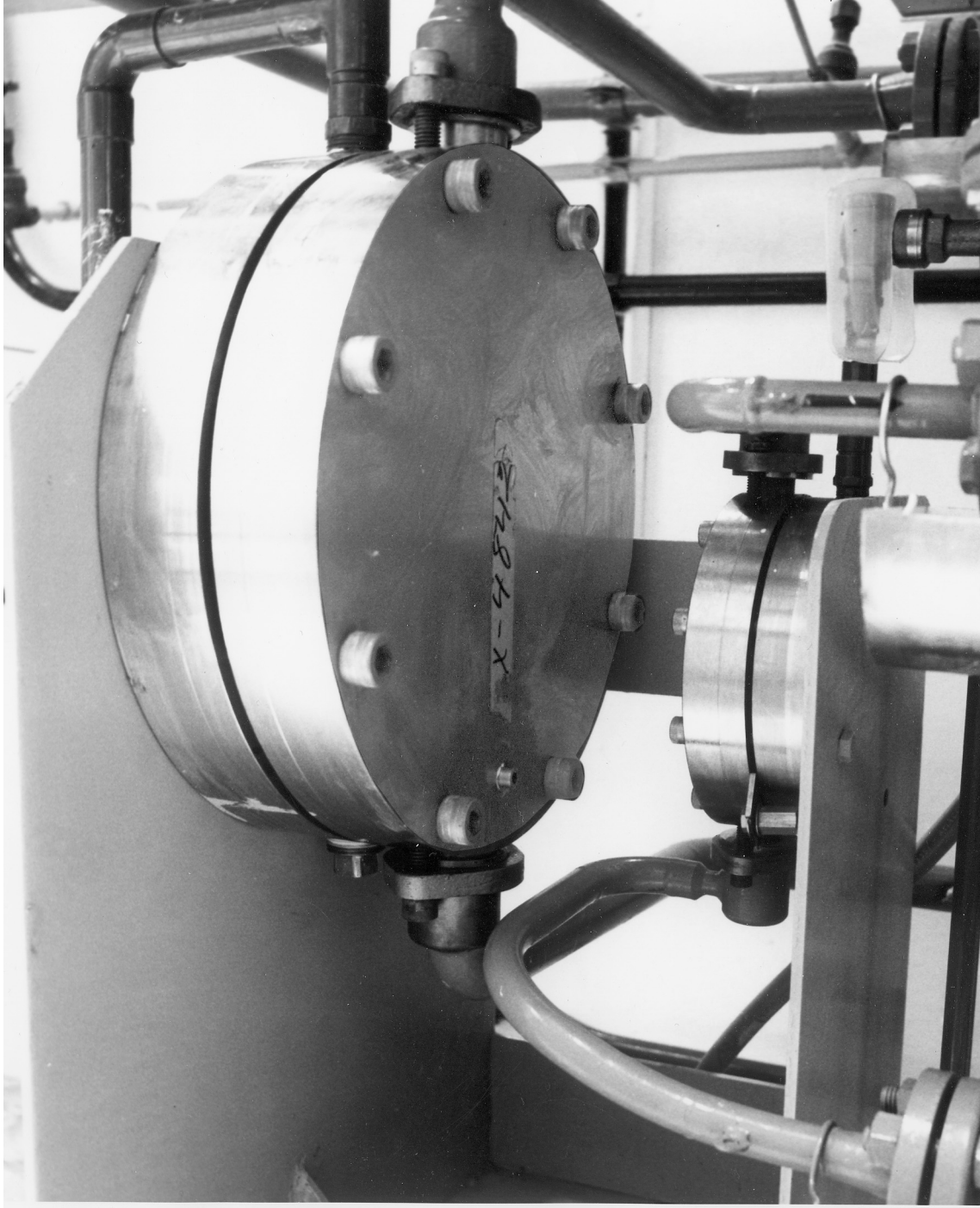


*Fig. 59. No more experiments were ever performed at Rocky Flats after this photograph in July of 1990. Several of the final nine tanks are seen. Sight Gauges, spray rings, inspection ports, Criticality Safety limit holders, a large portion of the Line Drainage System (including the funnel input for small sample returns), the elevated manifold ventilating tanks, and the Tank Calibration Station (white vertical pipe to the left of the clock) are all shown. (July 1990)*

### *Uranium Solution Pumps*

Three different pumps were required to obtain the necessary wide range of uranium solution delivery rates for performing experiments safely. They are shown on the six figures presenting the evolution of the handling system by the words “FAST,” “MED(ium),” and “SLOW.” Actually, a second set of identical pumps (to the far right in the final figure) were installed to serve the proposed two-concentration experiments; but they were never used and require no further discussion. The FAST pump was a 3/4-horsepower cen-

trifugal pump manufactured commercially by a company called ChemPump. A spinning rotor propelled solution up the output line. The FAST pump is shown in Figure 62 illustrating other aspects of the overall system. Both other pumps were manufactured commercially by a company called Lapp. They described their product as “Pulse-a-Feeder Pumps.” Their operation is described below. Both Lapp pumps are shown in Fig. 60. The pumps’ sizes correspond to the medium and slow solution delivery rates, respectively.



*Fig. 60. Uranium solution could also be delivered to experiments at two variable and much slower speeds through two pulsating pumps. The larger (left) was called the MEDIUM speed pump; the smaller (right), SLOW.*

Initially, the Lapp Pumps were mistakenly installed in the Assembly Room closer to the experimental apparatus than the tank farm. This never would have worked because the pumps did not have the ability to suck solution from an air interface. The mechanism required a “flooded suction.” This was achieved by moving the pumps to their permanent location low in the depressed pit housing the tank farm. Gravity would then provide this flooded suction to the pumps from every tank in the system. This move was made sometime before the summer of 1965.

The “FAST” pump, with a maximum delivery rate of a little more than one liter per second, was also located in the depressed pit in Room 103. The pump had a constant rotational speed and, therefore, a constant delivery rate. Slower rates, however, were achievable by requiring the solution pass through a “throttling valve” located in Room 101 near the Solution Base. This valve effectively interposed smaller and smaller orifice diameters as a restriction against that one-liter-per-second flow rate. This pump-and-throttling-valve combination gave good control down to about one-third the maximum. Below that, throttling became a little erratic and less dependable. The fastest speed of the “MED(ium)” pump was preferred at this point. This pump was a “diaphragm pump”; and it, too, was located in the pit in Room 103 directly under the two short tanks to the east of the stairway. A diaphragm pump has two liquid regions separated by a flexible stainless steel diaphragm. One liquid was hydraulic oil; the other, uranium solution. An electric motor pulsed the pressure in the oil. At high pressure, the diaphragm expanded a little reducing the volume available to the uranium solution on the other side. This squirted uranium solution through a check

valve built into the pump toward the experiment. A second check valve, on the input side of the pump, was forced closed. As the hydraulic oil pressure dropped, the diaphragm would flex the opposite way; and this action sucked more solution into the pump through the input check valve while, at the same time, closing the output check valve. The solution delivery rate varied from 4.5 liters per *minute* to a factor of about ten slower. Different rates were accomplished by varying hydraulic oil pressure. When even slower pumping speeds seemed prudent; another, smaller diaphragm pump similar in design to the larger could be used. It yielded a maximum flow rate of about 0.4 liters per minute but showed little change with oil pressure. At its lowest, it still pumped 0.25 liters per minute (4.2 mℓ/sec) into the experiment.

Large slab-like geometries of fissile solution can be extremely sensitive to solution height. In some instances, *unmeasurable* changes in height produced significant changes in the indicated positive reactor period of a slightly supercritical configuration. On these occasions, timed depressions of the spring-loaded switch operating the slowest pump produced an even slower solution delivery rate. That is, a “duty cycle” of ON for two counts and OFF for ten produced a slower solution addition rate by a factor of 5. In summary, solution flow rates were continuously variable from above one liter per second down to one liter per *hour*.

This “duty cycle” technique was used quite effectively on one occasion for an interesting ancillary study on criticality physics. The goal was to measure the possible linearity of neutron reactor periods as closely-related systems ranged from slightly subcritical to slightly supercritical. Here, the reactor period would swing from a few minutes negative to a few minutes

positive having passed through an infinite period (precisely critical). First, a critical slab was established using uranyl nitrate solution in a large, square, slab tank. The solution height read 133.8 mm. A very small amount of this solution was drained back to storage, although the indicated height did not change perceptibly. A few-minute-long negative reactor period resulted. The slow pump then introduced solution back into the subcritical slab using a very long “duty cycle”. The indicated height remained 133.8, but the negative period lengthened to several minutes. Incremental additions were repeated again and a negative period of several hours resulted. Three or four more timed increments, some as small as 5 seconds,<sup>46</sup> led to shorter and shorter positive reactor periods until a period of 3 or 4 minutes was obtained. Throughout all of this, the *indicated* solution height remained fixed at 133.8 mm as observed on the site gauge.

The solution transfer pumps proved to be very dependable throughout the entire life of the CML. The ChemPump required essentially no maintenance. Neither Lapp Pump ever leaked fissile solution; but their hydraulic side did continually leak very small amounts of oil. This had to be cleaned up and reservoirs refilled periodically. One other drawback to the pulse-type pumps involved their check valves. These did not allow the pumps to drain along with the lines. Therefore, the very small volume held up in these pumps would slightly compromise any new concentration. This hold-up may have been about the same magnitude as residual solution clinging to otherwise fully drained lines of the entire

<sup>46</sup>Five seconds from a pump moving one liter per hour added 1.4 ml of solution. This volume added to a 1.5-m square tank added only 0.0006 mm to the solution height! Still, the change in reactor period was significant.

system. Whatever hold-up may have existed in either place, it never caused any problems in establishing and measuring a suitable solution concentration for an experiment.

#### *Other Tank Farm Changes*

Over their lifetime of about 35 years, many changes were made to these tanks and related plumbing other than the ones already discussed. Tanks were painted white for the first time in July of 1965; and this may have been some sort of response to the three spills. Nonetheless, they were repainted a few times thereafter. They were assigned numbers in the 1970s. The original four became #441 through #444. The added three became #445 (the largest) and #446 and #447 (east of the stairwell). The replaced “plutonium tanks” inside the enclosure became #451 and #452. The never-finished third tank there would have been #453. The three tanks in the Assembly Room associated with the Coupled Assembly System were named #540, #541, and #542. The last two were later incorporated into the SCRAM system.

Many years later (probably during the 1980s), the tanks were given the diamond-shaped hazardous materials labels consisting of four smaller diamonds. These are recognized nationally and report the health hazard in the blue left diamond, the fire hazard in the red diamond at the top, and the chemical reactivity hazard in the yellow diamond to the right. All these are expressed on a scale of 0 to 4 with the latter the most hazardous. The bottom diamond of the larger one was reserved for special safety labeling. These labels can be seen on two of the tanks in the July 1990, photograph of an earlier figure. CML tanks earned the ranks 4-0-1 with the bottom diamond sporting a yellow-and-magenta “radioactive” warning.

Piping was also painted according to a standard color code. This was first done in October of 1968. Pipes and valves carrying uranium solution were painted magenta. In truth, several shades of magenta found their way into the tank farm over the decades. Two shades could be seen between Tanks #444 and #445 in the color version of the July 1990, photograph. Plumbing associated with tank ventilation was painted a light grey; and electrical conduit received a dark green coat. A pale green denoted potable water whereas light blue would have been used had any distilled water lines remained. Black denoted waste waters. Rocky Flats employed other colored safety codes, too. Safety equipment such as railings, safety chains, etc. were painted a lively yellow. Yellow and orange were both used as industrial safety warnings.

Floors throughout the Hot Area were painted quite often. The first time was July of 1965. The paint was a viscous epoxy paint that formed a relatively thick layer. These paint jobs included the floor in the Mixing Room, both on the main level and in the tank farm pit. Accumulated layers of paint could have built up, over time, a thickness that might have compromised each tank's volume calibration. That calibration depended on precise measurements made along the Sight Gauge *relative to the floor* using a 2-1/2 meter long Certified Linear Standard.<sup>47</sup> Because of this possible future problem, a "reference pad" was grouted to the floor—precisely leveled while resting on several millimeters of wet grout. These were added in November of

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<sup>47</sup>This was a length of tantalum bar with a T-cross section to which precision, engraved, metal, meter-long scales were screwed end-to-end. The finished Standard was certified by the Rocky Flats Chemistry Standards Laboratory and re-certified periodically. A portion of it can be seen in the figure describing the low-parallax machinist's square.

1969; and tank calibrations were made the same week with and without the pad. This allowed the old calibration data to be adjusted for the new situation. Pads were centered right underneath each tank's Sight Gauge and were made of 152 mm by 305 mm stainless steel plates 12.7 mm thick. Their working surfaces were never painted. Grout continued up the side to reduce the tripping hazard, control contamination underneath, and to protect this calibration surface from being dislodged.

Materials safeguards were enhanced in August of 1968 when most manual valves were physically locked out. This was an effort to make diversion of fissile solution more difficult. Many means of accomplishing this were used because each application seemed to be a little different. Sometimes, stainless steel aircraft cable was looped through the valve's handle and locked with a padlock. Sometimes the padlock simply passed through a hole in the valve's handle. Automatic valves were never locked out except by virtue of the control over keys allowing them to be powered. Truthfully, key control was an inadequate lockout because 110 Volt electric power could be applied to the control solenoids via clip leads and any electrical outlet.

Contamination control was enhanced, probably in the early 1970s, when metal drip pans were installed under every valve and any other point where a leak might occur. These drip pans were stainless steel sheet metal bent, rolled, or otherwise formed to fit each application. They usually hung from piping. After decades of service very few of them revealed any contamination at all.

One other major improvement was installed in the uranium solution handling system in Room 103. This was done in the late 1980s; but, sadly, it never had a chance to demonstrate its true value before the



The installation of this Densitometer required the removal of the manual valve on the output side of the FAST pump. That was not a serious loss because the manual valve immediately in series with it was perfectly sufficient to stop liquid flow. That valve was almost never opened unless the FAST pump was actually operating. The

only exception to that was in the line drainage mode. Many details of the solution plumbing system, at least in the vicinity of the Densitometer, are illustrated in Fig. 62. These include the FAST pump, contamination controls around valves, and the Solution Sampling Station (top of picture).



*Fig. 62. Several aspects of the handling system discussed over several pages are illustrated in this 1996 photograph. The level of Raschig rings on the floor, greater than the single layer that had existed for decades, is that established during worries over seismic stability. Uranium solution was delivered to experiments at a high rate early during experiments and moved among tanks within the Mixing Room via the centrifugal pump just to the right of center (with the numbers '270-09' stenciled on its side). The Solution Sampling Port (top) consisted of two manual valves in series. One (not seen) was a simple on/off valve; and the second could throttle solution as slow as a drop at a time. The tubing nozzle has a "T-shaped" wire inserted up its snout to prevent salt crystals from hardening. A white-faced drip pan with two sides protects the floor from contamination. The Densitometer shows at the right; and the absence of a manual valve at the output of the FAST pump is noted. Labels and cables are associated with decommissioning.*



Both Mass Flow Meters and Densitometers manufactured by this Boulder, Colorado, firm would be highly recommended. Any solution handling system—fissile or not—would benefit greatly from the data delivered.

### ***Changes Other Than Tanks or Plumbing***

#### *Walkway*

The fact that the original four tanks were flat topped ended up serving a useful purpose. These co-planar surfaces made a convenient L-shaped walkway. A sturdy ladder was built to access this surface, a little over a meter above the upper level of the Mixing Room. Workers walked along this path for many reasons such as access to the top Inspection Ports, although the trickiest task was to carry open beakers of uranium solution to pour into the funnel input to the Distribution Header. This path was fraught with tripping hazards: tank-top inspection ports, lifting lugs, and bolt circles which clamped the lid to the tank's top flange. Furthermore, the tank's circular geometry left holes between them through which a foot could easily slip. All these hazards prompted such great care on the part of workers with open containers of hazardous liquid in their hands that no problems ever actually resulted.

Still, a walkway made of embossed boiler plate closed up holes between tanks. This was installed in the summer of 1965 and solved one problem; but tripping hazards remained. That situation lasted five years until a portable L-shaped walkway was installed. This was elevated just enough above tank tops to clear all tripping hazards. It even had raised edges to prevent loose tools from rolling off. The fixture

simply rested on top of the tanks and could be removed easily for access to Inspection Ports. Waist-high posts joined by two levels of safety chain were added in April of 1967; and these minimized the risk of falling off the tanks. The railing and the short stairway are shown in the 1990 photograph of the final version of the solution handling system. By that time, all forms of walkway had been removed (February of 1979), believing the original condition provided the best overall safety.

#### *Rings on the floor*

The major spill of May 1969, that put about 250 liters of uranyl nitrate solution onto the floor of the pit area had many ramifications. One of these was that Management required one layer of borosilicate-glass Raschig rings be laid on the floor in a tidy compact array. This happened in early 1970 and is pictured in Fig. 63. All rings stood vertically and were packed together as closely as possible.

The leak had formed a "lake" that was a few millimeters deep in one area and, yet, left a perimeter of floor actually uncontaminated. This proved that the floor had a slight slope to it such that any large-scale spill would be deeper at one point than an average height. Analysis revealed that a complete release of the entire volume of any *one concentration* (a little more than 1000 liters) would fall far short of a critical height. On the other hand, if the entire 3000 liters comprised of three concentrations could, somehow, possibly leak onto the floor, implausible because experiments were never conducted in such a way that would make this possible, the resultant solution depth would be dangerously close to criticality. Management argued that an earthquake could cause all tanks to rupture and the one layer of rings *might* be necessary to prevent a criticality accident.



*Fig. 63. The pit floor of room 103 was covered with a single layer of Raschig rings for about two decades, although the worth of this action is questioned. Metal boiler plate covered frequent walking areas in this March 1970 photograph.*

Whether or not even this complete spill would lead to such an accident was not at all clear. Calculations showed the presumed model to be extremely reactive but still subcritical. It was a close call either way. Uncertainty, however, existed in the calculation. Was the code sufficiently validated? Did it properly treat the concrete reflection of the floor and the earth beneath it? Was the small reflection from equipment above the spill very significant? What concentration should be assumed? The average concentration (about 200 gU)—all 570 kg and a bit under 3000 liters—would eventually be attained; but what if “pockets” of higher concentration solution

floated about before homogenization could occur?

The argument that an earthquake might result in a complete spill also failed to acknowledge that the same earthquake would probably break water lines. In that scenario, a single layer of rings would be nowhere near sufficient to prevent a criticality if water flowed freely, forming a deep pool of unpoisoned uranyl nitrate solution of some lesser-but-still-very-reactive concentration.

The issue was perplexing. No one could agree on an accident scenario. Predictions from calculational models were not trusted. The dynamics of solution

concentrations during the crisis remained a mystery. The range of proposed solutions to the problem (no rings, one layer, or fill the pit) was argued by many. In the end, Management saw to it that one layer of hand-placed Raschig rings had been placed on the floor in 1970; whether or not this was reasonable remains uncertain to this day. Later records show that the rings and the walkways were completely replaced in the summer of 1979. This was probably due to too much contamination and/or dirt collected; but that is, admittedly, conjecture.

Late in the 1980s, arguments to remove the rings altogether finally prevailed; and the floor, once again, became visible. A few years later, however, and long after the

last experiment had been performed, fears over the seismic stability of the tank farm led to the pit area being filled about half-a-meter(!) deep with Raschig rings. This condition is shown in an earlier figure. The eventual demise of the CML was clear; so implications of a pit full of glass cylinders on operations was nil. About the same time and over the same seismic concerns, the entire nine-tank farm was made seismically stable. Spindly legs, which had served so well for decades, were suddenly not trusted. Wide stainless steel bands were placed around each tank and bolted to the walls as can be seen in the 1996 photograph of Fig. 64.



*Fig. 64. All nine tanks were stabilized against seismic events while they still contained uranium solution but long after the useful life of the solution. Stainless steel “belly bands” were bolted to walls, in this April 1996 photograph.*

In summary, the consequences of an improbable criticality accident scenario was weighed against the greatly increased chances for spills and/or hidden contamination problems. Accident prevention is always important; but so is contamination control. The balance between the two is reflected in vacillations throughout three decades of history: 5 years without rings, almost 2 decades with one layer, more time without rings, followed by the 1990s with the pit almost full.

### *"Plutonium" Glovebox*

The only other significant change in the pit area of the Mixing Room over some three decades involved the glovebox originally installed in the anticipation of handling plutonium solutions. This glovebox and the enclosure behind it would certainly have been necessary had plutonium solution ever been introduced; but since that area had become an extension of the "growing" uranium solution handling system, a glovebox really was not necessary. In fact, the glovebox made valve manipulations more difficult.

This situation was addressed simply by removing the face of the glovebox. This was done in late 1983. The stainless steel floor remained and was painted white to make contamination spots easy to see and clean up. This status is shown in Fig. 65. The (never-used) added Lapp pumps for the second concentration system can be seen at the near end of the one-time glovebox. The FAST pump was situated inside the enclosure.

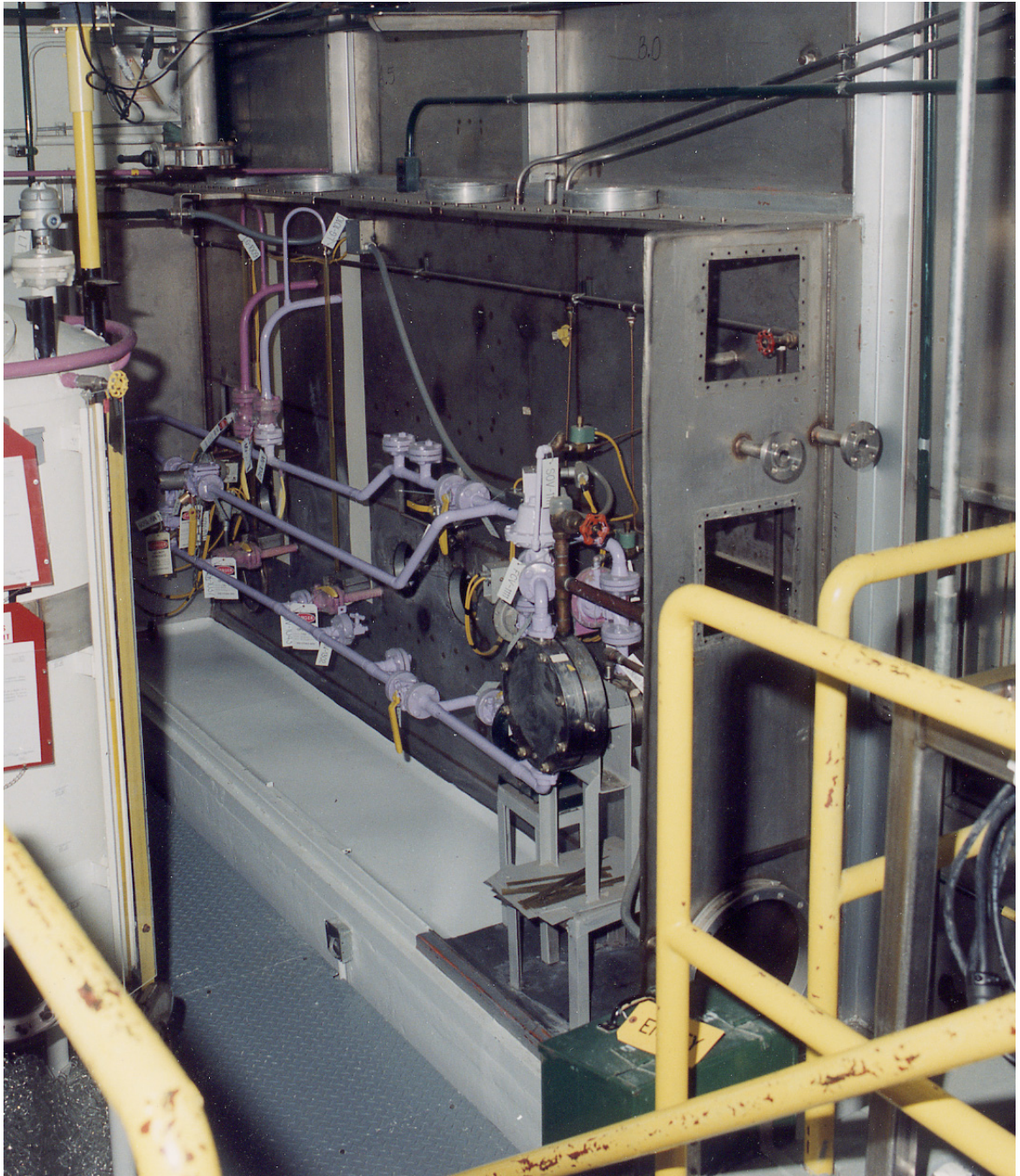
## *The Upper Level*

The upper level of the Mixing Room started life as a fairly open room with lots of unused floor space. Actually, it had the same floor elevation as most of the building; it is only "upper" relative to the depressed pit. The only original equipment consisted of an L-shaped laboratory work bench, an adjacent "fume hood," a safety shower, and the double-door airlock leading to the aborted plutonium solution system. This was spread out over about a 40 m<sup>2</sup> floor area.

### *Initial Construction*

The northwest corner housed the laboratory work bench made of painted sheet metal. A few drawers were topped by a polished metal working surface made of stainless steel. A raised shelf at the back along both walls formed a suitable splash guard. Later, this shelf supported a fairly tall L-shaped set of wooden shelves used for general storage. This work bench was devoted to laboratory analysis, small sample preparation and packaging, and other general laboratory functions. It had a metal sink formed into its surface; and this drained into the Waste Holding tank located in another area. Waste treatment will be discussed later. That route for waste waters was abandoned several years later; and the sink was removed and the hole covered over.

A one-person fume hood stood against the west wall just south of the bench. The well-lighted working surface was a bit less than a square meter; and it was stainless steel for ease of handling acid-based liquids. The front window could be raised and lowered to provide best draft into the exhaust at the rear of the commercial unit.



*Fig. 65. The face of the would-be plutonium solution glovebox was removed in 1983 to make the extension of the uranium solution handling system easier to operate. April 1996.*

The fume hood also had a very small drain that tapped into the sink drain. No known-to-be-contaminated liquids were ever disposed of down either drain; so contamination there would be minimal. This drain was covered over also about the time the drain line from the sink was taken out of service.

Perhaps the most amount of uranium-contaminated material ever handled in the fume hood took place during recovery from the Vent Line Overflow problem in Room 101 reported elsewhere. The filter housing removed from the line joining the SCRAM tank vent to the room's underground Hot Exhaust duct was opened inside the hood. It contained a paper filter saturated with uranyl nitrate solution and crusted with dried salts. The paper had to be cut away in chunks and immersed in dilute nitric acid. The liquid quickly turned yellow and generated a fairly high concentration solution. This liquid was filtered before being returned to the tank farm. The paper clumps were washed a second and third time until little additional uranium would be recovered. During this messy operation, the fume hood probably contained a couple kilograms of dried uranium salts.

The Safety Shower was just inside the double door between the Hallway and the Mixing Room. It was just to the north; and its drain system led to the same contaminated liquid waste handling system (which, again, will be described later). The safety shower head, itself, deluged the user with cold water and would most likely be called into service if a worker received a nitric acid burn. This was possible, of course, and that capability remained always available. The far more likely accident was that a worker would become contaminated needing quick but not immediate exposure to water. To that end, a Decontamination Deluge Shower was installed in the same

area. This shower mixed hot and cold water producing a more comfortable shower. A third item in that Safety Shower area was an eye-wash station. This flushed the eyes in case foreign items found their way into the eyes.

None of the three safety flushes were ever needed in Building 886. All three were tested monthly to assure proper functioning; but they were never needed for an emergency—an enviable record. The infrequent worker who became mildly contaminated—but never to an extent where any of the three safety measures were deemed necessary—was treated in other manners. The most significant use of the Safety Shower was the occasional disposal of a few buckets of mop water down its drain. Less than annually in the 1960s and 1970s, custodial people would be asked to mop the floors to get rid of dust, dirt, dead insects, and other normal accumulations. This was never done as a means of decontaminating a known spill; it was more likely a precursor to a fresh painting of the floors. The water was recognized to be unsuitable for disposal down sanitary drains.

When the building's meager liquid waste handling capability was shut down,<sup>48</sup> the drain in the Safety Shower was back-filled with about a meter of concrete; and this was leveled with the surface of the floor. This left the shower with no drain at all. The very infrequent use of any of the sources of water permitted this situation. Water passed directly to the floor would quickly evaporate; and, if larger amounts might ever be needed, portable vacuum pickups could be brought in.

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<sup>48</sup>This happened about 1980, but this could be wrong by several years.

The danger that water collected on the floor might find its way down into the pit area of the tank farm was a significant concern. An existing (original) 150-mm-high concrete berm between the two areas precluded this everywhere except for the set of stairs leading down into the pit. This route was blocked by grouting a 50-mm-high additional tread to each of the stair's steps. This not only prevented liquids less than that depth from flowing into the pit; but it also tended to equalize stair riser height. Before the added concrete, the last step into the pit was shortened by the layer of Raschig rings and their cover plate. A new berm was also installed under the pair of doors leading into the room. This was a gentle rise and fall (not abrupt) of concrete approximately 50-mm high. The berm was painted yellow to highlight the potential tripping hazard. Both steel doors were shortened to accommodate the change in floor profile.

Whether or not this plan for handling contaminated waste waters was really sufficient was never even tested. Hindsight would suggest that some means of connecting the building to the plant's waste water processing stream would have been wise. Indeed, why it never was so connected will never be known. It appears to be a simple design oversight.

The only other feature of the upper level upon completion of initial construction was the airlock entryway into the stainless steel room designed to house the "plutonium solution" tank farm. This simple stainless steel enclosure was about 1.6 m square. Both doors were hinged at the west and opened north.

### *Other Uses of the "Upper Level"*

This readily-accessible floor area conveniently served a number of other purposes throughout the lifetime of the CML. These are each discussed in detail in later sections but are briefly mentioned here for completeness. The largest of these was the facility installed to handle bare plutonium metal. By the late 1960s, the CML saw itself simply as a facility for performing critical experiments with bare uranium metal, bare plutonium metal, and uranium solutions—the only form eliminated from early thinking was plutonium solutions for reasons discussed elsewhere. This plutonium handling facility is discussed immediately below over the next few pages. A second use of this floor space provided the CML with some means of handling small quantities of water. This included both a source of water for small laboratory purposes as well as a means of disposing of waste waters. Large quantities of water in this room or an unlimited supply as from a pipe under pressure were undesirable because of the potential for water contact with plutonium metal (the metal is incompatible with water) and the possibility for adverse effects on a hypothetical uranium solution leak (unwanted dilution and added volume). Finally, solid waste drums, used to collect possibly contaminated solids, were always stored there as well. All waste handling is described in another section several pages later.

## ***The Plutonium Metal Handling Facility***

Shortly following the commissioning of the CML, C. L. Schuske decided that bare plutonium experiments might enhance greatly the usefulness—as well as the prestige—of the new laboratory. He assigned lead responsibility for this material to Douglas C. Hunt in the same manner as he had previously given that role for uranium metal to Grover Tuck and for uranium solution to this author. Hunt went right to work; and experiments were ready to go by 1967.

Three tasks immediately confronted Hunt. He had to design the plutonium metal components, plan an experimental program for them, and engineer a suitable storage facility. The first was easily done. He decided to imitate Tuck's design of the nesting uranium metal shells as a double set. He even decided to use the same nominal dimensions just in case the two fissile materials might, someday, be combined into a single assembly. The only deviation from Tuck's design was in radial thickness. Plutonium shells would be nominally 1.667 mm thick, half that of the uranium shells. Thus two nested plutonium shells might someday be substituted for a single uranium one. His second task followed Tuck's lead as well. The first few experimental programs would involve plutonium metal immersed in oil. The third task would be significantly more difficult because plutonium metal is known to be much more sensitive to moisture than uranium. The metal would have to be stored in containers with some sort of provision for handling the bare material as it was removed. The room containing this provision was called the Down Draft Room and the surface on which the work was done, the Down Draft Table. Then, the final

assembly of these components into massive spheres and hemispheres would need to be accomplished in an adjoining glovebox. Both would be located on the upper level of the Mixing Room in the large available floor space. This complicated third task, then, is the subject of the next two sections.

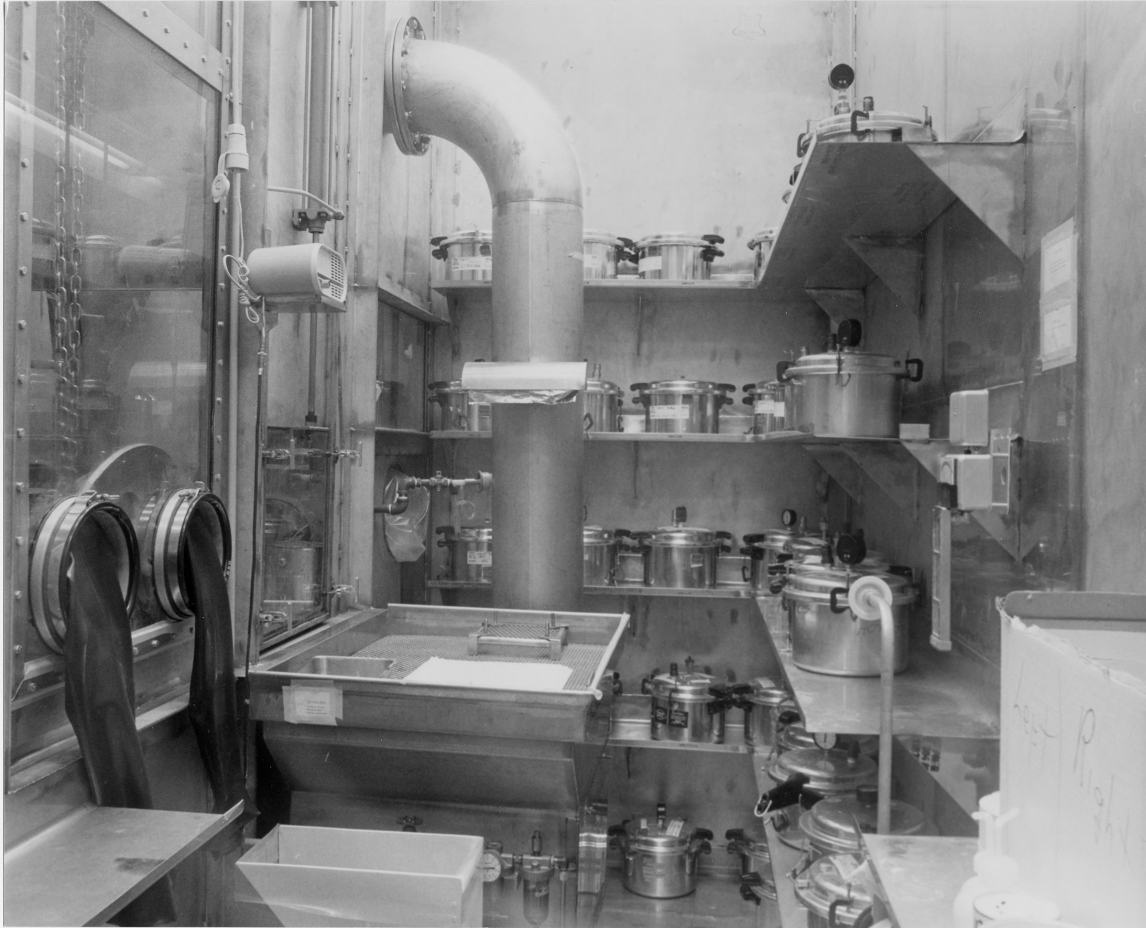
### *Down Draft Room*

This all-stainless steel room was 1.5 m wide by 4.0 m long (north/south) and stood 3.6 m high. Dimensions are not recalled better. The room had few windows and just one door in the south wall. The room sported four levels of L-shaped shelves along the north and east walls; and these held the pressure cookers used to store the metal. Its other principal feature was a Down Draft Table which was immediately adjacent to a guillotine door used to pass bare metal into the adjacent glovebox. All these features will be described in more detail below; but they are all seen in Fig. 66.

Commercial pressure cookers were probably the ten-quart size. Aluminum tops were fit with special features to accommodate their extraordinary contents. Pressure gauges and "quick-connect" nozzles through which a hose, connected to an exhaust system, could bleed off excess pressure. Why the concern over internal pressure is not recalled by this author who admits to inferior knowledge about plutonium chemistry.

The Down Draft Table was about 0.6 m square and stood about 1.2 m above the stainless steel floor. Recessed a bit below the top lip, a heavy wire screen was able to support the weight of a loaded pressure cooker without flexing. The screen can be seen in the figure. The solid square skirting around the table forced air, drawn down through the screen by the building's





*Fig. 66. Bare plutonium metal hemishells were stored in commercial ten-quart pressure cookers, in turn, resting on the floor and shelves inside the Down Draft Room. The Down Draft Table had a wire screen allowing air to sweep contamination into a filter near the bottom of the table. A large-diameter duct exhausted the Down Draft Table to the Hot Exhaust system for the building. A clear plastic guillotine door adjacent to the Table allowed bare metal parts to be passed into an adjoining glovebox. (February 1968)*

exhaust suction, through a wood-framed paper filter. This filtered air was again free of plutonium contamination. Room air drawn toward the screen while the cooker was open confined loose particles of plutonium oxide to the screened surface. A clean sheet of paper, carefully lowered onto the screen, formed a contamination barrier between cooker and screen. This kept the bottom of the storage container uncontaminated at the expense of a disposable piece of paper.

The guillotine door was foot operated. That is, a foot treadle operated a vertical piston shaft which drew the door upward. The door and the piston/shaft can also be seen in the figure; the foot treadle can not. Clamps on the guillotine door (seen in the figure) sealed the door to the wall when not in use.

*(Handling bare plutonium)*

Operating procedures for moving bare plutonium metal back and forth between the glovebox and storage containers are worth describing. Two workers were joined by a Radiation Monitor inside the Down Draft Room. Hunt was always one of the workers; the other was either Tuck or this author. There was not enough room for more than three persons; and, besides, the risk of personnel contamination was well above negligible. All three would be dressed in complete company clothing: white coveralls over white under clothing, steel-toed shoes over company sox, and a white cloth cap to cover the hair. Workers donned two pair of rubber gloves. The inner one was taped to their sleeves; and the outer one was checked often by the Monitor. Even a hint of contamination meant changing the outer pair. Workers were required to wear safety glasses and a half-mask respirator. Use of such minimal respiratory protection seems strange in light of modern respiratory protection requirements; but, at the time, they were considered quite adequate.

One worker carefully laid the paper sheet onto the wire screen. Motions were slow and deliberate so as to avoid stirring up loose contamination. Hands were checked for contamination before moving the chosen pressure cooker off the shelf onto the paper covering. Again, motions were slow. One worker held the body of the container while the other twisted the cover off. This cover was slowly moved back to the shelf, resting upside down on another sheet of paper. The worker closest to the foot treadle reached into the cooker and lifted the bare plutonium metal with his gloved hands. His outer gloves needed no checking; they were known to be contaminated. The shiny silver-colored metal

was intriguing to look at, especially in light of potential hazards.

The four latches were released on the guillotine door and the foot treadle was used to slide it open. Looking inside a plutonium contaminated glovebox without protection from any intervening surface had its own excitement as well. The held plutonium shell was moved into the glovebox, lowered to the floor, and pushed away from the opening. The door was allowed to close and clamped shut by the other worker. Both gloves were changed immediately; and sleeves were checked for contamination because of the possibility they may have contacted the floor of the glovebox. If none was found, the lid would be carefully returned to the cooker and twisted back to “closed”—again, a two-person job. The cooker was checked for contamination before being lifted from the screen. Once lifted, the bottom was similarly checked before returning the now-empty cooker to the storage shelf.

This procedure worked surprisingly well. Few if any surprise contamination spots were ever found. Perhaps the driving motivation for this great care was the dire consequences of sloppy work. Nonetheless, even half mask respiratory protection seemed to be adequate. The Down Draft Table probably accounted for this safe record. A few hours would be spent moving hemishells from or back to storage containers on either end of an experiment. The sight of a dozen or more plutonium metal hemishells—weighing a few kilograms each—strewn about the floor of the glovebox had its own sobering effect on the viewer.

Hunt’s initial design of one aspect of the handling facility was not able to benefit from the decades of experience gleaned by Rocky Flats production workers over the last four decades of the 20<sup>th</sup> century.

Exactly what environment would prove best for storing this material—known to be very reactive with humid air—was, quite honestly, not well known in 1970. Hunt sought advice in his design; but the result proved, in just a few years, to be inadequate.

A huge dehumidifier had been suspended from the ceiling just to the south of the Down Draft Room and above its doorway. This device would replace ordinary air within the room and the adjacent glovebox with very dry air. The design thought was that this very dry air would prevent corrosion. Furthermore, during experiments, the surfaces would be protected by coatings of a petroleum jelly and by the residual oil clinging to the metal after an experiment. All these controls proved insufficient as one pressure cooker was opened following the above procedure only to find a pile of yellow-green powdery compound where a metal shell had been expected. The initial worry was worse than the loss of a nesting hemishell; the chemical compound may not have been fully oxidized. If it were a sub-oxide, the powder might catch on fire to complete the oxidation process. This worrisome problem is discussed further in another chapter.

### *Plutonium Glovebox*

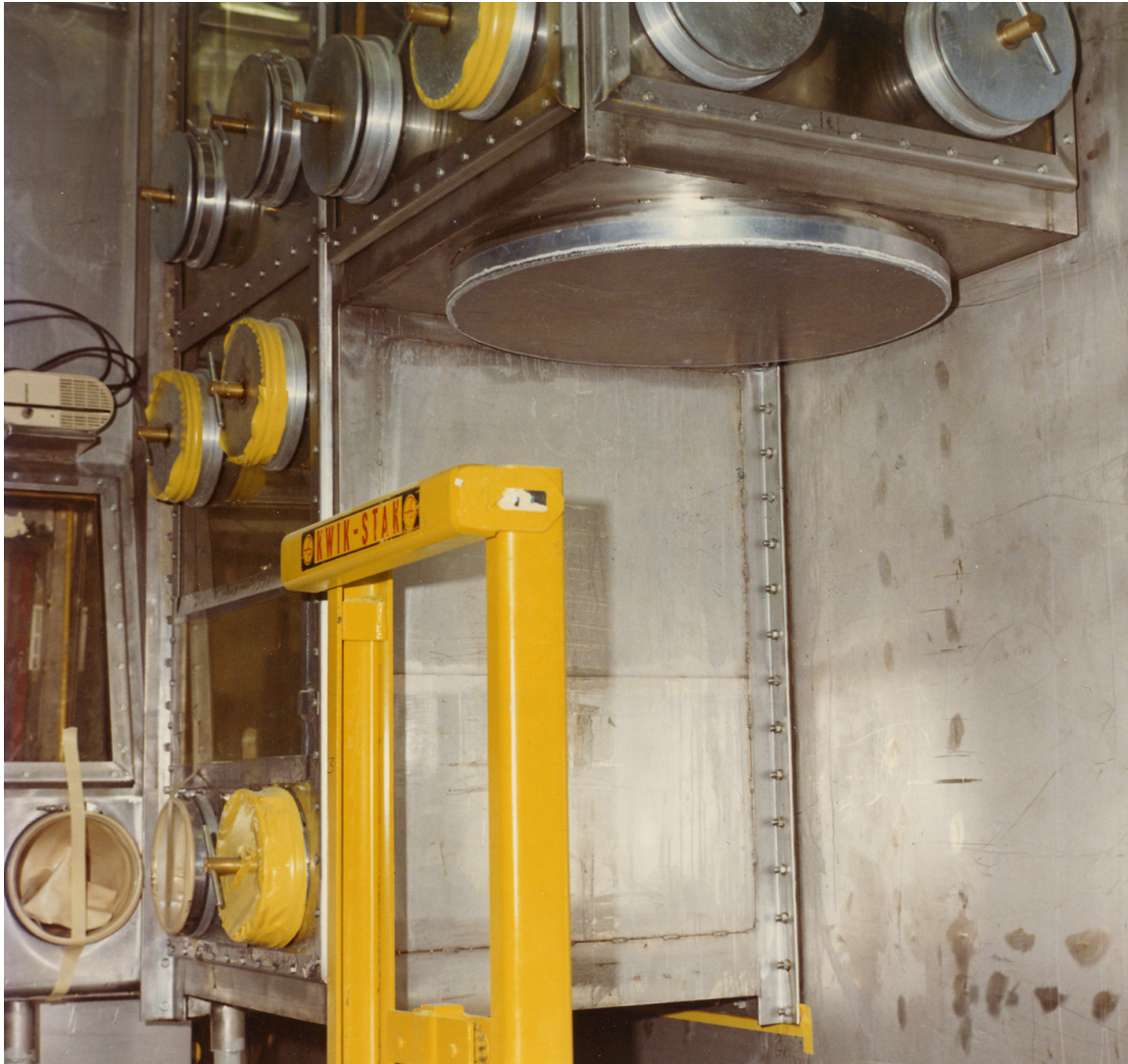
The glovebox adjacent to the Down Draft Room was also made of stainless steel, although it contained a number of windows and rubber gloves. The 2.4-m-tall glovebox was L-shaped and elevated about 0.9 m above the floor.<sup>49</sup> The east/west leg

was 2.0 m long by 0.9 m wide. Windows sloped in a little for worker comfort so the width above the windows was a little narrower than the 0.9 m. The orthogonal leg projected south and measured 1.5 m long by 0.8 m wide by the same height. Figures 67 and 68 show this south leg and a portion of the east/west leg in 1973 and 1997, respectively. The two photographs are 24 years apart!

Windows were 13-mm-thick plastic. The author recalls some discussion about using a glass bearing a small amount of uranium, called “uranium glass” to absorb soft gamma rays from residual older plutonium within the box. This would lessen the radiation hazard to sensitive eyeball tissue. Whether or not sheets of this uranium glass were actually attached over original windows is not recalled these decades later; however, plates of this glass were discovered in that room in 2001. This glass may have been used at one time.

The rubber gloves were a standard product at Rocky Flats. They probably were neoprene rubber, although they, too, may have been impregnated with lead for gamma ray attenuation. Gloves were installed at several heights; the figures show that. Those most used were the lowest level—comfortable when the worker was standing on the floor. Occasionally, higher gloves along the south leg were used to move a plutonium assembly into an experimental tank. Still, most upper gloves were never used. Both figures show a number of glove ports plugged by a standard plant-wide design employed for this purpose. The 1973 photograph shows that a few gloves were left then to clean the inside of the box as well as possible. This still-heavily-contaminated facility (on the inside) remained untouched, unused, and un-maintained for almost three decades!

<sup>49</sup>Some disparity exists here. The tops of the glovebox and the Down Draft Room are recalled to have been about co-planar. If so, the dimensions given here add to only 3.3 m, a little less than the 3.6 m height of the room. This disparity is probably due to measurement uncertainties.

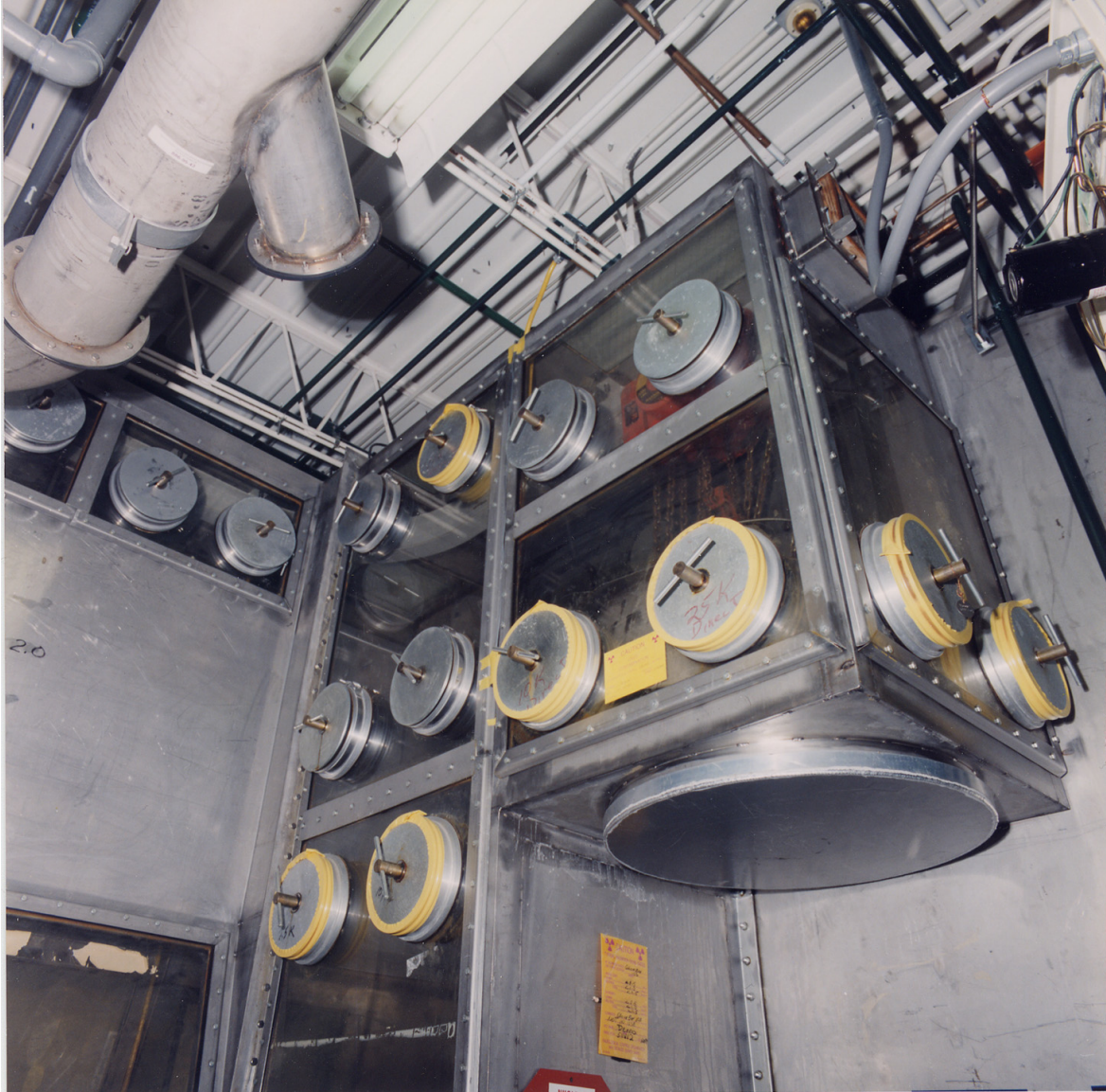


*Fig. 67. Plutonium experiments with bare metal ended when one hemishell decomposed completely within its pressure cooker. By 1973, glove ports were sealed off except for a few needed to wash down the inside. The large-diameter port once used to transfer massive loads of assembled plutonium has been sealed by the aluminum fixture at top center.*

The south leg of the L had part of the glovebox replaced by a large-diameter port, called the “bag-out” port. This shortened glovebox left the southmost wall only 1.4 m high. The almost-meter-diameter circular opening was used to move assembled spheres and hemispheres of bare plutonium metal from the glovebox into an experimental tank. Then, later, after the experiment in the Assembly Room was finished, the tank would be returned to

Room 103 and the metal returned to the glovebox. Both figures show the bag-out port covered by an aluminum plate but no experimental tank. When the box was in active use, that port was covered over with a large plastic “bag” instead of the plate.

Hunt recognized that plutonium hemishells would occasionally need a cleaning. Oil and petroleum jelly would need to be wiped off and some surface oxidation was expected. He installed an



*Fig. 68. Twenty-four years later, the plutonium contaminated glovebox remained essentially unchanged. That this out-of-service facility never caused any contamination incidents over that span and without maintenance is truly amazing. (October 1997)*

ultrasonic cleaner under the east/west length of the glovebox. This cleaner unit contained some kind of hydrocarbon chemical and had a water-coolant jacket. This unit was never used successfully. Instead, the grease and oil were removed by hand with paper wipes and loose oxide was burnished away using an abrasive cloth. Humorously, one could abrade the surface vigorously enough to create small

showers of sparks. These were particles of plutonium sub-oxide torn from the surface only to burn in the air within the glovebox. A tiny corner of the ultrasonic cleaner can be seen at the very lower left in the 1973 photograph. The entire unit was removed during the Christmas shutdown of 1976; and this author was grateful that vacation time did not place him at work during this messy and onerous chore.

A small weighing station had been installed at the west end of the glovebox. Details of this are not recalled clearly; but a liquid seal was used between the box's inside and outside. The balance was outside the glovebox where it could be periodically certified; and the holder for the part being weighed was inside. The commercial balance was on a shelf about a meter above the floor of the glovebox. Perhaps the occasional weighing was associated for the periodic requirement to account for material (plutonium) by weight.

*(Handling Procedures)*

The process of moving anything into or out of the glovebox was called "bagging out" or "bagging in." It is a routine worthy of description and will be illustrated by describing experimental configurations moved between the box and the experimental tank. The plastic "bags" were a very special design—heavy-weight plastic tubes about a meter-and-a-half long and less than a meter in diameter. Each end featured a large-diameter O-ring enclosed and sealed in folded-back plastic. They looked more like a cylindrical sleeve than a bag. Each new "bag-out" began with half of the previous sleeve clinging to a circular lip, part of the bag-out port. The middle of the last sleeve had been twisted tightly, wrapped in vinyl tape, and cut through. More vinyl tape sealed off the edges of this plastic knot. This procedure made the sleeve more resemble a bag. That old bag was carefully worked down the circular lip exposing just enough more of the lip that a new plastic tube could be stretched over the old one and seal against the just-exposed part of the lip. A similar connection was made to the just-returned experimental tank. This process, then, coupled

the glovebox to the experimental tank with the new plastic sleeve. Using the rubber gloves in the glovebox, the old plastic half-sleeve (now, a bag) was pulled into the glovebox; and this was repeated for the half-sleeve of plastic on the experimental tank. Removing both previous plastic obstructions provided clear access between the two and yet within the confines of a fresh plastic sleeve.

Next, the experimental assembly would be hoisted out of the tank back into the glovebox using a chain fall in the south end of the glovebox designed for that duty. Then, the entire experimental tank would be twisted several times to produce that tight knot in the middle of the plastic bag. A special rotatable fixture on the bed of a lifting device (called a "Kwik-Stak" and seen in Figure 67) enabled the twisting of the tank relative to the glovebox. Vinyl tape wrapped tightly formed a log-like knot of twisted plastic that was cut through in the center, checked for contamination, and sealed on both exposed cut ends by more tape.

The bag-out procedure worked quite well in spite of its cumbersome and time-consuming actions. Many such bag-outs were performed; and none ever caused a contamination incident. Again, great care was fostered by understanding the consequences of sloppy work. From time to time, used half-sleeves and other trash had to be removed from the glovebox; and this was accomplished by another "bag-out" into a smaller-diameter but longer sleeve designed just for trash removal. Working with bare plutonium metal generated a lot of contaminated trash.

When the end of experiments with bare plutonium metal became clear, the large-diameter port needed to be sealed by something more permanent than a twisted plastic sleeve. This author designed the

circular aluminum port cover seen in the two figures. Not thinking it would serve over three decades, the cover was designed with a foam rubber liner glued to the aluminum such that four spring-loaded screen door closers, attached to the cover, snapped into place. As the cover was raised against the port's lip, the screen door hardware merely rotated 90 degrees and clamped the cover in place. This extremely simple expedient served its purpose so well that no contamination ever was found in the vicinity of the seal. Considering that the foam rubber surely adopted a "set" and the installation saw many seasonal changes causing thermal expansion and contraction, that record is indeed remarkable. That simple design was installed in May of 1971!

The floor of the glovebox was used to assemble a planar collection of hemispherical shells into a spherical or hemispherical experimental assembly. It was a busy place with sometimes more than a dozen shells strewn about, a can of petroleum jelly, paper wipes, a degreasing liquid, sheets of abrasive cloth, miscellaneous tools, sometimes a considerable collection of trash, and two pair of worker's arms working through rubber gloves. The array of plutonium parts was a sobering sight for three reasons. The potential for a criticality accident with sometimes over twelve kilograms of plutonium laying on the floor of a single small glovebox prompted careful attention to actions. The collection produced a fair amount of soft gamma rays; and this observation lends support to the possible use of an absorptive glass. Finally, the combined neutron flux from all those parts constituted the "base count" for the approach toward criticality. All that was inside the glovebox. Outside, a rack containing electronic instruments associated with that careful approach as parts were

nested were fed by neutron-sensitive radiation detection chambers located under the glovebox; and the Kwik-Stak lifter with the rotatable wheel on its bed all made for a cosy environment.

Criticality safety was ensured during the assembly of the planar array of parts into a single spherical or hemispherical experimental assembly by using the Reciprocal Multiplication technique. This technique was limited to a multiplication of ten. It has been discussed in detail in the open literature and will not be repeated here. All assemblies planned for the program were built within this multiplication limit.

In summary, the plutonium handling facility was both a success and a failure. The principal weakness was in the atmosphere chosen for inside the glovebox and pressure cookers. Subsequent years at Rocky Flats found production facilities replacing air of any kind (dry or not) with an inert gas. Dry nitrogen was commonly used. The choice of dehumidified air instead of an oxygen-free environment almost certainly cut the overall program short by a number of years. The success was that a great many critical experiments were performed with this bare hazardous material with no criticality accident, significant release of contamination, or reportable personnel exposure to either gamma radiation or a neutron flux. The irony is that this handling complex was one of the first things abandoned by the fledgling laboratory; and, yet, the internally contaminated equipment remained in place for over another three decades.

## Waste Handling

Three categories of contaminated waste were routinely generated in the Hot Area. Soft and flexible solid materials included paper wipes, rubber gloves, plastic lab ware, the occasional contaminated company clothing, and other similar items; and this was called “Soft” waste. Glass lab ware, contaminated tools, small bits of metal or glass, paint cans, and other inflexible materials were discarded as “Hard” waste. The third category was comprised of possibly contaminated liquids. These would be liquids such as soaps, oils, cleaning fluids, etc. that had become (or may have been) tainted with fissile material. An important point is that pure uranium solution, regardless of its possibly very low fissile concentration, was almost never disposed of as either liquid waste or absorbed into paper wipes to become “Soft” waste. This author had a mental block against that practice lest the total inventory diminish because of the lazy practice.

Liquid waste handling is covered in this section rather than later when the Waste Holding Tank in an outside Holding Pit is described. That section will describe the physical features of the tank and its piping; but the procedures for disposing of waste liquids are covered here.

The CML used enriched uranium in two physical forms (solution and bare metal) as well as plutonium metal in two physical shapes (bare hemishells and canned metal cylinders), although these two were separated in time. Finally, they also used low-enriched uranium oxide beginning in the 1970s. Waste was generated within each of these material forms; and that waste was kept separate from other forms for material accountability reasons.

The CML had, early on, been assigned the Material Balance Area (MBA) designation of 0385; such that each of four combinations of material and form was granted an individual numeric designation as follows:

Enriched uranium solution	0385-71
Enriched uranium metal	0385-72
Plutonium metal	0385-73
Low-enriched uranium oxide	0385-74

The same number was used for plutonium as bare hemishells and, later, when the 125 canned metal cylinders weighing 3 kg each were introduced to the lab. The logic there was that the former was altogether gone from the facility before the latter arrived. Furthermore, canned units should generate very little waste.

The uranium solution provides one example of how these account number were used. MBA 0385-71 represented that fissile solution. It did so with respect to total inventory, waste drums, shipments of solution samples, etc. At any moment, the accepted physical inventory weight was the last periodic physical inventory measurement adjusted for known or estimated additions and deletions. Thus, if a number of solution samples had been sent from the building to another laboratory for analytical measurements, the determined volume multiplied by the known concentration yielded a measured mass to be subtracted from MBA 0385-71.

At some other time, a “soft” waste drum might be shipped out having collected wastes associated with only that system. These masses were always estimated and seldom exceeded a few grams. At still another time, the analytical laboratory might return excess solution for return to the inventory; and this represented another known addition. These additions and deletions were always so small relative



to the overall holding (about 570 kg) that they had little impact on the running inventory. In truth, the standard deviation of the physical measurement was orders of magnitude larger than most of these minuscule changes. Yet the changes were faithfully recorded.

### *Solid Waste*

Initially, solid waste drums, both “hard” and “soft”, were any, old, used, 55-gallon, open-topped drum. This practice continued through the 1960s. A drum might be delivered for this purpose having contained some possibly hazardous chemical; or it might be pretty badly dented or show considerable signs of rust. The drum would have had to have been in extremely bad physical condition for it to be discarded and not used as a waste drum. The odor emitted from these used drums as they were first opened in preparation for receiving waste was occasionally overpowering. Use of used drums contributed to one of the Plant’s major problems (although not involving the CML) dating back to the 1950s. There, buried drums leaked plutonium contaminated oil into the soil and eventually surfaced. That story exceeds the scope of this book.

The lesson was soon learned that solid waste is an important commodity that needed to be handled properly, stored and transported carefully, and its fissile content needed to be known with some degree of confidence.<sup>50</sup> Beginning in the early 1970s, waste drums had to be brand-new, 55-gallon, white-painted, steel drums with

the identification DOT-17C embossed into their bottom. No rust or dents were allowed; and the closure ring had to be in perfect condition as well. Disgusting odors were a thing of the past.

A “Soft” waste drum was prepared as follows. Two heavy-gauge plastic drum liners were placed inside the drum, one inside the other. Commercial drum liners came from the factory heat-sealed along the bottom forming an open-topped bag. Both liners were lowered into the drum, pressed against the inside, and excess plastic folded over the top and pulled partway down the outside of the drum. This fold protected the top edge of the drum from getting contaminated. The lid of the drum was used as a cover when not actually adding waste.

A “Hard” waste drum began the same as soft except that cardboard liners were added to the drum. This cardboard kept sharp points, broken glass, etc. from puncturing the plastic bags. The cardboard was a bit thicker than 1.5 mm. The bottom of the plastic-bag-lined drum received a circular disk of cardboard that pushed the bags out to the drum’s full diameter. A rectangle of cardboard the height of the tank by a little over its inside circumference was rolled into a cylinder and lowered inside the drum. The natural springiness of the cardboard tended to enlarge the diameter until it pressed the bags against the drum; but the seam was taped to ensure that maximum diameter. Again, the drum’s lid served as a cover between waste collections.

Sometime in the 1980s, the decision to lock out drums between use was made. A simple ring of springy stainless steel could encircle the drum just below its cover and be padlocked shut. Six “fingers” welded to the ring rose above it and folded inward such as to hold the lid closed against the

<sup>50</sup>Toward this end, the plant designed “Drum Counters” which were calibrated to read the contents of uranium or plutonium in a waste drum. While not perfectly precise, they certainly yielded results within, at worst, a factor of two. Usually they were much better.

drum itself much like the spread fingers of a giant hand might do. A key would be required to open the padlock in order to gain access to the drum; and this provided the “lockout” feature.

When either type drum became full, it had to be sealed and prepared for shipment. An operator would gather up the excess ends of the innermost bag, previously pulled down over the outside of the drum, twist it then tape it closed, and tuck the taped end down inside the drum. This procedure would be repeated for the outermost bag; and the combined closures retained any contamination inside two independent layers of plastic bags. Finally, the drum’s lid would be clamped in place using the commercial drum’s bolting ring. Tapping the ring with a hammer while bolting helped secure a few more turns of the closure bolt. Soft waste drums were closed in this manner. Hard waste drums were closed the same except that another cardboard circular disk was added between the plastic bag and the metal cover. After checking the outside for possible contamination and suitably labeling the drum, it was ready to ship out of the CML. Rocky Flats had a plant-wide procedure for handling such drums of waste; and this will not be repeated here.

Waste drum shipments out of the CML were not frequent. The uranium solution account (0385-71) was understandably the greatest generator of waste drums because liquids are harder to control than solids. Still, available records show that in one ten year span (1977 through 1986), 95 drums were removed from the building as Soft or Hard Waste from this account; and these drums contained an estimated 2,931 g of uranium. That is an average of less than 10 drums per year and an average of 30 g per drum. Distributions were not at all uniform with a few drums shipped out containing no uranium and one pair of drums were

believed to contain 324 g. Drum shipments also seemed to increase as the decade continued. The first five years of that example saw 38 drums containing 860 g of uranium leave the facility with the remainder spread over the last five years. Still, only about half a percent of the full holding of uranium was lost to waste in that one ten year interval.

Other accounts generated much less waste although detailed records are not available. Probably not more than one or two drums per year were shipped out of the uranium metal account (0385-72) or the plutonium account (0385-73). The uranium oxide account (0385-74) may have had a few more drums per year but mostly during the decade of the 1970s. A maximum of six drums a year is a guess based on recollection.

This detailed analysis of waste traffic in the solution account is possible because this author retains in his personal files<sup>51</sup> a detailed chronology of every transaction affecting either the uranium inventory weight or the total contained volume of the uranium solution account (0385-71). These 18 pages each contain 27 line-item entries of sometimes day-to-day activity. Shipments of laboratory samples and the return of unneeded excess, waste drums, periodic inventory measurements (both triennial and quarterly “book” values), and a few isolated other transactions are shown. Brand new precise triennial inventory measurements are entered in red ink because they constituted a new “starting point” for all future values of both parameters (total uranium weight and combined volume). DOE had accepted the new measurements as “true” in spite of any discrepancy between it and the previous precise inventory corrected along the way for known or estimated additions or deletions.<sup>52</sup>

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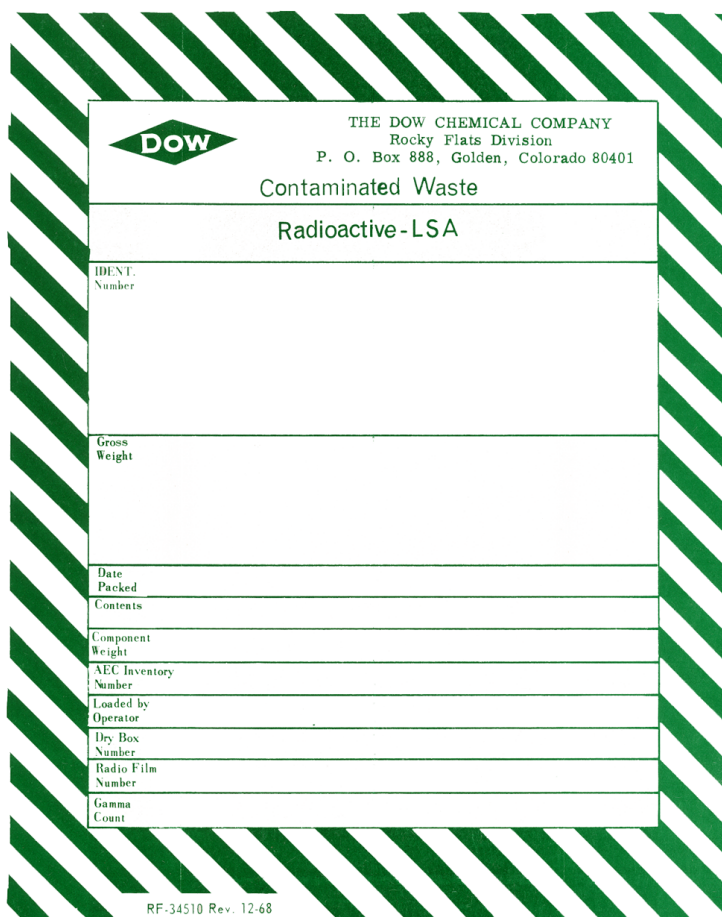
<sup>51</sup>These records will be donated to the LANL Archives upon completion of this book.

Indeed, all four accounts were well managed and documented. Furthermore, considerable effort was made to reduce waste generation altogether.

Drums to be shipped out of the building were checked for external contamination, issued plant-approved Transfer Tags, and held in a controlled access area until authorized handlers of inter-plant shipments of “accountable materials” arrived. CML staff transferred ownership of the drum(s) to these authorized persons by exchanging signatures. Guards at the security post in the perimeter fence surrounding the CML facility were notified that the contents of the drums *might* set off their radiometric scanners—in-  
 installed throughout the plant in the 1980s to preclude unauthorized diversion of fissile material as a Materials Safeguards measure—and the drums were wheeled down the main corridor through the Cold Area of the building. Loaded upon and locked within secure trucks, the waste drum(s) left the facility for further handling.

Probably every drum ever generated in the CML was designated “Low Specific Activity” (LSA) waste. This kind of waste was eventu-

ally shipped to a retrievable waste storage facility in Idaho. These drums carried the LSA label applied to its top lid. An historic version of this label is illustrated in Fig. 69, although later revisions reflected changes in plant ownership and other details.



*Fig. 69. Solid waste drums containing very low levels of fissile material were labeled “Low Specific Activity” (LSA) by drum labels affixed to the drum’s lid. Label style and content varied a little over the years; but this historic 1968 revision still carries the name of the original prime contractor.*

<sup>52</sup>Inventory weights were always recorded to the nearest gram regardless of the size of the overall holding. This is not a very scientific practice; but it did satisfy government requirements. The argument is that the *true* inventory weight can never be measured to better than some sizeable fraction of one percent because of unavoidable uncertainties in measurements. These uncertainties existed in volume determinations, concentration measurements, bias-correction determinations, density measurements, and so forth. An accumulated uncertainty of, say,  $\pm 0.1\%$  would be unbelievably precise. The calculated uncertainty for actual measurements was 5 to 8 times that. Note that 0.5% of the nominal solution holding (560 kg of uranium) would be 2,800 g! Expressing the uranium mass holding to six significant figures was never a statistically sound thing to do.

Sometime in the 1970s, the plant attempted to improve the accuracy of estimates of the fissile content of a drum. After its construction, all drums passed through a “Drum Counter,” located in another building. Its purpose was to measure the very low gram quantity of fissile material contained. The precision of this Drum Counter was argued at between  $\pm 50\%$  and  $\pm 100\%$ . If Drum Counter results differed markedly from initial estimates, adjustments were made to the running inventory; but this seldom happened with respect to CML waste. Any further discussion of CML solid waste or the Drum Counter falls outside the scope of this book.

#### *Liquid Waste*

Initial intentions in the 1960s were that liquid waste generated within the CML would pass to a large tank contained in an underground pit west of the building. The tank and pit will be discussed later, but the handling procedure will be covered here. The contents of this Waste Holding Tank were capable of being pumped into an output line that led to a vertical standpipe rising out of the ground just to the north of the pit. Interestingly, no plan was in place for the further disposition—beyond that standpipe—of this waste when the CML was commissioned in 1965!

Recognizing that deficiency, a 500-gallon horizontal tank was designed which could receive these liquids. The tank sat outdoors on a small concrete pad just north of the Holding Pit and close to the vertical standpipe. A hose could be connected from the standpipe to this Portable Liquid Dumpster. The Dumpster sat empty most of the time. When the Holding tank was close to full (less than 1000 liters), the waste water was pumped into the

Dumpster and transported the same day. The Dumpster had been designed with lifting lugs to match a standard plant waste hauling truck. This truck lifted the entire Dumpster off the ground and hauled it to the plant’s water evaporation pond a considerable distance north of the building. There, the Dumpster was allowed to drain its contents into the pond to experience solar evaporation.

The waste water to be disposed of was homogenized within the Raschig ring filled Holding Tank days before the discard process. It was sampled and shown to contain only milligram quantities of uranium because this water was going to be released to the outside environment. For safety, it had to be very very low in uranium content.

Even though the fissile concentration of the waste liquid was so low as to be obviously not a criticality concern, this Portable Liquid Dumpster was filled with Raschig rings before its first use. This was, perhaps, an unnecessary precaution; but at least a criticality accident could not occur while the Dumpster sat on CML grounds under any conceivable combination of accident conditions.

The years of operation of this system are not recalled. It probably began in the late 1960s or early 1970s at the latest. The last year of this service was probably sometime in the early 1980s. During its 10 to 15 year tenure, the sum of all solutions disposed of in this fashion amounted to not more than three grams of uranium! Shipments of this kind probably happened less often than yearly.

At least three factors influenced the demise of this routine. Most damaging was an electrical short circuit that occurred in the 440 volt lines between the building and the pit. This electrical failure was the direct result of heavy spring rains backing ground

water up into electrical conduits. Water in and near the Holding Pit had been a long-standing problem. In fact, water leaking into the Pit prompted the installation of a stainless steel Pit liner in May of 1966. This liner covered the floor and extended a meter or so up the walls. The combination of ground-water problems and the following growing issues prompted an early abandonment of the underground Pit altogether. Secondly, environmentalists questioned the wisdom of releasing even mildly contaminated liquids to the environment. Evaporation leaves residual sludge and salts; and Rocky Flats is noted for its occasional high winds. They feared the distribution of contamination over the countryside. Finally, others worried about the very slow collection of even low concentrations of fissile material in an uncontrolled liquid environment where precipitation was almost a certainty. Whether anyone seriously considered the possibility of a criticality due to the accumulated uranium and plutonium liquid waste residues from the entire plant is not known.

The demise of the Portable Liquid Dumpster option left the CML with no route for disposal of even small quantities of liquid waste short of hand carrying bottles of the waste to another building. The CML was not connected to the plant's liquid waste processing stream; and it had no provisions of its own. In retrospect, omitting any means of eliminating contaminated waste liquids was a serious oversight in the original construction of 1964.

Perhaps the CML could live with those limitations. Liquid waste generation had been minimized by inventing the Tank Calibration Station (discussed earlier). No process continually generated such liquids; and future activities—experimental or

not—could be designed with minimal liquid waste. The practice of carefully recovering even very low concentrations of solution and returning them to the uranium solution system tended to reduce waste. Finally (and honestly), small amounts of contaminated liquids tainted with foreign substances unwelcome in the pure uranyl nitrate solution could be absorbed in paper toweling and discarded as “solid” waste. Arguments were persuasive to forego any liquid waste avenues from the lab.

Persuasion notwithstanding, a small liquid waste handling scheme was designed and installed in Room 103. Sometime, probably in the early 1980s, a stainless steel, open-top, drum was filled with Raschig rings. A valve welded into the bottom permitted two routes for its contents. The liquid could circulate within itself as a means of homogenization; or it could be pumped into bottles. The top lid of the drum had a rectangular hole cut into it and covered with a coarse-mesh stainless steel screen; and this permitted small quantities to be poured into the drum. This simple, expedient, liquid waste system was located against the north wall of the Mixing Room's upper level. It was just east of the L-shaped laboratory bench and a short distance north of the west glovebox of the Plutonium Handling Facility.

This location would prove convenient for personnel from the Analytical Laboratory in another building (Building 881). The decision had been made some years earlier to avoid shipping uranium solution samples around the plant site by performing the rather straightforward laboratory procedures (Gravimetric Titration and Density Determinations) right on this laboratory bench and its adjacent fume hood. Occasional waste liquids from their occasional work could be discarded in this simple drum. The plan was sound; and the

drum did slowly collect waste waters. Generation was so slow, in fact, that the actual act of emptying the drum can not even be recalled. The system sat idle most of the time collecting more dirt and grime in its wire mesh screen than anything else.

Technicians from the Analytical Laboratory were accommodated a bit more involving this drum as well. They required very small quantities of ordinary tap water for their analytical procedures. This need was supported by mounting a small plastic water container a couple meters above the drum with a plastic line and a plastic valve allowing one to obtain small amounts of water. The overhead container was limited in volume and not connected to any automatic filling system; so it was never a steady source of water into the Mixing Room under any accident conditions (e.g. earthquake).

The entire system was used only marginally and probably could have not been built with no serious consequences. It never was a problem. It was just not that necessary.

## Hallway

The hallway in the Hot Area was given a room number (Room 108) probably for administrative reasons and for maintenance purposes. The area connected the Cold Area of the building through the Airlock to doorways to the three rooms in the Radiation Control Area. Room 103, the Mixing Room, lay to the west, Room 102, the Vault Room stretched to the east, and the Assembly room, Room 101, lay at the end of the Z-shaped Labyrinth to the south. The later expansion of Room 102 added a small alcove outside the room of about 1 by 2 m.

Hallway dimensions are hard to specify accurately; but the following was scaled from original drawings. The long portion

of the Hallway, excluding the Labyrinth, was about 2.5 m wide and a bit less than 6 m long. The floor was at the level of the Cold Area and a suspended ceiling of Celotex panels rose almost 3 m overhead. Sometime in the 1980s the Celotex ceiling was removed altogether.

The Labyrinth was 1.07 m wide along all three legs. North and south legs of the “Z” were equal in length to the thickness of the north wall of the Assembly Room (1.52 m); and the east/west run of the “Z” was about 3.3 m in length. The floor continued at the same level as the Hallway and the roof on the Labyrinth was 2.13 m high. These constraints in length, width, and height and the squared corners of the Z shape limited the equipment which could be brought into Room 101 from the north. Oversized items had to come in through the south door complex discussed earlier.

A light-weight steel door blocked the junction between the main length of Hallway and its Labyrinth extension. This door was kept locked to prohibit persons from entering the Labyrinth during experiments. This would have been rare in any case because access to the entire Hot Area was controlled at these times. Still, certain experimental operations sometimes called for people to access the Mixing Room during portions of the experiment. The door kept people from being exposed to radiation should a criticality accident happen just as a worker was in the Hot Area during an experiment. This door was also used as a material’s safeguards measure on those occasions where circumstances called for solid fissile material to remain in Room 101 overnight and unattended. For that reason, coupled with the enhanced security measures of the early 1980s, this door was hardened by having a additional covering of 9.5-mm-thick armor plate welded to it. Of course, the door’s

hinges had to be strengthened as well because of the weight of this extra steel.

The Hallway provided access to the other rooms, of course; but it also was a congregating place for workers awaiting their turn to exit the Hot Area at the end of a day's work. A sheet metal monitoring station for incidental monitoring for possible contamination on hands and feet (called a "Combo") was conveniently situated in the Hallway near the Airlock. One of the building's Criticality Alarm detectors was mounted high on the east wall close to the entrance to Room 102. In later years, two more detectors were added side-by-side. Occasionally, white waste drums were held in this hallway awaiting shipment out of the facility. This service was not practiced heavily because too many drums would clutter the area.

## **Airlock**

The Airlock was another very small floor area ascribed the honor of being called a room. It was Room 104. Albeit small, the room contained three doors. It served as the transition between the Cold Area and the Hot Area. The cramped space became an increasing problem as increased functions were called upon to be performed there. Initially, space was marginally sufficient. Only two barrels, a metal cabinet housing popular brands of half-mask respirators, and another "Combo" (a personnel surface contamination detection instrument) occupied what little space existed. People trafficked between the two portions on the building maneuvering around these fixtures.

That surface contamination instrument, the "Combo," was an electronic box fitted with radiation detectors. It measured less than a meter square and stood a little more than a meter high. Its sloped top was

designed for routine checking hands and feet for possible contamination picked up within the Hot Area. The sloped surface was fitted with an alpha-sensitive probe. Hands—both front and back—could be drawn slowly across the surface in search of contamination. The probe had a meter-long cord that permitted it to scan clothing, face, arms, and other body parts. Readout for this instrument was a simple electronic meter. Visual indication was accompanied by an audible "click" whose repetition rate was proportional to contamination found. A toggle switch transferred the instrument's attention to a foot probe. This was another, but larger, alpha-sensitive probe closer to the floor. A small slope made it comfortable to rest the foot lightly upon. This device was easy to use and policy required its use upon each exit from the Hot Area. Few people, if any, bypassed that simple safety expedient.

The "Combo" was colloquially called a "Tin Monitor." This term reflected the fact that the instrument performed much the same function as the human Radiation Monitor. Indeed, that was true and begs the question as to why it was there. The Airlock was a very important point to ensure radioactive contamination never left the Hot Area. Human Radiation Monitors provided that confidence as described later; so why was the electronic box there? The answer is that the task of preventing the spread of contamination was so important that multiple levels of checking was not at all unwarranted.

The two 55-gallon drums in the Airlock were associated with shoe covers, colloquially called "booties". One, painted light green, contained freshly laundered booties; and the other, painted yellow, housed used shoe covers until they could be laundered. The colors were chosen to convey common safety conditions: green for "go" or "ok";

and yellow for “caution.” Both drums were lined with plastic drum liners identical to those used in the preparation of LSA waste drums.

The respirator cabinet was a standard, metal, office cabinet painted white. It was fitted with compartments that housed a number of the more common styles of half-mask respirators. Lower shelves housed a few full-face respirators for more-contamination-prone activities. Plant policy on this changed over the years. Half-masks were acceptable for most kinds of work through the mid- to late-1980s. After that, just about every task required a full-face respirator. This author is not competent to judge the wisdom of either new or old practice. This cabinet had a small bin riveted to its side for the storage of plastic safety glasses. These were considered “visitor’s glasses” since wearing safety glasses were required in the Hot Area. Routine workers had their own personal safety glasses.

Clearly, these safety items left the few square meters of floor space with little room for personnel. Later, however, the Airlock became even more crowded as enhanced security measures imposed more upon the meager space.

The Airlock contained three doors. One was the door between the Hot Area and the Cold Area. It was 1.07 m wide by 2.13 m high. That door had a window in the top half. The original purpose of the window was to permit quick observation on conditions within the hallway—a safety measure. Later materials safeguards concerns dictated that this view be obscured off hours. The worry was that nefarious intruders ought not have the benefit of knowing what might be inside the Hallway. Still, CML staff argued hard for the safety aspect of being able to see inside the Hot Area during experiments. This impasse was solved by installing a moveable shield to

be in place off hours and lowered when necessary. The shield was inside the Hot Area and not accessible to intruders.

The second door was the same size and almost in line with the first. It was on the north side of the Airlock and led directly to the Main Hallway in the Cold Area of the building. This door was seldom used because one of the bootie drums sat in front of it. It was opened occasionally to pass larger items through the Airlock into the Hot Area. One example of this would be the welding machine used by Maintenance Craftsmen. Most personnel access passed through the third door enroute from the Hot Area directly to the room just outside the Men’s Change Room. Typically, workers leaving the Hot Area proceeded directly to the Men’s Room to change clothes and often shower; so the flow seemed natural. This measured only 0.91 m wide but was also 2.13 m high. All three doors had windows in the top half.

Another safeguards enhancement using up precious space in the Airlock was a heavy, metal-lattice, door superimposed in front of the existing locked door between the Airlock and the Hot Area. This heavily barred door was colloquially called the “gorilla cage.” It was installed late in the working history of the CML. It was locked in such a way that second locks protected first locks as a means of ensuring the “two-man rule.” This complicated locking procedure has been discussed elsewhere and will not be detailed further except to note that by 1990 more than half a dozen padlocks and combination locks were needed to pass through this one door! The door was alarmed to the plant’s security offices; and coded words, changed monthly, had to be given over the telephone immediately prior to access. In addition, a team of armed guards accompanied each opening of this door. Often, a



dozen people, two with machine guns, and half an hour's time were required to gain access into the Hot Area in the 1990s. Ironically, this single door was seldom even locked in the 1960s; and access was extremely simple.

Both doors into the Hot Area closed just above a small berm separating the Airlock from the Hallway. The Cold Area was protected against fire by a sprinkler system; and this berm was designed to prevent sprinkler water from flowing into the Hot Area. This water might have become contaminated and caused contamination to leak into unwanted areas. The berm was very similar to the one installed at the entrance to Room 103; and both were installed at the same time (some time in the 1980s).

Later-day plant safety measures called for the notion of a "Step-Off Pad" everywhere on plantsite where Hot Areas transitioned to Cold Areas. This, too, has been discussed elsewhere. Plant policy mandated certain conditions and personnel comfort measures (such as chairs to sit on); and these requirements could never be met in the small space of the CML Airlock. This unavoidable disparity with company policy was never pushed to resolution because the existing Airlock seemed to serve its intended purpose quite well; and the number of people passing through each day was much smaller than in larger buildings.

### **Cold Area – Initial Construction**

The Cold Area, perhaps obviously, was the antithesis of the Hot Area. The colorful term described the routine "living area" of the whole facility that was expected *not* to contain any fissile material contamination. Therefore, a Cold Area would not require protective clothing or other special

measures to safeguard personnel against either radiation or contamination. The Cold Area occupied more than half the building's floor area and was contiguous to the Hot Area to the south. Portions of the Cold Area supported functions related to the experimental program while the remainder might be described as the Office Area and the Office-Support Area.

### *Related to CML Experiments*

The most-important room for operations related to critical experiments was, without doubt, the Control Room (Room 112). Most of 1700 critical and critical approach experiments were controlled from the control Console, the central feature of this room. These few-hour-long occupancies brought combinations of fissile and other materials, located in another room, into geometries which were always extremely close to a prompt criticality accident. The pride that distinguishes any first-rate Critical Mass Laboratory derives from the physical barriers which protect experiments from ever bridging that sometimes very small gap.

An important room to experimental preparations was the Machine Shop and Electronics Room (Room 114). Its importance lay in activities performed well in advance of an actual experiment. The room had a small office (Room 105) contiguous to it. Initially planned for storage (and so identified on construction prints), the room doubled as an office for W. R. Sheets, although he and D. E. Payne could more often be found busy at one of the benches in the room.

Construction prints label Room 117 the "Count Room." This betrays the intention of using foil activation methods in critical experiments. As stated many times elsewhere, this never came to pass;

and the room was never needed for that purpose. Humorously, a thick 50-mm-wide copper bus bar had been installed along three sides of the room to serve as an electrical ground for the delicate electronic equipment thought to occupy the room some day. This may be the only office on plant site with a well-grounded bus bar running around its perimeter. Priorities shifted in the 1980s; and Rooms 105 and 117 were combined into a computer room.

Many other rooms also supported laboratory operations in one sense or another. For example, CML personnel occupied offices and the Mechanical Room maintained proper air flow through the Hot Area. These support functions are discussed in the description of the Office Area.

## Control Room

One of the most important areas in the Cold Area was the Control Room (Room 112). Nearly square, it measured 6.7 m east/west by 7.7 m. Walls to the south and west were 0.4 m thick concrete to provide added radiation shielding to workers. The east wall was back-filled cinder block typical of most of the building with a layer of insulation on the interior making it 0.25 m thick. The north wall between it and Room 114 was ordinary cinder block (0.20 m thick) and had no insulation on either side. The roof was the same tar-and-gravel-covered deck pan characteristic of the Office Area.

The Control Room had two entrances. One (0.8 m wide by 2.1 m) opened onto the Main Hallway central through the building. The other had a pair of doors leading directly to the outside. The pair measured 1.5 m wide by 2.1 m high. These outside doors served three purposes. Large items needed for apparatus construction could be

delivered through this opening. Actually, that purpose was never implemented because no paved roadway led to the door. Secondly, the route was considered an excellent safety egress route in the event of an unplanned nuclear excursion because it avoided any radiation streaming down the Main Hallway. This function was also never used because no accidents ever happened, although it was occasionally called into play during evacuation exercises when weather was pleasant. The final purpose served comfort; sometimes the door was propped open to provide fresh air during Colorado's beautiful spring and fall days.

Personnel access into the room was administratively restricted during experiments. This was a safety measure. Scientists conducting critical experiments need to be fully attentive during the crucial moments spent in the vicinity of criticality. Interruptions for any purpose were unwarranted because they could distract attention at a dangerous point. The minimum occupancy for this room (during experiments) was two certified Experimenters. Furthermore, during any reactivity additions, one of these had to be a Senior Experimenter (Tuck, Hunt, or Rothe). A third and, occasionally, fourth experimenter could be present in the room as well but only under certain conditions. Uninvolved visitors were occasionally allowed to witness a critical experiment; but they, too, were subject to limitations. They had to sit on the other side of a large office-sized table and refrain from unnecessary conversation. Questions could be written down and later verbalized. Noteworthy visitors included a television news reporter whose filmed story appeared on the ten-o'clock news, DOE visitors to the plantsite, top plant Management, and the occasional political figure. Some visitors performed audits of

experimental operations to ensure proper conduct of operations. In summary, the demeanor in the Control Room during experiments was professional and serious without appearing worrisome.

The Control Room became this author's office sometime after the last experiment was performed in the late 1980s; and he remained there several years—even past his official retirement from the company.<sup>53</sup> His office in this room at that time made sense in that he was the sole survivor of experimental operations. He could oversee the now-dormant equipment and provide input on its disposition.

Certainly, the most impressive feature of the Control Room was the Control Console. It also contained ancillary equipment behind the console and along the east wall. These will be discussed, in turn, next.

### *Control Console*

The major expanse of scientific equipment used to conduct critical experiments is displayed in Fig. 70. The distribution of apparatus varied little from this January 1969, photograph throughout more than three decades of productive use. Improved electronics instruments replaced older models. Color television sets replaced older black-and-white models in a few cases for better visual acuity. New inventions and novel commercial items filled in blank panel covers. Nonetheless, the overall functioning of the Control Console remained essentially unchanged from the first experiment until years after the final one.

The initial (1964) Control Console installation consisted of only six vertical “chassis racks”—not the ten shown in the photograph. Chassis racks are tall vertical columns the width of one electronic panel and separated by narrow, light-grey, bars. Four of these stood in a line across the back just behind the desk-like shelf in the foreground. Two more chassis racks stood at 45 angles to the first four at either end. Finally, but still in the 1960s, two additional pair of chassis racks completed the U-shaped Control Console seen in the photograph (at the extreme left and right sides)

Several categories of panels and instruments existed. Overall key lock control was one. Several panels pertained to the control of reactivity additions and the physical measurement of that parameter. Many panels recorded radiation levels in the vicinity of the experiment as part of the reciprocal multiplication technique. These included both digital and analog devices. A number of television monitors viewed the experiment from various angles; and an audio control allowed experimenters to listen to the characteristic sounds of an experiment. One panel was used to control neutron source movements. Finally, spare and unused components were stored out of reach yet readily available. Each component will be described in following subsections. All these will refer to the photograph of the Control Console; and that fact will be understood without repetition.

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<sup>53</sup>In retrospect, a retiree remaining in his old office might seem unusual. Unhappily, he was relocated twice to other locations on plantsite during his last years.



*Fig. 70. The Control Console was situated in the south half of Room 112. Almost all critical and critical approach experiments were controlled from this location. The few exceptions were configurations assembled by hand using the in situ technique. This January 1969 photograph shows the console after the addition of two pair of chassis racks on either side of the original six racks.*



*The four individual panels just above the horizontal writing surface controlled “Reactivity Addition Devices.” These and several other functions are described in considerable detail in the text.*

– Safety Control –

The most important feature of the entire Control Console was certainly a single panel featuring a number of key lock controls over various electrical functions. This panel, labeled “Safety Control,” can be seen in the rack below the clock. It is the second panel above the horizontal writing surface. Close examination shows six silver-colored key locks. Without prescribed keys, the entire ten columns of electrical equipment was totally disabled. These keys were stored in a locked repository and signed out daily to Experimenters requiring them. At least two keys were needed for every experiment. The first merely provided electrical power to the second; and that is the lock at the top center of the panel. The second key provided electrical power to only one of the four recognized Reactivity Addition Devices. These are the four key locks toward the left and right sides of the panel. With only one of these four second-level keys signed out at a time, simultaneous functioning of, for example, the Uranium Solution System and the Horizontal Split Table would not be possible. This was a safety measure to ensure that two different experimental programs would never be run at the same time. Safety consideration had never been given to the possible neutronic coupling between reactivity additions from *two simultaneous programs*. This kind of administrative error was highly unlikely in such a small group; but the consequences of a mistake could have been severe.

The sixth key, near the bottom center of the panel, was an “interlock override” key. This key allowed certain safety interlock functions to be overridden during Pre-Run Check operations. This key was not used once the experiment had actually begun. The importance of never bypassing safety

interlocks during an experiment was emphasized by administratively requiring that this key be returned to the repository before reactivity could be added.

This fundamental panel also contained the manual SCRAM button. This was the safety shutdown control that could be functioned at any time by any person if they had any concern that any aspect of the experiment was not fully under control. The button was bright red but appears dark just to the left of center near the top. Many electrical and mechanical aspects of the experiment could also initiate a SCRAM; but this single button would perform that function if any system failed. Frequently, this button was used to expedite the end of an experiment instead of going to the trouble of reversing reactivity flow (open the Split Table, drain fissile solution, etc.). By the 1970s, when DOE Orders pertaining to reactor control had been refined to include reporting requirements, any automatic activation of the SCRAM would have to be reportable as an “occurrence”; but intentional activations would still not be reported.

– Reactivity Addition Device Control –

Four individual electronic control panels were associated with the Reactivity Addition Devices mysteriously called “reactors” by DOE. Three of the four are seen just above the horizontal writing surface stretching across the four chassis racks at the back of the “U”. The one to the left (behind the microphone) controlled the Uranium Solution System. The panel to its right (below the clock) belonged to the Horizontal Split Table. Next in line, a (lighter grey faced) panel pertained to the Liquid Reflector/Moderator Apparatus. The fourth panel in the line, near the right end of the horizontal surface, was built for the

Plutonium Solution System. This was never used as explained many times before and, so, was not one of the four operational “reactors.” Controls for the fourth recognized “reactor,” the Vertical Split Table, are simply stored out of the way. It is the third panel up from the floor in the rack at the extreme right side. This panel, also, was never used simply because the Vertical Split Table was never used.

Each of the three oft-used panels will be discussed in some general detail in the following few paragraphs. No more will be said about unused controls. These panels enabled the Experimenter to add reactivity to the device in use both remotely and reversibly. These controls required essentially constant attention throughout each experiment. That is why they were so centrally located just above the horizontal writing surface. The optimum height of this surface was purposefully selected for maximum operator comfort. Sometimes, quick responses were essential in making sometimes delicate manipulations. Operators had both arms well supported and well rested to be able to stop reactivity additions quickly or make other proper responses to information obtained from other instruments.

The Uranium Solution control panel was colorful and brightly lit. Colored lights depicted the status of valves and pumps. Open valves showed yellow; closed ones, blue. Pumps showed red when operating; green when ON (ready) but not functioning. Typically, these lights appeared as clusters of four lights arranged in a quadrant. Some clusters were just lights; other clusters had centrally located electrical switches. These switches were either spring-loaded ON/OFF switches; or they were selector switches. This kind of design became more or less “standard” across the CML’s Control Console. Three spring-loaded push buttons operated the three

uranium solution transfer pumps described elsewhere. These pumps were called FAST, MEDIUM, and SLOW. Actual variable delivery rates for these pumps were selected by Experimenters before actuating the pump’s push button. Various rates were set by “dialing” different air pressures on the 3 x 2 matrix of white, round-faced dials enclosed by black squares on the top panel above the right side of the writing surface. These faces were calibrated in percent of a full air loading. Thus, one could set the FAST pump at 20% of its air loading; and that would correspond to a known and dependable solution flow rate.<sup>54</sup> That example corresponded to one liter per second. Of the six dials, the top three pertained to the uranium solution system. The bottom three were intended for use with plutonium solutions and were never used. Valve controls on the panel behind the microphone could be set to route uranium solution to the experiment, return it from the apparatus to storage, or recover it from the SCRAM tank.

The next panel to the right (and under the clock) controlled movements of the Horizontal Split Table. Again, colorful lighted indicators revealed the status of pumps and other information. Spring-loaded push buttons centered in these lighted clusters actually controlled table movements. A mechanical counter, similar to an automobile’s odometer, gave a coarse indication of the table’s closure. This counter can be seen between the two white-faced electrical meters. Those meters, in turn, indicated the final closure over the

<sup>54</sup>An important safety consideration was the ability to dis-allow operation of a “faster” pump during an experiment when it would no longer be safe to add solution at that rate. For years, this safety measure was accomplished by the simple expedient of sliding a piece of bent metal in front of the push button.

last 50 mm. They corresponded to a pair of spring-loaded differential transformers set a good distance apart. This final closure was most important to safety. Unequal response by the two meters would suggest one side of the table had encountered an obstruction and might suddenly bolt forward if that obstruction were, say, crushed. The readout was further used to show when the two table halves had contacted one another. In that case, efforts to close the table further would result in no movement of the differential transformer readouts. This was a very sensitive means of showing the exact condition of closure. Too much attempted closure past face-to-face contact would cause a table SCRAM. Later (in the 1980s), the Horizontal Split Table was equipped with an optical device which rode along with the south table. It indicated with good precision the table's status of closure at all points from fully open to face-to-face contact. That "position recorder" is not seen in the photograph.

The next control panel (third from left) is the lighter-colored one. It was built to control the Liquid Reflector/Moderator Reactivity Addition Device. Again, colorful lights with centered spring-loaded ON/OFF switches or electrical selector switches were associated with valves, pumps, and pumping speeds governing reactivity additions. Here, reactivity addition happened through increased neutron moderation and/or reflection via non-fissile liquids added to an experiment previously loaded with fissile metal. Unlike the uranium solution control, where solution flow rates could be set by air-loaded dials at the upper right of the Control Console, flow rates for the non-fissile liquid were fixed. Three rates were called FAST, MEDIUM, and SLOW; but a fourth rate was a combination of the last two flows. This panel is divided symmetrically into left and right. The left

side controlled the outer tank's filling whenever either fissile metal was used. The right side controlled the inner tank's filling whenever bare plutonium metal was involved. The spring-loaded push buttons at the bottom center of each half served as a rapid return mode for the liquid. It was similar to a SCRAM in that liquid returned to the reservoir at the same rate; but dissimilar in that the return could be halted by releasing the spring-loaded switch.

The fourth panel from the left along the working surface was never used. It was the counterpart to the uranium solution control but for plutonium solution which never were part of the CML's capability. The similar appearance of the two control panels betrays the similarity mentioned.

The Vertical Split Table, although it existed within the Assembly Room, was never used as previously stated many times. A control panel had been built for it, however, as part of the original design package. This never-used panel is shown stored out of the way in the extreme right hand chassis rack (third panel up). It, too, appears quite similar to its Horizontal Split Table counterpart.

– *Radiation Indication and Recording* –

Critical experiments result in high fluxes of neutrons and gamma rays. Indeed, measuring these fluxes are integral to the reciprocal multiplication technology used to monitor safe approaches to criticality. Neutrons were measured three ways. Ionization detectors in the Assembly Room struck by neutrons generated a quasi-DC electrical current proportional to the instantaneous neutron flux. This was indicated by a very sensitive analog meter called a "linear picoAmmeter." Two such detection channels followed every experiment; so two meters were required. Both of these



appear as identical light-faced panels on the diagonal chassis rack to the left of the working surface. One is directly to the left of the microphone; the other, two panels below it. The black knob in the center selected the full-scale current range; and most experiments covered several decades beginning about a few picoAmperes.

Attention to these instruments had to be paid faithfully throughout an experiment because a SCRAM was initiated if ever the instantaneous current spiked to 100% of full scale. An even higher trip point was set at 130% of full scale. This not only initiated a SCRAM; but it also set off the Building Alarm. This was discussed elsewhere and was equivalent to a Criticality Alarm. The white-faced dial to the left essentially indicated the percent of full scale for the instantaneous current. The paper strip chart recorder just above the upper picoAmmeter gave a continuous inked trace of these growing electric currents. One inked trace was red; the other, blue. Statistical fluctuations usually produces ink traces almost 20 mm wide early in an experiment. As criticality was attained, improved statistics narrowed the width of these traces to only a couple of millimeters. The paper moved downward with time; so time increased upward on the finished recording. Increasing current caused the trace to move to the right. Strip chart readouts from just two programs have been preserved for posterity; and these reside in the LANL Archives in Box 28, Folder 29, through Box 29, Folder 29. They are interesting and a detailed study reveals much about the physics of (and statistics of radiation variations throughout) an experiment.

These linear Ammeters were not very useful early on in an experiment. Their electric currents were too low to have much statistical meaning. Early stages of

an experiment were monitored by a set of four neutron-sensitive proportional counters. These chambers, located in the vicinity of the experiment, recorded individual pulses corresponding to individual neutrons. These pulses were counted on the digital readouts seen on the diagonal chassis rack to the right side of the working surface. Four detection chambers meant four digital readouts seen stacked one atop another. In addition, four rate meters are lined up side-by-side near the bottom; but these were not used by the Experimenters.

In use, the neutron flux would be counted each time a pause in the reactivity addition was made as part of the reciprocal multiplication approach technique. Commonly, between 3000 and 6000 neutrons per 30 second counting interval would be measured at the start of an experiment. Neutron counting rates grew to many millions in the same 30 seconds by the stage of an experiment that this measurement device was no longer useful. Dead time losses (undetected neutrons because of instrument capability) caused a non-conservative underestimate of the true reciprocal multiplication. Because of this problem, the linear picoAmmeters were used later in the experiment. They did not suffer from dead time losses. The proportional counter channels had no built-in SCRAM capabilities.

The innovative Electronics Technician, "Bob" Sheets, invented a device to measure the instantaneous reciprocal multiplication. This device held a pre-dialed initial count rate,  $C_0$ , in memory and divided any subsequent radiation rate,  $C(t)$ , into that preset rate. Thus,  $C_0/C(t)$  was continuously recorded on the meter. Two of these "1/M meters" can be seen, albeit edgewise, on the second chassis rack from the far right about one-third of the way down. Two of the four proportional counter instruments

were selected to be recorded continuously on the strip chart recorder seen at the top of the diagonal chassis rack. Again, one was red; the other, blue.

The last neutron measuring device was a bit more complicated. It also received a quasi-DC electric current from an ionization chamber near the experiment; but this instrumentation on the Control Console recorded the natural logarithm of this current as well as the time-rate-of-change of it. The panel, itself, is the third panel up from the working surface and under the clock. Its light-grey face contains two white-faced dials, one for each aspect of the neutron flux. The log of the neutron flux is roughly a measure of the “power” of the critical assembly, although even at its highest, only a fraction of a Watt was ever generated. This dial had two SCRAM trips separated a couple decades apart. The

lower one initiated a SCRAM without tripping the Building Alarm. The upper did both. The time-rate-of-change meter was proportional to the instantaneous neutron reactor period of the critical assembly. The shorter the period, the closer the assembly was to a prompt critical configuration. In general, Experimenters kept the average positive reactor period longer than a few minutes. This dial had a single SCRAM trip point: 15 seconds. Both the “power” and the period were recorded continuously on the strip chart recorder panel just above the meter, itself (just below the clock). Again, the colors were red (power) and blue (period). One example of these traces, less their colors, is given in Fig. 71. The figure illustrates what Experimenters were looking at and inferring from them during the all-important final stages of a typical experiment.

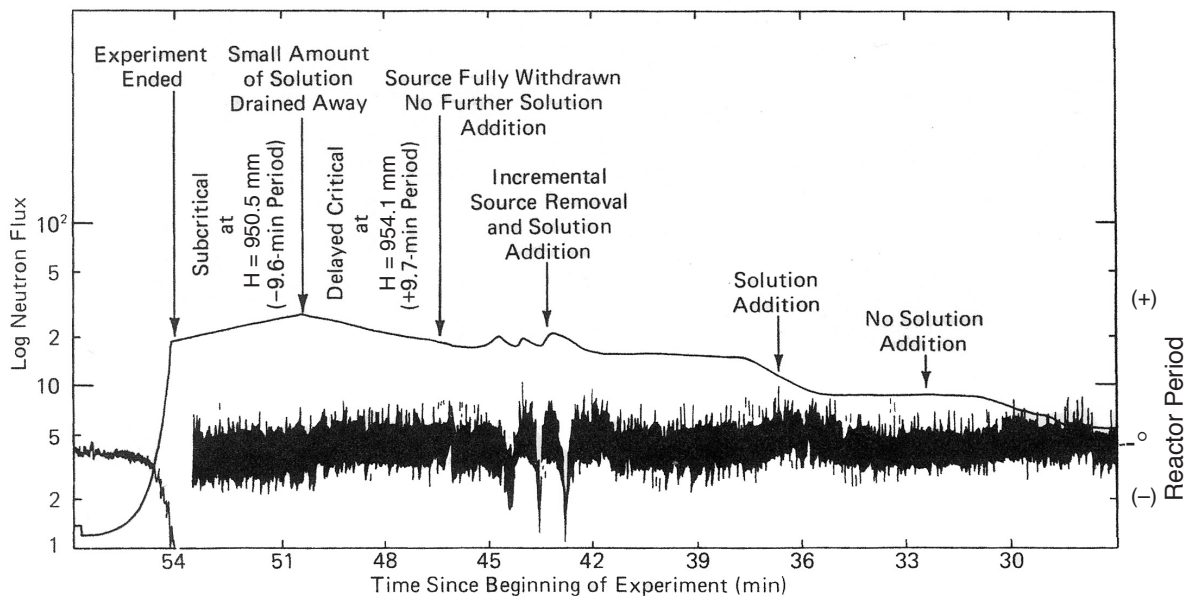


Fig. 71. Strip chart recorder traces provided Experimenters with a great deal of information during an experiment. The instantaneous time-rate-of-change exhibits large statistical fluctuations. The natural logarithm of the neutron flux shows here as a solid line, although actual traces did exhibit decreasing fluctuations as the flux increased (statistics improved). Note that time proceeds from right to left on this figure and spans about half an hour. This system remained at or near critical between 46 and 54 minutes into the experiment.

Only one instrument was associated with the gamma ray flux present in the Assembly Room. This, too, was an ionization chamber designed to respond to gamma radiation. The panel on the Control Console measured the natural logarithm of this flux. The meter is the bottom panel on the diagonal chassis rack to the left of the working surface. The center of this panel shows a white-faced rectangular meter. The log of the gamma ray flux was also continuously recorder on the strip chart recorder seen at the very top of that diagonal chassis rack. The Log Gamma meter also had two SCRAM trip points. The lower one initiated a SCRAM only. The higher, like other meters, caused a SCRAM and tripped the Building Alarm.

– *Closed Circuit Television* –

A number of closed circuit television systems (CCTV) viewed many aspects of an experiment in progress. These systems, perhaps more than any other, experienced many changes, additions, and upgrades over the three decades of useful service. Four TV monitors are seen in the photograph under discussion; but only two of them were used in those early years. The number of CCTV systems grew to a maximum of, perhaps, as many as four over time. Their quality improved as replacements were purchased with better definition (more “lines per inch”). When color television became available commercially, that feature was added to a couple of CCTV channels. Color introduced a whole new aspect of visual acuity previously lacking in black-and-white sets.

The many advantages of multiple CCTV systems was recognized early on and used to best advantage. Rotating the camera to avoid optical interference between fiducial lines being viewed with retrace lines caused by fly-back transform-

ers has already been mentioned. The vertical movement of one camera to follow along with the rising height of liquid in an experiment without tilting it has also been mentioned. Most other cameras were mounted on remotely-controlled devices which allowed them to tilt and pan, permitting them to survey an entire scene. Cameras had zoom capability which improved greatly their value.

Some cameras were used simply to view aspects of the experiment to assure normal functioning. A camera might watch the south half of the Horizontal Split Table approach the fixed north. Another time, it might view down into the Annular Tank or the tank used for non-fissile reflector additions. Other programs would find the camera looking under the Solution Base hopeful of detecting a few drops of leaking uranium solution before a major puddle had formed. This is one strong application of color TV because the yellow solution was more easily seen. Still other camera applications found them actually providing data on the reactivity addition parameter. For example, TV cameras were used to view solution heights on the Solution Base, the Liquid Reflector Apparatus, and on the elevated platform for both Annular Tank studies.

– *Audio* –

Audio communication between the Control Room and the Assembly Room was surprisingly important. It was used during the Pre-Run checking procedure. One Experimenter walked around Room 101 performing various tasks and speaking to the other in the Control Room. The latter would record responses from the former’s actions on the Pre-Run Check Sheet. It was also used during experiments. Uranium solution experiments benefitted from the

ability to listen to the hum of the SCRAM valve solenoids. Solenoids straining against too much hydrostatic pressure hummed a lot louder. Trained ears could hear the clicking sound made as certain remotely-controlled valves functioned. Audio was also important for the *absence* of sound. Sound heard during experiments supposedly silent gave a rapid clue that something might have gone wrong. The best example of this was the time one metal arm broke loose and fell against its lower neighbor during the so-called Christmas Tree program.

The microphone can be seen at the extreme left edge of the working surface. It stands in front of the control panel for uranium solution experiments. The few audio controls, most notably the loudness control, are contained on the panel seen dark on the diagonal chassis rack to the left of the surface. That puts it between the two meters for the linear picoAmmeters.

– *Neutron Source Control* –

An external source of neutrons was required for every experiment using uranium as the nuclear fuel. This source had to be present during the approach to criticality; but better data was obtained if it was withdrawn before actually attaining criticality. This meant that the source had to be cable of being moved (withdrawn) remotely. Through the first decade or so, this was done by winding a long aircraft cable onto a spool with the source attached to the other end. Methods for moving the source were improved a couple of times over the years by the clever Electronics Technicians. The pinnacle was the use of a radio signal transmitted through the thick walls by a wire to an antenna in the Assembly Room. That radio signal controlled the movement of the crane near the ceiling of the room. A fixed length of aircraft cable passed over a pulley allowed movement of

the bridge of the crane to withdraw the source. Then, after collecting critical data, the source could be *reinserted* without reentering Room 101 to continue on to another experiment. This improvement allowed as many as four separate (and different) critical experiments be performed without access to the room. A plastic laboratory funnel was machined to collect the returning source and guide it back into the small-diameter tube usually used to hold the source in a fixed location within the experiment.

Bob Sheets and Doug Payne were very clever and quite innovative people. Their many contributions to experiments are readily acknowledged.

– *Miscellaneous* –

Only a few additional panels were ever added to the control Console over the decades. These do not appear on the picture under discussion these last several pages because they were added after the photograph. One of these additions worth of comment was the panels associated with the Mass Flow Meters. One of these readouts was associated with the larger device in the Assembly Room. This device could record a few thousand kilograms with a precision of a few tens of grams; they were that good. A smaller readout responded to the smaller device in the same room; and it had a precision of a couple grams out of a few hundred. A third and similar meter was installed in Room 103 and measured the density of the solution at the output of the FAST pump. Used only once, the precision was unbelievably good as discussed elsewhere; but the device was not used often enough to prove consistent high precision.

Another kind of measuring device was installed after the picture was taken. These were multi-dimensional location readouts working on an optical principal. They, too,

were amazingly precise. One, called an “X-Y recorder” because of its ability to measure in two dimensions was used to measure the table closure of the Horizontal Split Table. A slightly more complicated device was called an “X-Y-Z recorder” because of its three dimensional capabilities. This device probably was never used, although that statement is not made with great confidence.

Finally, the picture in the figure discussed over the last several pages shows an open-mesh metal trough just above the ten sections of chassis packs. This sheet metal construction rests just behind the 24-hour clock above, in turn, a strip chart recorder. This trough carried the myriad of electrical cables from the Control Console to the wall behind the console. There, cables were passed from overhead down through the many large-diameter conduits shown very early in this chapter illustrating construction in 1964.

#### *Behind the Control Console*

A few important safety and control components were located behind the Control Console and against the south wall of the Control Room. Cables just mentioned passed overhead, entered the conduits, and ended up in Rooms 101 or 103. This wall also had the main electrical circuit breaker panel for the entire Control Console mounted on it. Experimenters became very familiar with this breaker panel through daily use.

Another feature in this area was a temperature recording device. This could be used any time; but it was primarily intended for use when the Assembly Room Leak Rate was being measured. Six temperature probes could have their information transmitted to this device. Its graph paper rotated such that a full 24 hours

corresponded to one full rotation. This temperature gauge was seldom used other than for leak rate data.

#### *– Earthquake Detector –*

An earthquake just at the moment that a fissile solution experiment was at or very close to criticality could be a dangerous coincidence. The earthquake would cause the solution’s surface to move in a wave pattern. This wave could move outward against the wall of the tank, reflect, and form a prompt critical height when the solution congregates at the center. A mechanical device to detect an earthquake and initiate a SCRAM before the wave could reflect back upon itself could actually prevent a criticality accident.

The CML had two different earthquake detectors in service during its three decades. The first was a long cable with a weight hanging from its bottom end. This “pendulum,” suspended from the highest point of the peaked roof, wouldn’t move unless an earthquake happened. The cable was closely surrounded by a loop of wire down near the weight which cleared the cable by only a couple millimeters. Any motion would cause the cable to contact the wire loop and complete a circuit causing a SCRAM of the experiment in progress. This simple but clever expedient suffered from one flaw. It might respond to longitudinal surface waves but might be a bit insensitive to pressure waves coming from deep within the earth. The second earthquake detector was a commercial apparatus designed to respond to expected earth movement in a quake. The unit was glued to the bared concrete floor of the Control Room against the south wall and behind the Control Console.

Neither device was ever called into action during an experiment. Humorously,

the pendulum device circuit tripped once (not during an experiment) but no earthquake had been felt. A telephone call to a local Denver university noted for its seismic activity detection was contacted. When told of the incident and the time, they stated that no seismic activity had been noted. They checked their instruments and called back to say that a very small earthquake had, indeed, gone unnoticed at the time the CML's device tripped. The pendulum also tripped on very rare occasion when an especially heavy truck passed by Building 886 a few dozen meters north of the building.

#### *East Wall*

One electronic panel of note existed in the middle of the east wall of the Control Room. This panel was called the SCAM panel (not SCRAM), although the meaning of that acronym is not recalled. The panel was easily seen from the front of the Control Console; and its information was of interest to Experimenters. The panel consisted of three rows of several square indicators back lite by small light sources. The lights burned at about half voltage when conditions were "normal"; and the brightness increased to full when the condition became abnormal. If the indicator was dark, that channel was suspect of being non-operational; and the burned out bulb would be replaced.

This SCAM panel reported the status of various liquid levels, the status of the facility's exhaust fans, and a number of similar safety measures. Liquid levels sensed, for example, were liquids collected on the floor of the Mixing Room under solution storage tanks and under the Solution Base in Room 101. These devices, when they became abnormal, did not initiate a SCRAM; but they did sound a

very irritating and raspy horn that demanded immediate attention through its irritation.

#### **The "Shop"**

Room 114 was integrally linked to experiments and was contiguous to the Control Room on its north side. Although labeled "Laboratory" on original construction drawings, it was really a small machine shop, electronics facility, and an area for constructing small mechanical devices to be used in experiments. Almost square, the room measured 6.4 m (north/south) by 6.7 m. Long benches along the east wall were usually strewn with electronic components being tested or calibrated or even new gadgets being invented. A small stone-topped sink handled chemicals used for etching printed circuit boards and other industrial purposes. Whereas the east half of the room was devoted to electronics, the west pertained more to mechanical work. A small machine shop consisting of lathe, mill, bandsaw, bench tool grinder, and metal break often saw service in that capacity.

The room was a bee-hive of activity as well as a central congregating site for lab-related persons. Ideas were discussed, designed sketched, and options argued. One occasion proved otherwise. Not much work was done the day the Challenger space shuttle exploded even though the room was full of people. Attention was riveted on the small television monitor jury-rigged with a make-shift coat-hanger antenna to pick up commercial stations.

A very small office (Room 105) off this room to the northeast opened onto this room. This tiny area, less than 3 m square, housed the Instrument Technician's desk along with racks of small-parts cabinets for electronic components, fastening hardware,

and similar items. Space was at a premium there.

### **Foil Counting Room**

Another room initially planned to be associated with experimental studies was Room 117, called the “Foil Counting Room.” The original intent was to activate various metal foils by neutron bombardment during experiments and then to estimate properties associated with the critical configuration by a technique called Neutron Activation Analysis. The room was never used for this purpose because that method was never adopted at the CML. The room quickly became another office and remained so for many years. Sometime in the late 1980s or early 1990s, the wall between it and the above-mentioned Instrument Technician’s office was removed; and the two rooms became one. That larger room served as a Computer Room in which Criticality Safety Engineers could perform computer calculations related to plant safety question.

### **Mechanical Room**

Room 111, on the west side of the building but south of the lunchroom, housed all the building’s utilities. This included main electrical breakers, steam for heating, domestic cold water, water for fire suppression, ventilation, the criticality alarm detection panel, batteries for the building’s emergency lighting supply, and a few other lesser features. The room measured 12.9 m north/south by 8.1 m. Two doors faced west. The corrugated roll-up door near the north end was used for deliveries of day-to-day supplies and for removing waste drums from the building. The second door, just south of the first, was an ordinary person-sized door. As stated

before, these two doors became the *defacto* main entrance to the building. A pair of light-weight steel doors opened onto the Main Hallway along the east side of the room. The room often saw heavy traffic. Most people routinely came and went through this avenue; and the space was occasionally used for auxiliary non-fissile experiments. The room was often noisy and its temperature depended on the out-of-doors; so this latter use tended to be more common in spring and fall transition seasons.

### *Electrical*

The north wall featured mostly electrical breaker panels. Most of these were 440 Volt systems with heavy duty contactor breakers. These breakers were arranged in a matrix spanning about two-thirds the north wall and extending well above head height. Many of these contactors pertained specifically to experimental components (the FAST pump, for example); and they were used by Experimenters to disable and lock out certain equipment at appropriate times. These physical lockouts were safety measures to preclude accidental use of wrong equipment at the wrong time. The rest of the north wall sported a couple of large panels of ordinary household circuit breakers. These protected lights and outlets in the various rooms and other low-power electrical features.

A series connection of heavy-duty automobile batteries provided backup electrical power for emergency lighting throughout the building. This was located along the west wall and just south of the door to the Main Hallway. At some time (but not recalled when), Building 886 got a diesel-powered Emergency Generator which was located outdoors somewhere west of the building. Details about the bank

of batteries and/or the generator are a little uncertain because that system was not this author's responsibility.

#### *Water*

The west wall housed steam and water inputs to the building. Steam for heating the building and other purposes entered a reservoir just south of the smaller door. Potable water valving, the fire-water line into the building, and a few other water-related features spread along this wall as well. Fire-water suppression plumbing was painted a bright red. The fire-water feed line had a water-driven bell in series with the water flow. If the water ever flowed, the bell would sound telling firemen that the system was functioning. Potable water piping, on the other hand, was painted a light green.

#### *Criticality Alarm*

One electronic chassis rack stood free-standing in the middle of the room. This panel was part of the Criticality Alarm detection. Six electrical meters represented the status of the six Criticality Alarm detectors spread throughout the building. Each untripped detector showed up as a nearly full-scale indication on its corresponding meter. If any detector had tripped, the meter dropped to zero; so one could tell the status of the six detectors by checking their meters. Since sounding the Criticality Alarm required any *two* out of the six detectors to trip, this panel was useful in ensuring that all six alarms were always in the "ready" state. This panel was used in later years as the place for initiating the occasional planned Criticality Alarm test and evacuation. Previous to that, the Building Alarm would intentionally be tripped to produce the same effect.

#### *Ventilation*

Air-supply plenums are only half the total air flow components of the building. The other half is the exhaust duct work. Combined, the two regulated the overall movement of air from the fresh and uncontaminated out-of-doors Colorado environment, through the building and its many rooms in both Cold and Hot Areas (and even through plutonium contaminated gloveboxes), guided it into some form of filtering system, and, finally, returned the air back to the atmosphere as once-again uncontaminated. This treatment of air is neither simple in design nor practice; but it is essential to the health and safety of persons living downwind. The detailed way this complex problem was dealt with in Building 886 will be discussed later.

#### *– Air Supply –*

Four separate plenums provided air input for the entire building. Only one of these fed the Hot Area; the other three served the Cold Area. The air intake to the Air Handling Unit in Room 111 was through a 1.8-m-wide by 0.9-m-high grill opening onto the Main Hallway. The sheet metal handling unit extended into the Mechanical Room about 4.9 m. It was about 1.7 m wide and not quite so high off the floor. Both the width and height increased toward the west end where four exhaust plenums projected forth. All four plenums rose toward the ceiling with rectangular ducts guiding fresh air to their areas of service.

One plenum ("Zone 2") served the entire office area. It was nominally balanced to 3120 CFM and measured 510 mm wide by 460 mm high. The plenum size got smaller as it progressed to rooms further away. This single plenum attempted to serve 15 offices and really could never be



well balanced. One office might be cold while another, hot; others suffered from too much air flow or not enough. Air supply design was marginally adequate at best for this building. Zone 1 served only the Lunchroom with its 560 CFM. It was small at only 410 mm by 150 mm. The third zone supplied air to the Control Room, the “Shop,” and the Men’s Rest Room. It measured 460 mm square at its beginning and boasted 2655 CFM, when properly balanced.

The fourth zone had the largest plenum at 610 mm by 510 mm. Zone 4 supplied the entire Hot Area. Its balanced delivery was 3635 CFM, although, in truth, all these “balanced delivery rates” were more engineering goals than realized fact. This fourth zone plenum had a few branches. One branch plenum (460 mm by 250 mm) supplied air to Room 102 at its northeast corner with a nominal flow rate of 1000 CFM. Room 103, across the Hall, was serviced by three identical (spaced apart) branch plenums. Each was 300 mm by 250 mm and delivered 735 CFM each.

Ironically, a very small plenum (150 mm square) branched off the lone plenum serving the Hot Area to supply fresh air to the Women’s Rest Room. The air was still fresh and uncontaminated; but the supply to that room being tied to the supply to the Hot Area somehow seems sexist.

Each plenum opening into each room passed through a circular diffuser. These diffusers also had manual dampers that could be opened or closed to increase or decrease air flow. The combination of people mis-handling diffusers to their own rooms and the over-extension of a marginally designed system to supply air to four more offices past the original ten all contributed to the inefficiency of this air-supply system. When the four new offices

were added in the northeast corner of the building, air feeding them lacked heat or cooling, depending on the season. The distance traveled and the demand for air enroute drained the system almost completely. One solution was to install a heater “booster” and install it in the plenum to northern offices. Even this did not work well.

Room 101, the Assembly Room, had no fresh air intake from the Air Handling Unit in the Mechanical Room. All air entered that room via a separate sheet-metal Air Handling Unit mounted about half way up the wall in the southwest corner of the Assembly room. Air could also enter the room, of course, through the Hallway and Labrynth (Room 108) if proper doors were open. Fresh air to this second handling unit was through a 250-mm-diameter duct about half way up the west wall on the outside of the Assembly Room. It can be seen on some earlier construction photographs shown earlier in this chapter. Actually, that input line through the 1.2-m-thick concrete wall had a “S-curve” built into it for some no-longer-recalled reason. Nonetheless, once inside the room, that duct passed through a large air flow valve before entering the 3.9-m-long by 1.8-m-wide Air Handling Unit. A small walk-in chamber (to allow filter changing) opened onto a 3 × 3 array of the same 610-mm-square HEPA filters. Provisions existed for these nine filters to each have a thin furnace filter preceding it. These served as “pre-filters” to the nine absolute filters. The next chamber in the sequence provided heating and cooling. Cooling was accomplished by chilled water in the coils. Heating may have been steam; but this detail is not clearly recalled. The last chamber featured a noisy blower fan which blew temperature-controlled air into the room.

The Assembly room was isolated from the environment every time an experiment was in progress. The intent of this action was to contain all radioactive byproducts in the event of a prompt nuclear accident. The air flow valve mentioned in the previous paragraph was closed. In addition, the two exhaust ducts (discussed below) were also closed. With all Blast Doors sealed shut, the room was completely isolated from the outside world at these times.

– *Exhaust Ducts* –

The four plenums just described above supplied air; but the exhaust system removed it from the building. Exhaust sites were all located within the Hot Area. They exhausted individual rooms but all came together in a single duct connected, in turn, to a filtration system, to be discussed later, before releasing possibly contaminated air to the environment. This ducting was all circular in cross section and made of stainless steel; but the diameters varied to suit needs. Each room's exhaust air passed through an "absolute filter" at the exhaust site to keep the inside of the duct as free of contamination as possible. These were 610 mm square by about half that thickness. They were wood-framed paper filters called "high efficiency particulate air" filters, or HEPA filters.

Room 102 was the simplest. A single exhaust site existed diagonally opposite the air supply. Its 250-mm-diameter duct passed overhead into the Mixing Room where it coved into the main exhaust duct. Room 103, the Mixing Room, had five exhaust sites. Two of these were to the south and east and in the depressed pit area of the Tank Farm. Both were 152 mm in diameter. A third site (203 mm diameter) inside the stainless steel room, against the west wall, designed for future use with

plutonium solutions. A fourth, also 152 mm in diameter, was situated in the northeast corner of the upper level of the room. The final exhaust site in the room served the fume hood against the west wall but to the north. This was the only site to have a different design for the absolute filter housing. It was contained in an overhead chamber, seen in Fig. 72, and was accessible from one of its faces.

The six exhaust ducts serving the two rooms left Room 103 via a 406-mm-diameter overhead duct exiting the building through the south wall of Room 103. From there, the duct found its way to an exhaust plenum; but the discussion of that part of the system is delayed until a later subsection.

The Assembly room (Room 101) had only two exhaust ducts; and even one of these was quite small. In retrospect, this design seems undersized for the large volume of the room. That small duct (100 mm diameter) exhausted the would-be plutonium solution glovebox along the west wall. Since plutonium solutions were never used, this exhaust probably was unnecessary. The larger duct was much more interesting. Its exhaust site was the *inside* of the Walk-In Hood in the Assembly Room. The site was two HEPA filters wide; and this housing fed a 250-mm-diameter duct which proceeded west before turning down. It entered to floor close to the north Blast Door and continued half a meter under ground. There it turned west again, passing through the footing of the west wall (see 1964 photograph), before rising again only to turn south and enter the same exhaust plenum as the duct from Room 103.

In summary, the entire air flow system was designed to require air to flow toward regions of progressively lower ambient pressure. This was a means of preventing

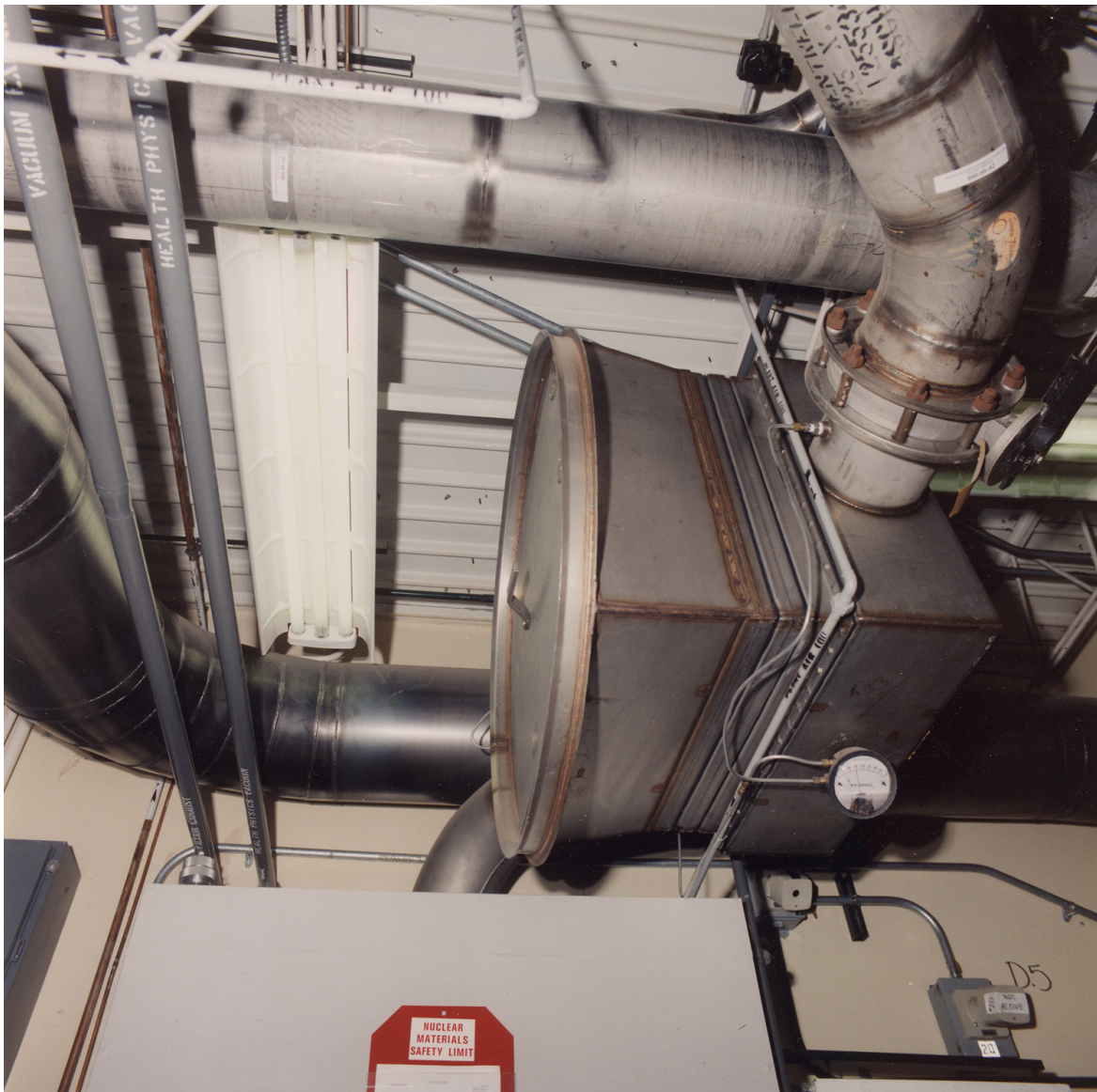


Fig. 72. The fume hood in Room 103 was exhausted through a wood-framed filter housed behind a circular opening. The shiny duct work behind the housing exhausted the Cold Area and only passed through this room. Other duct work (top) exhausted various portions of room 103.

the movement of air backwards from regions of high contamination to regions expected to have lower contamination. Doors, walls, filters, and other features defined distinct pressure areas—in descending order of nominal pressure (at least between fans)—as follows:

- The Out-of-Doors*
- Cold Area Offices*
- Air Handling Unit in Room 111*  
*(supply fans to four plenums)*

- Hot Area: Rooms 101, 102, & 103*
- Down Draft Room (103) and Walk-In Hood (101)*
- Exhaust Ducts Leaving These Rooms*
- Input Chamber to the Hot Exhaust Filter Plenum*  
*(exhaust fans)*
- Filtered Air Exiting the Hot Exhaust Filter Plenum*

Finally, the fully-filtered air exiting the Hot Exhaust Filter Plenum was allowed to return to the out-of-doors via a chimney of some kind.

## Room 106

This was a small room off the southwestern corner of the Mechanical Room. It was used for the storage of miscellaneous “junk”—mostly related to the CML, Building 886 as a whole, or whatever. It was not well maintained and was often quite messy. It was straightened up every few years; but this never became a priority. The room was only 4.4 m by 4.2 m.

## Office Area

Interestingly, the main entrance to the office area was *intended* to be the door facing east at the north end of the building. This has been alluded to before. Circumstances dictated that this door would seldom be used. People preferred to enter the building through the Mechanical Room on the west side of the building for several reasons. This door was much closer to the Guard Post through which one had to pass for security reasons. Snow, rain, and Chinook winds made this shorter path very attractive. For three decades, then, people ranging from top plant management and important visitors all the way down to the most common worker entered the building through this most enigmatic, unattractive, noisy, and often-cluttered room. This access became so “matter-of-fact” that no one paid any attention to such a strange entrance to a building.

Offices consisted of one larger-sized office for the Manager with two smaller offices adjacent to the south for administration. One of these was occupied by the Secretary; the other, a non-technical Administrative Assistant. The latter would manage budgets, order materials, oversee the accountability of nuclear materials and forecasts for future needs, and a host of other functions important to the smooth

operation of the facility. Many years later, the need for an assistant diminished; and the position was terminated. Each individual was expected to assume these responsibilities personally.

With that need gone, the wall between the two rooms was reduced to half its height forming one larger administrative area. The Secretary occupied one of these; and “safes” (more formally called “repositories”) for retention of classified information, a few non-classified file cabinets, and other routine office furniture filled up the other. Later technical advances brought a copy machine and, much later, a FAX machine to this area as well.

Humorously, secretarial ministrations evolved along with technology; and day-to-day typing provides one example. In the 1960s, reports were typed by hand on an electrically driven mechanical typewriter using carbon paper (itself, an archeological artifact) to obtain multiple copies. Errors would be corrected by rolling up the platen, laboriously erasing the error from each page, blowing away eraser crumbs, and re-aligning the text to continue. Later, office correction fluids produced a major simplification. Still later, the invention of the computer with its word processing capabilities relegated these early methods to the same category as dinosaurs. This evolution of office management technology closely parallels mathematical calculations wherein the slide rule gave way to the electro-mechanical calculator which, in turn, succumbed to electronic calculators with LED displays.<sup>55</sup> This awesome evolution has been discussed elsewhere in this book.

Five two-person offices north of the Manager’s complex accommodated most of the technical staff. One more small office was the never-used Foil Counting Room; and the small room off The Shop

(Room 105) officed one more. A Conference Room (Room 116), which doubled as a Lunch Room, rounded out day-to-day personnel facilities. Off the main hallway, a Mechanical Room (Room 111) housed electrical, water, heating/cooling, and similar building-comfort equipment; but this room has already been discussed in great detail. The building contained a larger Men's Room and a smaller Women's Rest Room plus an incredibly small janitorial closet for cleaning supplies. In later years, this cramped space housed two "back-flow preventers" which would never permit water once in the Hot Area from ever returning back into the potable water system. One serviced cold water; the other, hot.

The Men's Room had two showers; the Woman's, none. Humorously, a female occasionally needed to take a shower after working in the Hot Area. This necessitated a guard stand by as "watch" to ensure privacy and maintain modesty. This "watch" did not happen often; but the building, a product of the 1960s, was not gender equal. The delicate sex was treated to a comfortable leather couch in the Women's Rest Room—itsself, a Chauvinistic symbol. The Men's Room featured two toilets, two urinals, and about 15 lockers. Street clothes were left in the lockers while company clothing was being worn.

The alcove outside the Men's Room and between the Main Hallway and the

Airlock became the Radiation Monitor's working area. This was both convenient and practical. The Monitor was readily available to the Airlock and positioned to oversee movement which might carry contamination out of the Hot Area. Records were kept in the desk; and equipment resided on the desk. A machine for counting alpha particles from contamination smeared onto circular disks of paper was one. The Monitor's belt-mounted, hand-held, alpha particle detector also resided there.

#### *Office Area Modifications*

Four more offices were added to the northeast corner of the building in the 1970s. Staff was growing in number; and, even with two persons per office, added space was necessary. The original, although seldom used, exterior door opening to the east was simply relocated further east; so the four new offices simply opened onto the now-extended east/west Hallway. A few years later, even more offices were added in the form of a portable trailer fixed in place a few meters east of the above addition. The trailer was numbered T886. The area between the two was covered over forming an alcove. The exterior door was again relocated, this time facing north; and entrance to Building 886 was via this alcove. As stated above, this nominal Main Entrance never overcame the convenience of access through the Mechanical Room (Room 111)—only a few steps from the Guard Post. The alcove was just wide enough to serve as an entryway and still have a small bank of storage cabinets on either side for office supplies.

Initially, the facility under Schuske's control was to contain only two groups: the CML for performing critical experiments and Criticality Engineering for overseeing plant criticality safety. After his death,

<sup>55</sup>This author's professional career was first exposed to the computing facility at the Naval Research Laboratory located in Washington, D.C. A huge room was filled with many racks of identical book-sized Eccles-Jordan circuits. Each of these was a simple on/off switch in simple terms. Air conditioning was required to compensate for the heat produced by the multitude of vacuum tube heater filaments. Half a century later, even greater computing capacity can be found in a palm-sized calculator carried in a shirt pocket.

other features came under the purview of the group; and many more persons were needed to staff these functions. These bore descriptive titles such as Safety Analysis, Human Factors Engineering, Document Control, and, perhaps, a couple other. Schuske's original 14 persons grew to a staggering 100 or more persons. The building and the trailer became insufficient to house all of these people. Two more trailers were introduced and planted further to the east—right in the parking lot—and to the southeast. These were numbered T886B and T886C after the first trailer was re-named T886A. The expanded building, including T886A, is shown in Fig. 74. Trailers T886B and T886C are not shown.

Advances in technology precipitated another change in office configurations. During the 1970s, computers were big, bulky, and even centralized off site. This author recalls delivering bundles of data processing cards to another government facility in Boulder, Colorado, one day enroute to work and picking up the results of the calculations the following morning. One computer served many users at both government-owned facilities. The personal computer, however, came into its own in the 1980s. Computer simulations of criticality questions could now be done individually and on a dedicated machine. To accommodate this new-found technology, two rooms in Building 886 were combined into one and served as a computing center. The two rooms in question were the never-used Foil Counting Room and the Electronic Technician's office contiguous to Room 114. The wall between the two was removed and the doorway to the room walled over. A long bench housed a number of personal computers on which even the most complicated computer codes could be run in a very short time. Calculations which used to take days and a huge com-

puter a decade earlier could now be performed in a few minutes from the comfort of this Computer Room.

This concludes the detailed description of Building 886. The Hot Area was described in considerable detail. That detail decreased as the areas discussed became less and less associated with critical experiments. The building was located within a secure boundary defining an area well identified as associated with Building 886. Some of those ancillary facilities were associated with the CML; others, not. Still, all of these will be discussed below with detail appropriate to their role in criticality experiments.

#### *Ancillary Features*

Building 886 was located within a fenced area a few times larger than the building itself. The building was about centered east/west in the 83 m between these fences; and it was only 6.6 m south of the north fence. North and south fences were separated by 105 m. Only five ancillary building away from Building 886 and other features warrant discussion in the following subsections. These aspects of experimental concerns included facility exhaust air, the collection and storage of waste liquids, the storage of used and new experimental apparatus, and facility services such as sewerage and electrical supply. The layout of the fenced perimeter, as it existed in the mid-1970s, is displayed in Fig. 74.

This fenced area was identified as "Area 3" on security badges. In the 1960s, anyone with Q-cleared security status could visit almost any area of the plantsite; but, a decade or so later, security enhancements caused the plant to be divided up into a number of separate security areas. A properly cleared worker could visit any

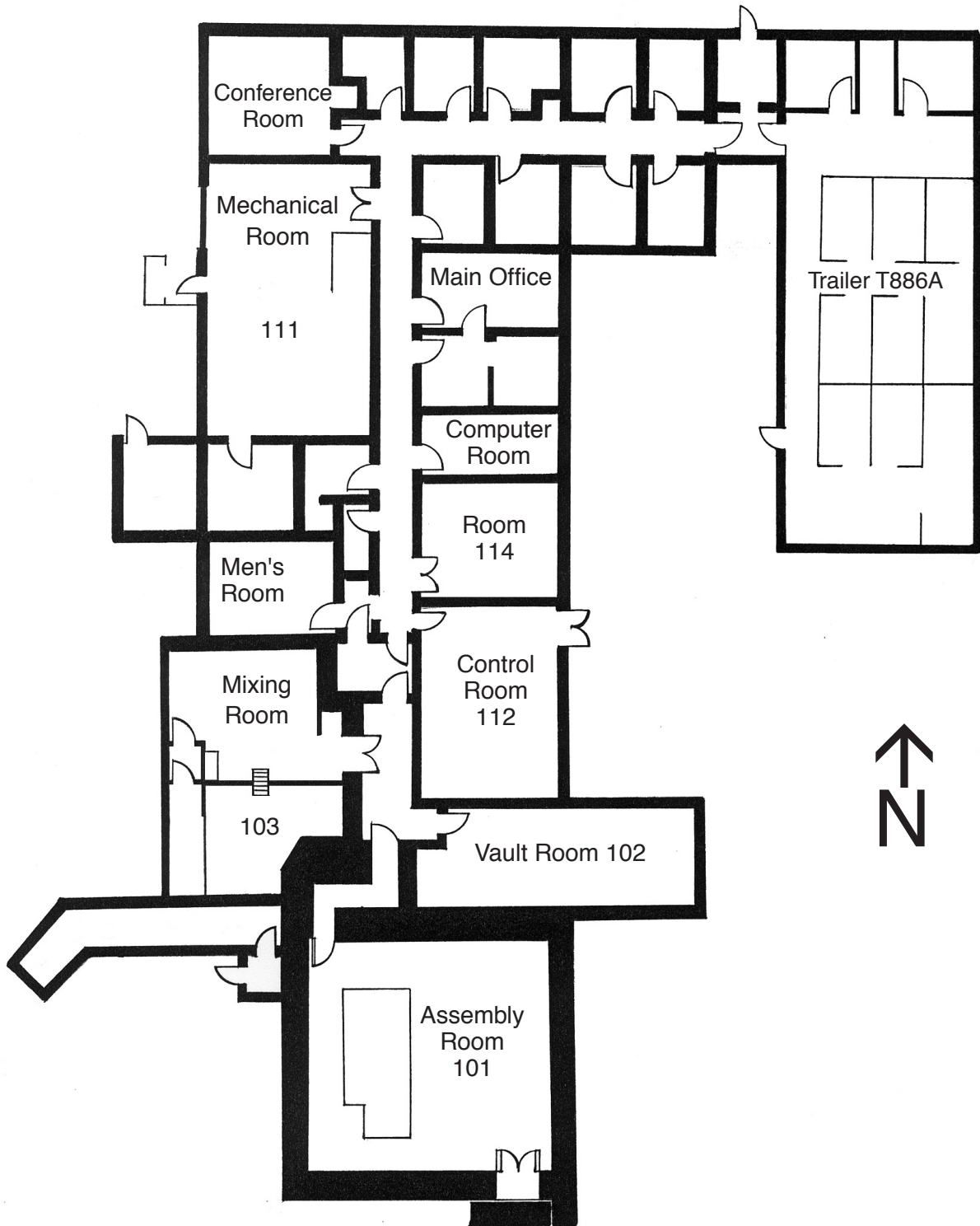
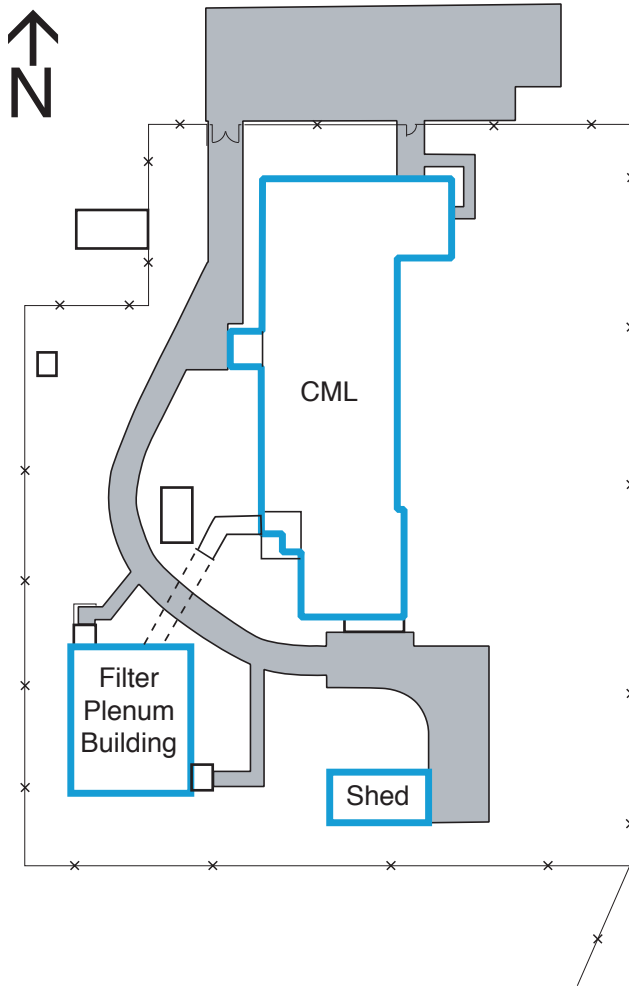


Fig. 73. The floor plan of Building 886 after about 1980 shows four new offices (top, right of center), additional office space in the form of Trailer T886A (upper right), an expanded Vault Storage Room 102 (lower, right of center), the tunnel to the Filter Plenum Building, Building 875, (west of the Assembly room), and a small room (west of the building) for certain control functions. The notch in one office along the north wall was related to a plant-wide criticality safety training program.



*Fig. 74. Building 886 was about centered east/west within the perimeter fence. The four-office addition at the northeast corner has been added in this mid-1970s layout. The filter plenum building, Building 875, has replaced the original sheet-metal plenum and joins the main building by an underground tunnel. The Waste Holding Pit (unnamed rectangle) is just to the east of the driveway providing access to the sheet-metal storage building (shed), Building 880, straight south of the Assembly Room. The Sewerage Lift Station (close to the west fence) and the Electrical Power Pad (northwest) are also shown. The Guard Post, added later, would be built just west of the double gate truck entrance to the concrete driveway north-west of the main building.*

area for which he/she was authorized but could not visit other areas without certain management approvals. Not many people on plant site had a “3” on their badge. That was not because the work there was that secret. Rather, most people on plant site never had need to visit a criticality laboratory.

The next few sections will discuss these ancillary buildings. Some of them were envisioned early on and became part of the initial construction. Some of them were changed as years passed; other buildings were added for one reason or another.

### **Filter Plenum – Initial Construction**

The initial construction of 1964 found the two Hot Exhaust ducts from inside the building, discussed above, entering an outdoor sheet-metal “Hot Exhaust Filter Plenum” that led, in turn, to a tall metal chimney. Both can be seen in the shade of the west face of the Assembly Room in the 1964 photographs at the beginning of this chapter. This simple housing was used between 1964 and the early 1970s. The plenum actually consisted of two rooms. One was the plenum, itself, which was 1.98 m wide by 2.05 m high and 3.23 m long (north/south). The length of this room



was bisected by two back-to-back racks of HEPA filters. Each rack contained a  $3 \times 3$  array of nine 610-mm-square wood-framed filters. These commercial filters were mounted in a steel framework to facilitate occasional changing and to prevent unfiltered air from leaking past. Potentially contaminated air from the building entered from the north chamber through the two ducts described above. This air was drawn through the double bank of filters into a second chamber.

A 1.9-m-long “transition section” transformed the almost square cross section of the second chamber to a single 508-mm-diameter stainless steel pipe duct. This duct led the now-clean air through a huge blower where it was released up the 17.6-m-tall stainless steel exhaust stack. This stack was also 508 mm in diameter.

The second room contiguous to the 3.23-m-long two-chambered plenum was an airlock. This airlock existed to the west of the plenum, was also made of just sheet metal. It measured 1.30 m wide by the same 2.05 m height and 3.23 m length. This airlock is the site of this author’s facial contamination incident from the Vent Line Overflow problem first discovered in late 1967. A single sheet metal door centered in the west face provided access to the airlock. From there, two similar doors provided access into each chamber on either side of the filter banks. These access doors were only opened infrequently and, then, just to change the filters.

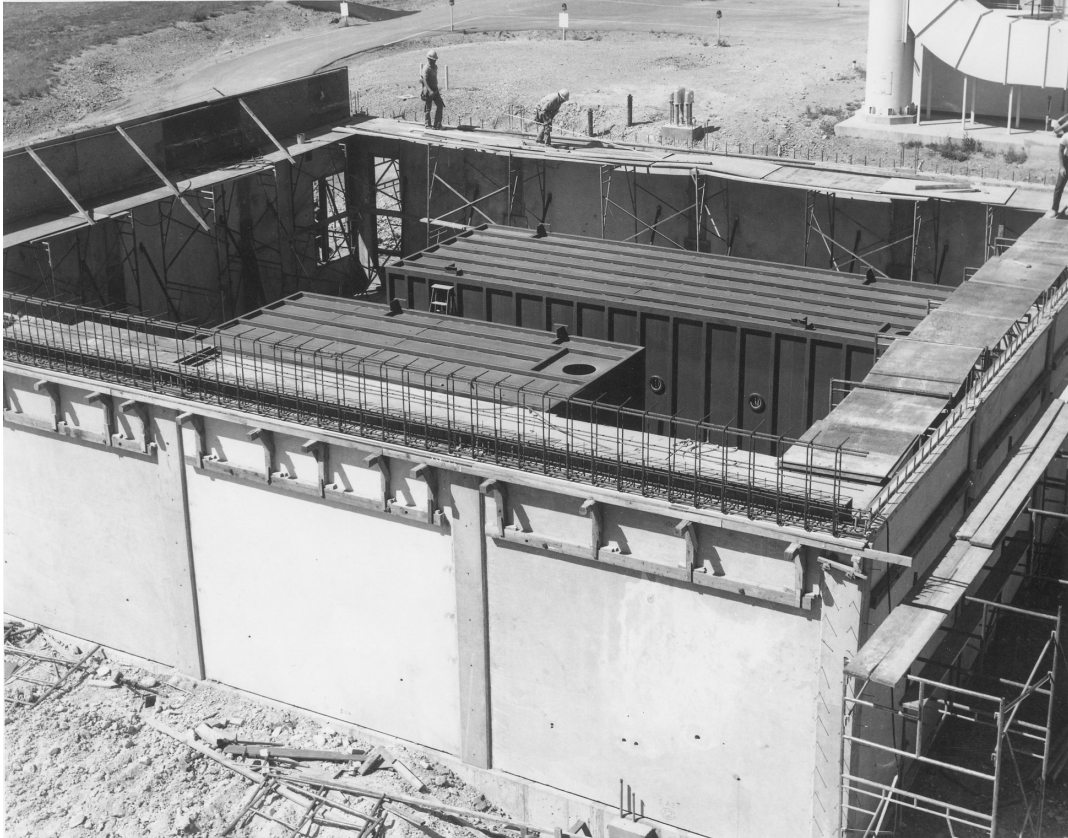
## **Building 875**

The worst industrial fire in the nation’s history happened at Rocky Flats on Sunday, May 11<sup>th</sup>, 1969. Ripple effects from that event were wide-spread. One of them was that Building 886 received a replacement Filter Plenum. The simple

sheet metal construction was no longer acceptable and was replaced by a concrete building, numbered Building 875, of quite large proportions. The building was situated several meters southwest of the southwest corner of the Assembly Room (13 m west and 3 m south). The new building was essentially built to house two side-by-side steel filter plenums. The building, 60% larger than the outside of the assembly Room, served no other purpose.

Building 875 is shown during construction in Fig. 75. The photograph is dated August 1973; and two men are standing in the southwest corner. The building is almost finished in the photograph, lacking only its roof. The outside dimensions are 18.4 m (north/south) by 16.6 m; and it stands 5.33 m high. The interior of the building contained two filter plenums; and these are also seen. The smaller had two banks of filters and filtered air drawn through the Cold Area of the building. It measured 6.7 m long by 4.2 m wide and 3.2 m high. This plenum was labeled “FP-01.” This air had passed all the way through the Hot Area via a large duct but was nowhere opened to the Hot Area at any point. Thus, its interior was certain to be uncontaminated. The longer plenum, labeled “FP-02,” had four stages of filtration and filtered all air drawn from the Hot Area. That plenum was 10.1 m long and 3.5 m wide. Both appeared to be the same height.

A chamber with an anti-chamber existed in front of the each bank of filters in each of the two-stage and four-stage plenums. This was designed for occasional personnel access to change the bank of filters. Two chambers probably were designed to provide access to filters while the system was operating without upsetting air pressure differentials, although they may have merely provided



*Fig. 75. The tiny sheet metal filter plenum of 1964 was replaced by a huge concrete building, Building 875, as a direct result of the Rocky Flats fire of May 11, 1969. The building was under construction in August of 1973. The shorter plenum inside the building would filter air drawn from the Cold Area. The longer one would have four stages of filtration for air from the Hot Area.*

better contamination control as “hot” filters were changed. The support structure for the front 3 x 3 matrix of filters for the two-stage plenum, but without filters present, is shown in Fig. 76. The view is through the door between the anti-chamber and the inner chamber. Successive filter banks (two or four) were separated from one another by about 1.5 m, the inner chamber width. Air entered this chamber at a very high rate of speed; so a conical diffuser (Fig. 77) was employed to avert a direct blast onto the face of just one filter. That air entered the first chamber through a 460-mm-diameter duct. Combining the size of the duct and the velocity of the wind, a lot of

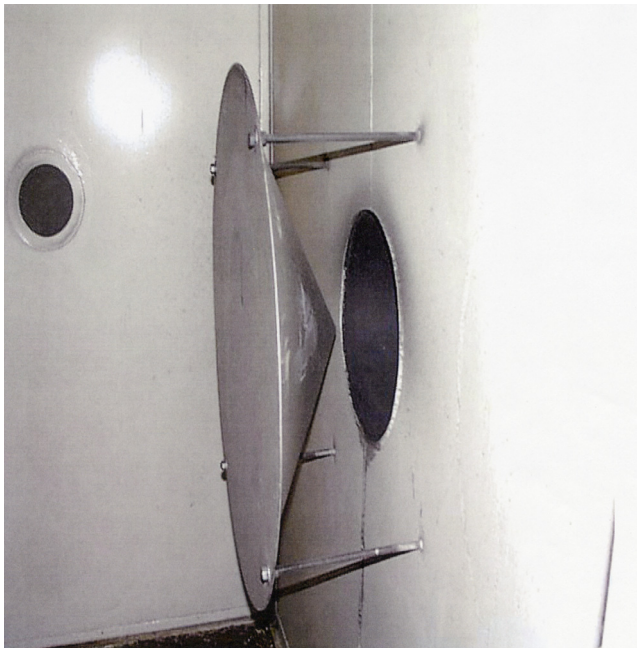
air was being moved at any given time.

A drawing of the building showed an extra chamber apparently preceding the first filter bank for each filter plenum. That is, the four-stage plenum showed five “filter banks” and six chambers while the two-stage plenum showed three “filter banks” and four chambers. This author can not confidently resolve this mystery at all. The only clue comes from one photograph of the inside of one of the plenums showing an array of “De-Mister Screens.” Quite probably, that extra bank of something shown on the drawing was a 3 x 3 matrix of de-mister screens. This detail could be in error.

Air exiting the final stage was really completely free of any contamination. This now-clean air was then discharged up a short stack into the environment. A powerful blower motor was used to create the suction on the building and blow exhaust

air up the stack. Exhaust stacks extended only a short distance above the roof of Building 875. Only one blower at a time was needed for each plenum; but a second served as a backup in case the first should fail. Both were used in alternation to

*Fig. 76. Filters have been removed from the front bank of nine filter locations in the two-stage filter plenum FP-501. The view looks from the antichamber into the chamber containing the filters.*



*Fig. 77. Diffusers just inside the first chamber prevented a strong blast of exhausted air hitting just one filter out of the matrix of nine.*

equalize wear and tear. When one was running, the other was idle. The two blower motors for the Hot Area filter plenum, FP-02, is shown in Fig. 78. With two of four blower motors operating at all times, Building 875 was a very noisy building. People had to shout to one another to be heard; and a time limit existed

for time spent within the building without hearing protection.

One real or imagined concern was that a fire in the Hot Area of the main building could send heated gasses into the exhaust plenum itself. This could, in turn, set the paper filters on fire. Such a scenario could burn the filter medium and remove protec-



*Fig. 78. Two blower motors provided suction on each portion of the building (Cold Area and Hot Area) through each filter plenum (Fp-501 and FP-502); but they were used in alternation. One was operating while the other was idle.*

tion against radioactive contamination being released up the exhaust stack. To prevent that seemingly unlikely catastrophe, the front surface of the first filter bank was fire-protected by a sprinkler system. An overheat condition in that first chamber would automatically trigger the sprinkler system; and the at-risk paper filters would be wet down by a fire-suppression water spray. If de-mister screens did, in fact, precede the first filter bank, then the region protected by this water is not certain. Water may have sprayed on screens or filters; but this detail is not certain.

Exactly how water would affect filtration remains a mystery because the water spray never functioned. Two concerns seem obvious: water-laden filter paper may preclude the flow of air altogether and soggy filter medium might tear away from the wooden frames producing the same effect as a fire. The validity of these concerns is not at all known.

This fire-suppression safety measure precipitated another and independent safety concern. That same front bank of filters might well contain collected particles of fissile material. The water could dissolve this contamination forming a fissile solution. The worry was that a criticality accident could occur if the water collected deep enough and the concentration became high enough. This seemingly improbable scenario could be avoided by collecting the fire-suppression water in a critically safe tank. This was accomplished by installing a drain in the floor of the front chamber and collecting the water in a very large, Raschig ring filled, below grade, collection tank. This large-diameter stainless steel tank could hold many thousands of liters of fire-suppression water.

This author does not have much confidence that the entire fire-suppression scheme just described would ever have

worked as hoped. Two concerns were stated above. In addition, the huge ring-filled tank required the same maintenance (Raschig ring inspections) procedures as every other fissile solution storage tank on plantsite; and it also begs the question: what happens to excess water when the tank becomes over full?

The new Filter Plenum Building (875) and Building 886 were connected by an underground tunnel. The main purpose of this tunnel was to convey the two large-diameter exhaust ducts (from Cold and Hot Areas) from Building 886 to their respective filter plenums. The tunnel contained many other lesser connections; but these seem unworthy of further comment. One short exhaust duct did pass between the Waste Holding Pit (described later) and an exhaust duct; and this is important because it figured into one of the Anomalous Events discussed in another chapter. The tunnel was adequately wide (about 2.3 m) for people to walk through without bumping into things. Its floor was 4 m below the floor of Building 875; and this was the level on which the fire-suppression water-collection tank was installed. The difference in elevation provided a convenient gravity drain for the water.

Actually, the part of the tunnel close to Building 886 rose above grade and is shown during construction in Fig. 79. This photograph was taken in May of 1974; so the new plenum building probably went "online" sometime that summer or fall. The dogleg left of center in the photograph is the place where the tunnel transitioned from below to above grade. The tunnel's working cross section was about the same at both levels. The photograph was taken before the above-grade portion was connected to the south wall of Room 103 and the west wall of Room 101. In fact, the original sheet metal plenum



*Fig. 79. The new Building 875 connected to the CML via an underground tunnel which rose above ground at the dogleg to the left of center. The above-grade portion has not yet been connected to Building 886. The top duct will bend and connect to the short penetration in the south wall of room 103. This will exhaust the Cold Area. The lower will connect to the duct (far right, below center) shown still connected to the original sheet metal plenum building. (May 1974)*

building has not yet been removed (lower right) nor has the exhaust duct from the Hot Area Rooms 102 and 103 (far right) been rerouted. It will later connect to the lower of the two ducts extending from the temporary wall at the exposed end of the tunnel. The new duct exhausting the Cold Area is shown projecting through the south wall of Room 103. It will turn 90° and connect to the upper duct of the two in the tunnel.

Building 875 had one other small filter plenum in its southwest corner. It was designed only to provide a negative pressure to the building itself. The small plenum was labeled FP-503 and occupied 4.9 m by 1.9 m of floor space. The floor plan for Building 875 is presented in Fig. 80 as it existed in the mid-1970s. The L-shaped wing north of the north Airlock served as a windbreak. Winds in Colorado can become very strong; and this windbreak was an attempt to provide some protection as the building was exited.

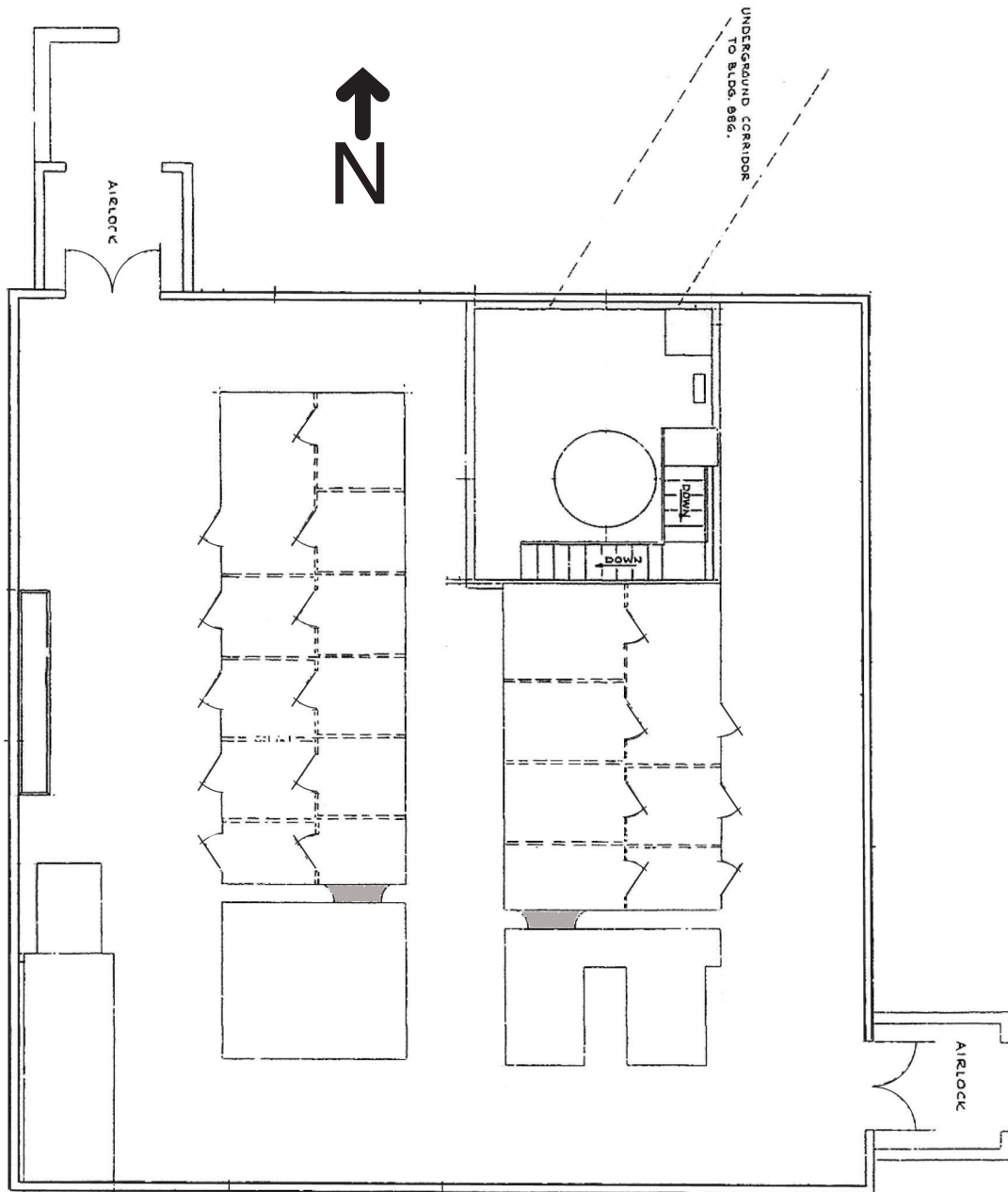


Fig. 80. Building 875, the replacement filter plenum building, probably went into service sometime in 1974. The longer plenum serviced the Hot Area; the shorter, the Cold. The small plenum in the southwest corner maintained the building, itself, at a negative pressure. Water from the fire suppression system at the first stage of filtration would have been collected in the large-diameter tank shown in the bend of the stairwell.

### Holding Pit

Another ancillary structure was the below-grade Holding Pit about 9 m west of the west side of the building. It was

originally designed to hold three Raschig-ring-filled “Holding Tanks” associated with CML activities inside the building. One held possibly contaminated waste waters but nothing that could be called

fissile solution. The other two were originally intended to hold fissile solutions (one for uranium and one for plutonium). The naive intention of these tanks in 1964 was that they would receive irradiated fissile solution following an accidental prompt criticality accident somewhere in the building. They would store it for a few weeks or months until the radioactivity had decayed to a low enough level that experiments could, once again, resume. Then, the “cooled off” solution would simply be pumped back to storage; and programs would continue as though nothing had happened. The fissile solution would be out of service for only that short interlude—viewed as merely a nuisance interruption. Enlightened thinking as early as the 1970s recognized that such a naive resumption would be highly unlikely if such an accident were to happen.

The Waste Holding Tank was, indeed, used for its intended purpose for over a decade; but the other two, not. The would-be plutonium solution holding tank was removed sometime in the early 1970s; and little more will be said about it. The other tank remained but with an uncertain future. Perhaps it could serve as a second Waste Holding Tank. At one point, it was considered to be a tank where solution concentrations could be *increased* through some kind of evaporation process; but that application will be discussed later. At any rate, the tank ended up essentially unused throughout the entire three decades on CML lifetime.

The Holding Pit was a simple concrete box mostly buried under ground. Interior dimensions were 5.18 m long (north/south) by 3.05 m wide. It was 4.27 m tall from the top of the floor to the underside of the “cover.” Walls and floor were 0.3 m thick. The cover was 0.15-m-thick concrete cast into three equal segments, each slightly wider than one-third the length of the

room. The full cover overlapped the walls a little. Each cover segment was cast within a welded rectangular frame of structural steel channel stock. The very top of the underground pit rose 0.4 m above the nominal grade level. It is shown best still under construction in the 1964 photographs at the beginning of this chapter. The three-sectioned cover was designed that way so that a portable crane could be brought in to lift each of the sections and set them out of the way if access inside the Holding Pit were ever needed for some reason. This design feature was never utilized until the end days.

The Waste Holding Tank was numbered #440. It was Raschig ring filled and generally followed the design of the first four uranium solution tanks except larger. The liquid capacity was 1000 liters. It had a dished bottom and a flat cover bolted onto an external flange. The other two were assigned numbers #449 and #459. The Uranium Solution Holding Tank (449) was identical in size, shape, and capacity as the Waste Holding Tank. The Plutonium Holding Tank (459) was much smaller and removed even before it ever could get dusty.

To summarize the CML’s routine tank numbering scheme, the nine solution storage tanks in the Mixing Room were numbered #441 through #447 and #451 and #452 which were located in the stainless steel room along the west wall. The tanks in the Assembly Room, always considered “auxiliary tanks” which could serve various uses such as extended storage, special program tanks, and additional SCRAM capacity tanks, were numbered #540, #541, and #542. The three tanks in the Holding Pit were #440, #449, and #459. All these seemingly arbitrary number assignments perhaps give some clue as to the admittedly weak numbering scheme conceived by this



author so many years ago: Tanks numbered in the #400's were *not* located in the Assembly Room whereas #500-series tanks were located there. Ignoring the first digit, then, tanks in the #40's were associated with uranium solution while tanks in the #50's were intended for plutonium solution service. Ignoring the first two digits next, tanks ending in zero were to be waste-collection tanks, those ending in numbers 1 to 8 were routine solution storage tanks, and, finally, tanks ending in 9 were considered holding tanks for irradiated solution following a nuclear excursion. This numbering system bore little resemblance to the actual use-history of the tanks in question.

Two below-grade lines connected portions of the building with the Waste Holding Tank (#440). One was a large-diameter line connecting to the Assembly Room. The original thought was that this large-capacity tank would hold possibly contaminated water (but not fissile solution) after an experiment. The water might have served, for example, as a neutron reflector. The original drawing for the facility had even called for a "Tamper Tank" which was to have been a cylindrical shell around some other tank which could be filled with water as a neutron "tamper," that is, a neutron reflector. This approach to neutron reflection was never used; so this nominally 76-mm-diameter line<sup>56</sup> was also never used. The second below-grade source of waste water to this same tank was a smaller line (nominally 25-mm-diameter) coming from the Mixing Room. It led water from the laboratory sink, the safety shower and eye wash station, a cooling-water jacket to the ultrasonic cleaner incorporated into the plutonium metal handling facility, and a couple of other

places in the Mixing Room to that tank for interim holding of possibly-contaminated water before disposal. Only *slightly* contaminated waste water ever flowed through this small-diameter pipe; and the volume discarded was also quite low. One estimate is that not three grams of uranium ever flowed through that buried line during the entire years of service. This line from the Mixing Room did not enter Tank #440 directly. Rather, it connected with the larger line, discussed first, just outside the Holding Pit. Whether or not any of this slightly contaminated waste water ever flowed backwards toward the Assembly Room, contaminating some length of this otherwise never-contaminated pipe, is not known. The possibility exists and was considered by demolition personnel.

The other two tanks were intended as fissile solution holding tanks. One (#449) would serve enriched uranium; the other (#459), plutonium. Both were connected to the Mixing Room by separate nominally 25-mm-diameter below-grade lines. The two buried lines lay close to one another the whole distance between the Mixing Room and the Holding Pit. The two lines left Room 103 just above floor level of the depressed pit housing the storage tanks. The lines passed through concrete walls at the southwest corner of this room. The two lines entered the Holding Pit still close together. Only inside the pit did they split and feed different tanks. The line serving uranium purposes led to Tank #449, essentially identical to the Waste Holding Tank. The line serving plutonium purposes led directly to Tank #459 which was much smaller (100 liter). This line was flanged closed at both ends when the plutonium tank was removed before it ever had any chance to be used.

<sup>56</sup>This is the line discussed in the Anomalous Events chapter which broke before the building was even finished due to heavy truck traffic close to the building. It was replaced by stainless steel, although even that line was never used.

### *Portable Waste Water Disposal Tank*

Collected waste waters in Tank #440 had to be disposed of; but this detail had never been incorporated into the original design of the facility. That 1960s design did include an output line from the tank which passed through the north wall of the Holding Pit, still below grade, only to make an upward turn to a capped-off screwed connection just slightly above grade a fraction of a meter north of the Pit. This nominally 25-mm-diameter stainless steel line might be called the Holding Pit Standpipe. No provision had been considered for connections to that waste water discard Standpipe in 1964.

That problem was soon addressed, however, once the facility began operations. The solution was to construct a horizontal tank which would be called the “Portable Liquid Dumpster”(PLD) tank. Accurate dimensions are not known, no photographs can be found, and the tank no longer exists; so the following general description will have to suffice. The tank was a horizontal right circular cylinder rather than a vertical one. It was a little more than a meter in diameter and, perhaps, two meters long. Both ends were dished and fitted with lifting lugs. These lugs were made to match the lifting features of the plant-wide trash hauling trucks. In use, then, waste waters would be transferred to this tank, and the plant’s trash collection group would lift and haul the now-full tank from its concrete pad to the plant’s Evaporation Pond which was used by many other buildings for evaporative disposal of very-low-level possibly contaminated waste waters.

The horizontal PLD tank rested on two wide pads, spaced a distance apart and gusseted to the tank’s body for strength. This stable construction defined a “bottom”

to the tank, provided a sturdy support for it, and kept it from rolling about. The top of the horizontal tank, diametrically above, had a central raised port, a good fraction of a meter in diameter; and this dome was closed off with a flat circular cover. Except for wheels, this overall design somewhat resembled a modern-day railroad tank car with a single raised dome.

A fill connection in this dome allowed a coupling to the Holding Pit Standpipe so waste water could be pumped from Tank #440 directly into the portable tank. A few-meter-long length of flexible hose (much sturdier than a garden hose) was used for this transfer. The tank was vented to the atmosphere through a filtered vent line along the top of the PLD tank. Finally, a valved connection close to the bottom of the tank could be used to allow waste water to drain harmlessly into the Evaporation Pond.

The design worked well during its several years of use. Water held in Tank #440 would be mixed and sampled before being transferred into the PLD tank. This water never proved very high in fissile content. Contamination was measured in “disintegrations per liter” rather than any fissile concentration in “grams per liter.” In spite of this proven low fissile content, Management insisted that the tank be filled with Raschig rings as an additional criticality safety precaution. These rings were introduced through the raised dome. This conservative decision at least postponed any (extremely unlikely) criticality accident until after the waste water had left the CML facility’s perimeter fence. Once the water was transferred to the PLD, the truck would pick up the entire unit and haul it off to the Evaporation Pond. Once drained, the now-empty tank would be returned to await the next service. It was usually returned the same day or the next. Records show that

only a hand full of transfers were ever made in this fashion; and the total amount of uranium ever to pass through this entire process was less than three grams.

This procedure was abandoned when the plant decided it no longer wanted to maintain an Evaporation Pond for any building's use. This plant policy was probably a response to an environmental criticism; but this political question is not known for certain.

The approximate size of the PLD tank can be estimated from one recalled fact and one estimated ratio. The tank is recalled to have contained "500 gallons" including its Raschig rings; and a mental image of the tank recalls that it was, perhaps, 50% longer than its diameter. Combining these tenuous notions implies that the PLD tank may have been about 1.3 m in diameter and 2 m long. Those estimates seem reasonable to this author's recollection.

The PLD tank rested on a special concrete pad poured especially for that purpose just off the curved driveway that extended all the way around the west side on Building 886. This driveway connected the parking lot at the north of the building with the southern access to the Assembly Room, discussed much earlier in this chapter.

### *Evaporator*

With the Uranium Holding Tank not needed for its original purpose, another use for Tank #449 was proposed. This novel concept would free experimenters to reduce uranium solution concentrations whenever desired by simply adding water. Concentrations could be tailored to suit existing equipment rather than requiring new apparatus be made to suit existing uranium solution concentrations. The new concept would also reduce the number of

uranium concentrations routinely maintained in the storage farm in Room 103. A single maximum concentration—in the vicinity of 400 gU/liter—could be maintained and any lesser concentration easily prepared for a specific experiment. The temporary new concentration would be formed by diverting a determined volume of "stock" solution into an empty tank and adding just the right amount of water to produce the desired concentration. This brand new concept would greatly simplify storage and handling issues. It would also reduce time spent on periodic solution inventories. Finally, it would reduce the overall volume of fissile liquid stored. Instead of separate 1000-liter holdings for three different concentrations, the entire inventory of 560 kg could be contained in about 1400 liters of 400 gU/liter solution.

That brilliant proposal was to install a Solution Evaporator somewhere. The evaporator, then, could be used to reconcentrate the temporary reduced-concentration solution back to stock concentration. This idea evolved principally because Tank #449 sat idle in the Holding Pit and was still plumbed to the storage farm in Room 103. The procedure would be simple. The temporary concentration, after it had served its purpose, would be discharged to this now-idle tank. It would be continuously cycled through the evaporator with the removed water collected in the Waste Holding Tank (Tank #440) until a concentration close to the stock value had been achieved. Then, the reconcentrated stock solution would be pumped from Tank #449 back to Room 103.

Several models of evaporators are commercially available; and each had advantages and disadvantages. The operational principal selected was met by a commercial firm called Rototherm®. Their unit was called a "Thin Film Wiping Flash

Evaporator”. Here, a cylindrical ring of low concentration solution was to be wiped continuously against a steam-heated jacket surrounding the outside of the rapidly rotating ring. Wiper blades welded to the rotating inner cylinder would wipe a thin film of the solution against this static hot jacket. This would cause steam to flash away from the feed solution only to be condensed and ultimately collected in Tank #440.

Again, precise dimensions of the commercial device are not known; and it has been long gone from the facility. It was first installed in May of 1968 and removed but a couple years later. Because of the time passed and poor record keeping, the following general description will have to suffice.

The commercial Rototherm unit was, perhaps, just about a meter long. The rapidly rotating (1100 revolutions per minute) inner sleeve, called the rotor, was a length of stainless steel thin-walled *pipe* nominally 100 mm in outside diameter. Four wiping fins were welded along elements of this pipe at 90° intervals; and these were about 25 mm in width. As the rotor rotated, the four fins left a thin film of liquid, possibly a millimeter thick, against the static cylindrical shell outside the rotor. This shell was the steam heated jacket referred to above. The inside diameter of this jacket was about 150 mm; and the outside diameter of this steam chamber is recalled to have been, perhaps, 300 mm in diameter.

The ends of the meter-long rotor were welded closed with circular disks; and concentric axes extended out either end to allow rotation cushioned by a delicate set of carbon bushing bearings. Both ends of the steam jacket were also welded close by still-other circular disks; and these (static) disks contained the above-mentioned

carbon bearings. Steam inlet and outlet connections kept a fresh supply of hot steam available for flash evaporation. The design for admitting feed solution into the 25-mm-thick rotating annulus and removing the concentrated solution is not recalled; but some design did exist.

The theory seemed sound. Past commercial units apparently had a good “track record” as reported by the company. The entire system was installed against the east wall of the Holding Pit. The useful and innovative new feature was turned on for a test operation with great expectations. This maiden run involved no fissile material just to ensure everything worked as expected. These hopes, however, were quickly shattered along with those fragile carbon bushing bearings.

The reason for this failure of the carbon bearings was not immediately clear to anyone. The company could not explain it; nor had they ever encountered a similar failure before. Staff at the CML, usually quick to understand physical phenomenon, were puzzled and perplexed. Soon, however, the true nature of the difficulty emerged.

Months earlier, when shown the design of the commercial evaporator, CML management balked at the hollow core of the spinning rotor. This Manager worried that a leak into this normally vacant region could possibly permit a full cylinder of high concentration solution forming within a 150-mm-diameter region reflected by a thick blanket of water. That cylinder might be about a meter long; and his concern, of course, was to guard against an unplanned criticality accident. His required resolution of this dilemma was to insist that the manufacturer simply replace the hollow rotor with a solid one. No one recognized flaws in that demand and the company agreed to the substitute design; so the

Thin Film Wiping Evaporator was installed in the Holding Pit with a heavy solid rotor in place of a lighter hollow one.

Early testing of the design—much different than the manufacturer intended—revealed that the rotor's graphite bearings could not withstand dynamic forces resulting from this much more massive rotor. Moments of inertia are different for solid and hollow cylinders; and the physical consequence is especially large while spinning at 1100 revolutions per minute. These carbon bushings broke readily in response to the more-difficult-to-balance dynamic forces trying to control the heavier, fast-spinning rotor. The lesson learned from this unusual situation is that engineering design changes intended to reduce one improbable risk may introduce a new and unforeseen concern.

Sadly, this new wrinkle in CML operations had to be abandoned; and an expensive piece of equipment was discarded without ever generating any useful product.

## Storage Shed

Building 886 did not contain anywhere near enough storage space. Experimental apparatus, old equipment from completed programs and new items for future studies, and a wide variety of other objects related to CML activities had no place to go. An inexpensive storage facility was proposed to ensure it would be included in the plant's budget. The frugal result was a sheet metal building built upon a concrete slab without heat, insulation, lighting, electricity, water, gas, or any other amenities. The building was, in fact, exactly the type bought by small American farms to store farming equipment out of the weather. The Butler Brothers® building cost \$14,000 in the late 1960s. It was simply called the Storage Shed or Building 880.

The 9.1 m by 5.5 m single story building (3.7 m tall) had three windows to admit some light during daylight hours. It was almost never accessed at other times. It had two doors. A personnel door existed near the east end of the long north wall; and a mechanically-driven roll-up garage-sized door filled the shorter east wall. This equipment door was operated manually using a chain fall drive. The roof was also simple sheet metal over spaced trusses and was not insulated. The roof pitch was not steep. The building was built upon a simple concrete slab. No effort was spared to keep cost down.

The manually operated door was the frequent source of troubles involving birds. They would often build their nests in the covered housing designed to collect the door segments as the chain fall raised the roll-up door. These nests would be torn apart as the metal collected causing nesting materials to flutter down upon operators. Neither birds nor operators were pleased. Sometimes, so many nests existed that the roll-up door became difficult to raise.

Many items were stored in this shed; and some of them are especially worthy of note. A row of heavy-duty steel shelves were built close to the short west wall; and a couple more shelves lined the north wall. The latter contained many components from sets of nesting mild steel and boron-alloyed stainless steel hemishells. These were identical in dimension to the fissile shells described elsewhere in this book; and the intent was, of course, to couple fissile metal against steel components to vary the conditions of experiments. These shells, then, had been in intimate contact with both enriched uranium and bare plutonium metal. They had been, therefore, contaminated at one time. The shells were "decontaminated" and wrapped in plastic bags before being stored; but two cautions seem prudent at this time. First, these bags

quickly deteriorated and disintegrated, exposing once-contaminated surfaces to the environment; and, second, surface decontamination efforts in the 1970s may not have removed deeply seated contamination for the 1990s. Shells exposed to plutonium metal had been “pickled” in acid in an effort to remove any contamination soaked into the metal’s surface. Surprisingly, these metal hemishells are not recalled ever to have been a source for any contamination within the Shed; but this fact is considered more good luck than good planning.

The Shed also housed a set of 103 boron-alloyed stainless steel plates. These had been immersed in uranium solution during the very first experiment involving that medium. They had been exposed many times for long periods. Although heavy contamination had been washed away before being stored, the plates’s rough surface, sheared edges, and hidden notches would have made a thorough cleaning very difficult. Some residual contamination is almost certain to have remained. These plates were stored in the Shed for decades in a wooden box loosely lined with sheet plastic.

Many past experiments had used cast concrete panels as neutron reflectors; and these panels would or could be used again on future experiments. These panels came in sets of several; and at least two sets of different size had been made over the years. Considerable floor space within the Shed was consumed with this storage. Some of the concrete was known to have been mildly contaminated during earlier use; and this contamination was painted over in an effort to fix it in place.

Used and spare plumbing hardware was stored in the Shed as well; and this mostly included manual and automatic valves associated with the uranium solution handling system. Unused pieces rested on

shelving; but contaminated (used) valves were contained in sealed drums. In spite of the ongoing storage of many once-contaminated items, the Shed is believed to have remained surprisingly free of casual contamination throughout its lifetime.

The Shed was the repository for new equipment awaiting introduction into the building. Perhaps the largest of these items was the very expensive next-generation Annular Tank which, as history evolved, never actually was used. The tank was so expensive because it was machined to final dimension rather than just rolling plate stock and welding its edge. Precision on finished dimensions really pushed the capability limits of the manufacturing industry. This huge tank was so precisely machined that even its delivery route and date from California were carefully selected to avoid temperature and pressure extremes which might alter the finished product. This masterpiece of the manufacturer’s art sat, crated within a wooden box, within the Storage Shed for several years while the plant lost its battle toward “Resumption” of normal plant operations.

The Shed was never a tidy place. Old and new equipment, contaminated or not, were intermingled and strewn about leaving little more than a labyrinth walk way within the building. Items were piled upon one another almost reaching the ceiling. Stored items included many deserving storage; but this author confesses to keeping some items more out of a sense of history or nostalgia or the wishful—but improbable—hope they might again someday be needed. He does tend to be a “packrat” as testified to here and in the foolish retention of the low-enriched uranium oxide long after that program had been finished.

As crowded as this building was, it was not enough. A few years later, a commercial Cargo Carrier was purchased to provide additional storage space for smaller items. This Carrier is similar to those often seen transported across the country on railroad flat cars. In addition to storing experimental apparatus, hardware, and some electronics, this Carrier was used to store out of the weather the pair of commercial Roller Conveyors used whenever heavy components were to be introduced into the Assembly Room through its south door. A fork lift truck would carry these conveyors from their storage roost to align them such that they might carry heavy loads from the concrete pad outside the building into the interior of Room 101.

Storage space was so scarce that the Cargo Carrier was not situated immediately adjacent to Building 880. Instead it was offset a few meters north to permit a two-sided enclosure and simple roof to provide minimal weather protection for a few items of storage. This simple construction happened in the spring of 1981. The Storage Shed, Cargo Carrier, and the enclosure between the two are shown in the wintery photograph of Fig. 81. This 1994 photograph shows that still some weather-resistant items had to be stored on pallets out of doors. Access to all three storage areas faced east which was a concession to the fierce winds often found blowing from the northwest across plantsite.

Several years later, probably in the late 1980s, a second Cargo Carrier was installed; but this was primarily intended for used office equipment and need not be discussed further. This Carrier was located a couple meters east of the Assembly Room with its access face coplanar with the south wall of that room.

All this clutter remained long after the eventual demise of the CML had become a certainty. In fact, the new millennium would arrive before most of these stored items could be disposed of.

### ***Sewage Lift Station***

A final ancillary building was the one associated with sanitary waste removal. This cinder block building measured only 2.4 m by 2.8 m and was several meters west of the building slightly north of center. It can be seen to the far left in Fig. 16 (top). The building warrants no further discussion.

### ***Transformer Pad***

Building 886 had its own electrical substation. High voltage came to this pad located several meters west of the building about in line with its north end. Transformers there provided 480 Volts to the electrical breaker panels along the north wall of room 111 as described earlier in this chapter. The transformer pad was always enclosed by a chain-link fence for safety because of the high voltages within; but later, during the years of grave sabotage concerns, that fence was topped with spirals of razor ribbon wire

### **Fences**

As constructed in 1964, the entire building was surrounded by a 2.44-m-high chain link fence with three strands of barbed wire at the top. This served as a security fence. Distances from the fence to various faces of the building are: north–5.5 m, east–30 m, south–28 m, and west–27 m. An additional east/west fence separated the experimental area to the south from the office area on the north.



*Fig. 81. The Storage Shed was a simple sheet metal building built upon a concrete slab. The commercial Cargo Carrier to the building's left was displaced a few meters to permit construction of a two-sided enclosure to produce a little additional storage area. Still, many items were simply left out in the weather. The four black objects against the west wall of the Shed (right) were neutron reflector/moderator pieces associated with the Shielded Annular Tank program. The nearly square,  $H=D$ , stainless steel tank (center) had been used for a number of non-fissile experiments involving Raschig rings. That important study investigated the size of void spaces within a bed of rings which might go undetected during a standard plant volume-calibration of such a tank. The surprising result of this study was that a critically large volume could escape detection unless careful scrutiny of the calibration data was performed. The grey drums in the background stored boron-rich earthen materials often used in casting plaster or concrete components for nuclear experiments. (February 1994)*

It served as an “exclusion area” fence. When experiments were being performed, gates were to be locked to preclude personnel from entering close to the outside of a building inside of which a critical experiment would be in progress. This secondary fence was 20 m south of the north fence on the west side and 11 m south if it on the east.

Sometime in the 1970s, this internal fence was removed from both sides. Calculations had shown that the Assembly Room was so effective at shielding radiation from a hypothetical accident, that a person immediately on the other side of a wall would receive negligible dose. In retro-

spect, this may not have been true for all accidents in all likely areas of the building. A solution criticality accident in one of the storage tanks along the west wall of the Mixing Room may have led to some radiation just outside that wall. The back-filled cinder block wall may not have adequately protected a person standing just outside it. The point is mute, now. No accident occurred; and the potential is gone. Nonetheless, that secondary fence did not exist during most of the 1700 critical experiments performed at Rocky Flats.

The government became increasingly concerned over safeguards and security at



all its nuclear installations country wide in the late 1980s and early 1990s. The threat of terrorist attack appeared more real as did concern for internal espionage. To counter these concerns, safeguards measures over the entire plant were greatly enhanced. Measures were also incorporated at the CML. A spiraled band of razor ribbon wire was installed all around the existing fence perimeter. The relative thin and vulnerable roof of the Mixing Room was similarly protected with an area of this material. Other measures were taken inside the building; but these will be discussed elsewhere.

## Building 986

Governmental concerns grew so much that the unfortunate set of circumstances which ended up with Building 886 outside the Perimeter Secure Zone (PSZ) prompted concern over the plant's ability to safeguard this one separated building on top of those within the PSZ. The CML was the only building on the south side of Central Avenue to hold considerable quantities of Special Nuclear Material (SNM). For years, the plant duplicated efforts. Whatever was done inside the PSZ was repeated, at least in principal, for Building 886. This effort is what prompted the concertina wire above the fence surrounding the building's perimeter as well as the same wire coiled on the roof above Room 103.

Safeguards concerns, coupled to the existing facility's shortcoming with respect to its inability to perform plutonium experiments produced an exciting idea. The construction of a *new* CML was proposed. This new CML—Building 986—would be built *inside* the PSZ and would enable experiments with both uranium and plutonium. The idea immediately met with

much applause by the staff of Building 886. It garnered enough support from Rocky Flats plant management to put the notion on the plant's capital improvement budget proposal. This all took place somewhere in the early- to mid-1980s.

Building 986 would be built inside the PSZ on a hill just to the west of Building 991, the plant's shipping and receiving building for fissile material. The hill would play an important role, described later. CML staff set out vigorously—and with naive confidence that the new facility was all but a certainty—to design a “dream laboratory.” There would be two experimental wings—one for uranium and one for plutonium. Each wing could handle solid metal, fissile solutions, and any physical form in between. It would be much larger and would benefit from some of the learned shortcomings of the existing CML (more storage space, facilities for preparation of apparatus, etc.). Both wings would share a common, albeit larger, Control Room wherein all the latest advances in technology could be found. It would contain state-of-the-art electronics and high-definition TV.

The dream would use methods other than just the reciprocal multiplication technique for the safe approach to and the attainment of criticality. Toward that end, a neutron generator was to be included; and this would produce bursts of neutrons via the neutron stripping reactions (d,d) and (d,t). The dream escalated to the notion that the lab might even perform prompt critical experiments.

The hill on which the facility would be sited was to serve a useful purpose. Fissile solution storage tanks would be built on the lower level with experimental rooms (Assembly Rooms) built on the plateau. Solution would have to be pumped uphill to the experiment and could drain under

gravity back to storage. In summary, Building 986 would be a state-of-the-art critical mass laboratory with a projected long history of useful safety-related experiments for the national good.

The new facility was recalled to have been expected to cost \$20 million. Every year, however, the proposal was bypassed by Congress, and the projected cost increased. In time, the whole project was scrapped as being too expensive for its projected benefit. By way of comparison, the brand new Building 86 only cost \$870,000 in 1964 dollars.

By the time the Building 986 doors closed before opening, the technical design had progressed pretty far along. Equipment to be purchased was even identified by model number and cost. A talented Rocky Flats artist from the Graphic Arts Department had drawn an imaginative frontal facade including the two taller towers for the Assembly rooms behind the Office Areas.

The following thought may have been part of the original thinking behind Building 986; or it may have generated following the cancellation of the proposal. This detail is not recalled these many years later, although it probably was the latter. The notion was that whatever form the CML took at Rocky Flats, it might, in some sense, become a northern component of the criticality facilities at Los Alamos National Laboratory. One might even call it "LANL-north." This concept could have been extended throughout the entire DOE complex of criticality facilities. It could have included the CML at Hanford, Washington. Under this plan, Los Alamos (LANL) would focus on special programs, unique situations, prompt critical experiments, training, and a number of other programs. They would, however, relinquish all experiments relating to uranium studies

to Rocky Flats; and all studies involving plutonium would be performed at the facilities at Hanford, Washington.

Advantages of such a distribution seem obvious. There would be less duplication of expensive facilities throughout the DOE Complex. Each facility could focus on a single material responsibility. The occasional programs involving critical systems using each fissile material could be done at two different laboratories but by the same experimenters. The government would also benefit from less duplication of SNM holdings; and inventory and safeguards problems associated with different materials would not have to be duplicated.

The idea had a lot of merit in this author's opinion. In truth, however, the concept was probably never discussed seriously outside of Rocky Flats. Whether or not this idea would have had merit remains debatable; but, obviously now, the debate is mute.

## **Deactivation**

### **< Decommissioning**

### **< Decontamination**

### **< Disassembly**

### **< Demolition**

As early as the early 1980s, one member of Rocky Flats' top management, a gentleman named Art Benjamin, repeatedly asked this author: "How and when are you planning on ever getting rid of your uranyl nitrate solution?" This annoying question was easily dismissed with a confident reply: "Never!" He pointed out that the need for critical experiments will continue far into the foreseeable future. He confidently argued that the Rocky Flats CML would continue to contribute to the nation's stockpile of useful nuclear safety data for many, many decades. Either arguments were convincing or the question was more

rhetorical because the conversation usually ended there.

Evidently, this author was not a successful prophet. Though arguments still stand, the direction the nation has chosen has been determined. Even though criticality safety engineers continue to use computational schemes which have not been fully validated by direct comparison with precision measurements, Safety Limits—based on these computed results—are written daily at Rocky Flats and other DOE facilities. Hopefully, the nuclear industry will be lucky and avoid encountering those few hard-to-recognize situations where the vagaries of criticality safety might lead to a nuclear excursion in one of its facilities. A disquieting thought is that criticality safety may come down to a matter of luck.

The long-term continued functioning of the Rocky Flats CML was naively assumed well into the 1990s. This expectation is testified to by several activities in and around the CML. First, the December 1989, triennial inventory of uranium solution was performed in arduous detail and fully in anticipation of another three years of productive research. Storage tank maintenance had been performed. Raschig rings had been inspected, and their incorrectly-determined “failure” (to satisfy boron content specifications) was viewed merely as an annoying deterrent to getting on with planned programs. During the inventory, solution properties had been both accurately and precisely determined to begin another next three-year’s studies. Second, replacements for the 125 plutonium metal cylinders (which had been returned to the production stream in 1983) were designed and ordered. Even an allotment for over 300 kg of weapons-grade plutonium metal had been set aside for this purpose; so the plant, evidently, also

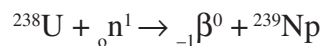
anticipated continued research. Even new double-containment housings for the new 3 kg plutonium metal cylinders were made. These would be a great improvement over previous containers which had contained too much stainless steel. New ones were much thinner without sacrificing contamination control. They had been carefully engineered to tolerate the physical phase changes of the mysterious metal as it experienced thermal cycling. The new cans would be welded shut using electron-beam welding. They would be the epitome of good design. About 130 sets of double cans were manufactured during the very late 1980s only to be summarily discarded—never used—a decade later. This author retains one example of the artful design in his personal collection.

Other clear evidence that the entire plant did not accurately read “handwriting on the wall” lies in a term frequently heard on plant site in the years following the FBI raid. Everyone talked about “Resumption” and what had to be done for that to happen. It was used in daily messages, person-to-person conversation, and published propaganda. Almost everyone, from top management to the hourly worker, expected the plant would eventually “resume” production. Alas, that never happened. Even the presidential termination of certain weapons programs in the early 1990s did not precipitate alarm nor point to a recognizable end. In retrospect, however, it may well have been the harbinger of what was blowing in the wind.

## Uranium Oxide

Actually, the first action toward closure of the CML began in the early 1980s—long before any raid or talk of plant closure. The uranium oxide was determined to be removed from the CML. This material had been brought to the lab specifically for a nearly-ten-year-long study performed at the behest of the Nuclear Regulatory Commission. That study ended in the late 1970s; and the material was not really needed anymore. Clear minds suggested its prompt removal; but this author balked arguing that this material *might* come in useful on some future study. Possibly more to avoid paperwork and the physical effort required to ship it, the material was allowed to stand dormant in Room 102 for several years. The decision was eventually made, however, to overrule this author's pack-rat penchant; and an agreement was made with another DOE facility to receive this material.

Before the oxide could be shipped, considerable discussion ensued regarding its possible plutonium contamination. Plutonium could have found its way into the oxide two ways. Building 886 had had a contamination incident involving plutonium compounds (1983); and the uranium oxide could have gotten contaminated simply by close proximity. Second, the low-enriched uranium did contain  $^{238}\text{U}$ ; and some plutonium would be formed when exposed to high fluxes of neutrons via the following nuclear process:



followed by  ${}^{239}\text{Np} \rightarrow {}_{-1}^0\beta + {}^{239}\text{Pu}$

Much discussion was required to convince everyone that neutron fluxes involved in *zero*-power critical experiments were so low that the inbreeding of plutonium was negligible.

Once convinced, the first shipment went to the Fernald Plant in Ohio. This plant previously had been called National Lead of Ohio and had been the original source of the material in the first place. That shipment of a couple dozen cans went so smoothly that the remainder was expected to be shipped out with equal ease over a period of a few months. That did not prove to be the case. The next shipment was packaged in approved shipping containers and transferred from Building 886 to Building 991, the plant's fissile material transportation building, to await offsite shipment. About that time, however, the Fernald plant was experiencing its own political problems. Rumors were heard of military vehicles patrolling the streets of this once-sleepy Ohio village in demonstration against certain plant practices. While dealing with their own problems, they were hardly in a position to receive some more controversial materials from Rocky Flats.

All movement of any of this oxide became frozen for many years. During that time, the original inventory was divided between the Fernald Plant, Building 991 at Rocky Flats, and Building 886, the original location. Finally, the year was 1995 (November) before the last of the low-enriched uranium oxide was shipped out of the CML. It finally found its way to Building 991; but, frankly, its disposition beyond that building is not at all known a few years into the new millennium. This still-substantial holding may have been shipped away from the plant to some unspecified location; or it may still reside at Rocky Flats, adding to that plant's SNM disposal problems.

## ***Uranium Solution***

The first action to truly signify the demise of the CML was the removal of the huge inventory of uranyl nitrate solution. How one transports 560 kg of very hazardous *liquid* across many state boundaries—recognizing that these 3000 liters are sufficient to form about 700 *simultaneous* critical masses—is no trivial question. Where it should go is an equally perplexing wonderment. What shipping containers should be used? What chemical form (liquid or solid) is best for shipment? What type of vehicle should be used? How does the federal government obtain cooperation from intervening states? A couple of years would be required to answer these questions before the physical re-location could even begin.

Every question seemed to be multifaceted. The chemical form to be shipped illustrates the point. Liquids would be easily dispersed into the soil if a vehicular accident should burst open the delivery truck. Major rivers would have to be crossed if it went east; and a release into the Mississippi River might contaminate significant waterways of the world. Clearly, delivery as a liquid presented some serious challenges. Solids, on the other hand, posed far fewer environmental concerns. Still, transporting solids, however, presented two new concerns of its own. Metal would be much more attractive to potential terrorists; and the threat of unauthorized diversion (theft) was considered quite real. Furthermore, operations anywhere at Rocky Flats had been legally curtailed. No “operations” or “production” could take place while this constraint was imposed. The physical processes of converting so much liquid into a large number of metal ingots was viewed by many as a production operation. They argued that

making that conversion would fly in the face of clearly defined constraints.

Another perplexing quandary concerned which “approved shipping container” was to be used. The “FL-10” container looked quite promising on first reading. However, its government-approved certification was about to expire; and it would no longer be “approved” by the time the liquid could be shipped. Another problem was that the container held only ten liters; and the whole nation did not own a sufficient number of them. Multiple shipments would have to be made reusing the existing ones (if their certification could somehow be extended); but this would just prolong the entire process over months or even years.

A new shipping container could easily be designed which would hold more liquid at a time. The problem with that approach lay in the length of time required for governmental certification of any new shipping device. Such testing—and the certain design improvements to follow—could take many years.

The first action along these many and varied lines began about 1992. A working committee was formed consisting of about 15 talented and experienced persons representing many safety disciplines. This author was a member of that dedicated group. In fact, his retirement in March of 1993 required he be re-hired as a consultant immediately in order to remain active in the group. That role lasted about half a year by which time a decision had been reached.

The FL-10 would be used to ship the solution in trucks; and procedures were initiated to extend the container’s legal certification. The solution would be pumped into small sets of FL-10s in the Mixing room of Building 886 and these loaded onto a specially designed truck called a “Safe Secure Transport” (SST).

These trucks would carry twenty-four FL-10s at a time to a nuclear facility located in Erwin, Tennessee. Between 15 and 18 round trips would be required to transport the 3000 liters of feed solution as well as a few hundred liters of rinse water.

The plan seemed good. All committee members felt all loose ends had been properly addressed. The committee was about to disband, congratulating itself on a job well done, when top management at Rocky Flats summarily announced that the plan had been scrapped! The reason was never shared. The committee was merely directed to propose an alternate scheme.

More months of deliberation did produce a second proposal. It was new and innovative. This new proposal would begin by bringing *onto* the plant several thousand liters of *additional* uranyl nitrate solution. This liquid would be almost pure  $^{238}\text{U}$  with essentially no fissile component ( $^{235}\text{U}$ ). The novel plan was to blend the highly enriched solution with the non-fissile solution until a blended enrichment of about 8%  $^{235}\text{U}$  and a concentration of below 20 gU/liter had been attained. This final liquid would be subcritical; so the blending could be done directly in the very large unpoisoned volume of a commercial stainless steel tanker truck. The blending would take place using the Venturi effect wherein the non-fissile liquid would flow past a nozzle sucking into its stream a portion of the very reactive stock solution. The two liquids would homogenize within the delivery pipe before the mixture flowed freely into the tanker truck.

This proposal seemed clever and met with considerable support from persons impressed with its uniqueness. This author and some others were fearful of the approach for several reasons. First, the very novelty of the idea means it had never been

done before. Maiden voyages of new designs seldom sail smoothly. Second, the mixed solution, while admittedly subcritical (and therefore safe) appeared dangerously close to a critical combination of concentration and enrichment. Any small anomaly in the Venturi suction procedure could allow too much fissile liquid to mix with too little non-fissile solution allowing the targeted parameters to be exceeded. Any slight impurities in the mixed liquid could initiate precipitation during the transport of the solution across the country's highways. Precipitation could form a critical fluid volume within the body of otherwise safe liquid. Finally, the thought of transporting thousands of liters of solution west across the country just to turn around and ship twice the volume back east was not comforting.

A couple of years were spent investigating this path. Fortunately, it was abandoned before any actual implementation took place. The calendar read "1995" before the original ploy of using repeated shipments of FL-10 shipping containers was re-adopted.

The first physical act towards removing the uranium solution was to mix and sample it. Homogenization was important to obtain truly representative concentrations of the solution. Accurate concentrations, in turn, were necessary to know how much uranium was being shipped in a given volume. The amount shipped would later be compared with the amount received at its final destination in Tennessee. Whether or not the two concentrations existing after the December 1989, precision inventory were blended into a single concentration (about 200 gU/liter) or was left as two distinct holdings is not known to this author. The point is relatively unimportant though, because the shipping

container used was approved for either contingency. This mixing and sampling was completed in September of 1995.

The solution was transferred, a small portion of a tank at a time, to a portable device called a “Bottle Skid.” This framework held three fixed-in-place cylinders; and each of these held enough liquid (10 liters) to fill a plastic cylinder which would later become the central element of the packaged FL-10 shipping container. The bottle skid remained on the upper level of the Mixing Room as illustrated in Fig. 82. The solution transfer process was very slow and spanned the remainder of 1995, all of 1996, and a good fraction of 1997.

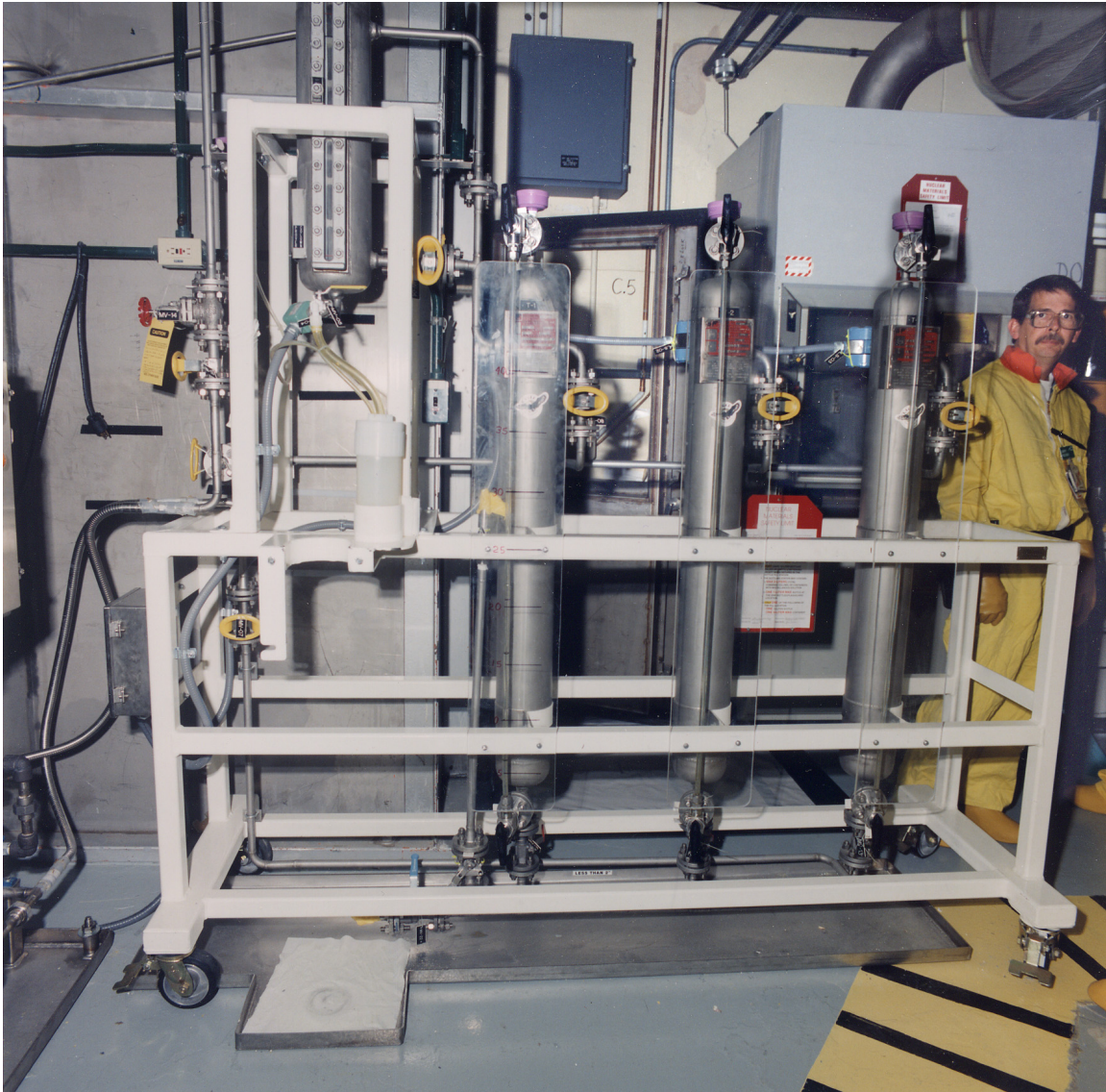
By March 1997, all bulk solution had been drained from all CML tanks, properly packaged, and shipped to another DOE facility, Nuclear Fuel Services (NFS), in Tennessee. A few more months were required to drain all lines leaving only minimal hold-up in pumps, valves, and horizontal flanges. This solution disposal was completed by July 1997, and this is believed to have included the rinsing of tanks and lines with water. The date on the photograph of the bottle skid is October 1997, showing that it had remained in Room 103 at least until then.

The NFS facility transferred the solution from the FL-10s into very long, ceiling-mounted, pencil tanks to await further processing. This author’s understanding is that the fuel has already been downblended to an enrichment suitable for nuclear reactor applications. It already has or soon will be processed into fuel pellets at some other facility; but its career as a criticality research fuel is over.

### *Raschig Rings*

With the threat of a criticality accident gone, the Raschig rings were no longer needed. Plant personnel charged with their disposal considered them trash and set out to rid the facility of these 90,000 glass cylindrical rings in short order. This author, however, objected to such crass treatment for objects that still had value. These rings had a story to tell; and he advised DOE to listen. The rings had been immersed in concentrated high enriched uranyl nitrate solution for over thirty years. The environment had been both caustic and radioactive. This CML—probably unlike any other place in the world—had a captive set of Raschig rings whose history had been carefully monitored for decades. The rings had never been changed since first installed in 1964. Furthermore, the precise nature of the caustic solutions occupying these tanks was equally well known. This situation provided a golden opportunity to study the physical properties of well-used and abused Raschig rings.

To their credit, DOE heeded that advice and budgeted some funds to test a subset of the full ring packing. Most rings removed from each tank were bagged and placed in drums for unceremonious disposal. A small bag full from each tank was diverted, however, and collected in a separate drum. Each bag was carefully labeled as to which tank the rings came from. Thus, nine bags in this separate drum were shipped to the Analytical Laboratories at the Los Alamos National Laboratories. There, an interesting set of studies, discussed in detail in another chapter of this book, revealed that none of the rings had lost any mechanical strength or suffered any preferential leaching of boron out of the glass during their more-than-three decades exposure to a very harsh environment.



*Fig. 82. The “bottle skid” was used to remove the uranyl nitrate solution from the building in the mid-1990s. Each tall cylinder was inserted into an FL-10 shipping container. (October 1997)*

All used borosilicate glass Raschig rings were removed from the CML by June of 1997. Progress was being made at dismantling the once-proud CML. Only the tanks themselves remained from the original uranium solution handling system.

#### *Tank Removal*

The Raschig-ring-filled tanks from the Assembly Room (#540 and #542) were removed from the Walk-In Hood by July of 1997; but they sat idle awaiting further action for about an additional two years.



Final removal was accomplished for these tanks as well as the nine storage tanks of Room 103, itself, in a manner that would have raised pangs of horror for many. Anyone trained to regard the interior of the Mixing Room as potentially contaminated and the outside environment as a place to be kept isolated from the other might worry about the intended plan. Indeed, a square hole was cut right into the pan-and-tarred-gravel roof above the Mixing Room, Room 103. The size of this hole was less than a meter larger than the lid of the largest tank to be lifted through it. The hole had to clear the tank and lifting paraphernalia as well as pose little risk of tearing the sheet plastic covering. The hole had a square contamination-control perimeter built up on the roof; and this could be closed at night via a hinged cover which opened toward the east.

The tanks were clearly heavily contaminated on the inside. They had contained fissile solution for more than thirty years and had been merely rinsed some time earlier. Rinsing would never be expected to decontaminate a stainless steel surface. The outside of the tanks probably contained some occasional low level contamination because they sat in a potentially contaminated area for that same length of time. They had never been overtly contaminated save for the contamination incident of May 1969. They had been painted many times; and some small amount of contamination may have been sealed under coats of paint. Because the condition of the exterior of the tank was not risk free, the tanks were wrapped in heavy plastic sheet.

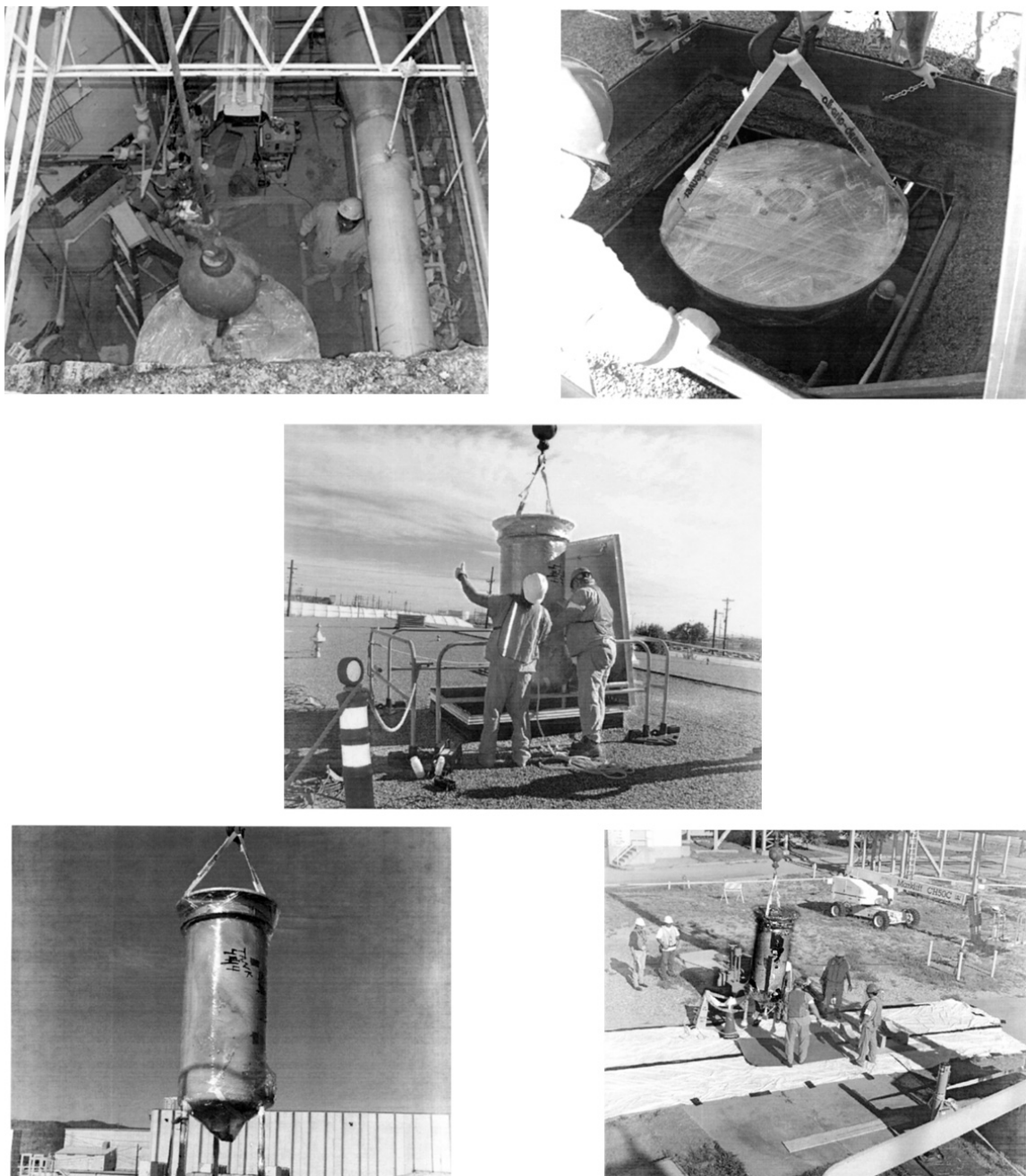
An interesting series of pictures depicts the process of transporting tanks from within Room 103 to a receiving and packaging area out of doors. The packaging area was just on the driveway passing to

the west side of the building. Large protective sheets were spread over the ground to protect against any errant contamination release. The pictures do not necessarily depict the same tank; but, taken as a series, they accurately portray the process used. Five photographs have been blended into one figure: Fig. 83. The scenes look down into the Mixing Room showing the crane attached to a tank, the top of a tank just peeking through the hole in the roof, the tank raised clear of the roof, the same tank suspended in space, and, the final scene in the sequence, a tank being lowered onto the packaging location. All tanks were removed from Building 886 by the end of August 1999.

### ***Uranium Metal Hemishells***

The last fissile material remaining in Building 886 was the complete double set of nesting uranium metal hemishells. These items had been used in several hundred experiments with essentially no signs of wear and tear. Wisely, these still-useful components were not considered waste. Their disposition was to be transferred from the CML at Rocky Flats to the counterpart facility at LANL, called the Pajarito Site. These 260 kg of uranium metal, still in the form of 80 nesting hemispherical shells, were given to that lab by September of 1999. The date is somewhat uncertain; the transfer could have been some time earlier.

What LANL plans to do with these components is not known. They served Rocky Flats well; and, hopefully, will be put to good use at their new home. With that material now gone from the CML, the building was devoid of all fissile material.



*Fig. 83. The uranium solution storage tanks were removed from Room 103 through a hole cut into the roof (see roof truss at top of first photograph). A portable crane lifted each tank, one at a time, from the building. This collage shows a tank still inside the Mixing Room, lifted to the surface of the roof, just clear of the building, suspended in free space, and about to be lowered to the driveway on the west side of the building. There, the tanks were packaged for discard. At least two of the photographs pertain to Tank #444. (Summer 1999)*

## Equipment

All that remains to discuss is the removal of the apparatus and hardware associated with the so-called Reactivity Addition Devices. The massive Horizontal Split Table had been introduced as a piece of used equipment (from Brookhaven National Laboratory) in 1964; but now it was slated for discard. It left the facility by July of 1998. The Vertical Split Table left a few months later (September). That piece of apparatus had occupied the north half of the Walk-In Hood in the Assembly Room for 34 years during which it served no scientific purpose. The most use that can be attributed to it concerns its functioning as a ladder and walking platform. Experimenters, elevated a couple meters above the floor, sometimes needed to walk on its framework as they moved about tending to equipment built upon the Solution Base.

The Annular Tank, a tall and large-diameter experimental vessel, was removed from the building in August of 2001. That open-top tank had been left heavily contaminated on the inside when the last experiment had been performed over a decade earlier. Yellow cake could easily be seen covering many sectors of the interior walls. The weight of this uranium residue is not known; it just looked like a lot.

The Walk-In Hood in the Assembly Room was cut apart into manageable pieces and removed from the facility by the end of the year 2001. This Hood had housed the Solution Base and the never-used Vertical Split Table ever since 1964. It had been the starting point for about half the 1700 critical-approach experiments performed at the CML.

The status, then, of major components still remaining in Building 886 at the end of 2001 was that Room 101 was mostly cleaned up. Apparatus throughout the rest of the Hot Area, however, remained

essentially untouched. Room 103 continued to house the still-plutonium-contaminated Down Draft Room and its associated glovebox. That room also still had the heavily contaminated Fume Hood. The Assembly room still housed the Elevated Platform in its southeast corner.

During 2001, more progress was made. Room 102 was already empty; the shelving had previously been disassembled and shipped away. Room 103, whose tanks had been removed in 1999, was further cleaned up. The Fume Hood and the Down Draft Room were disposed of. The Elevated Platform construction in the Assembly Room was also removed by the end of January, 2002. The floor to Room 101 was jack-hammered during the last week of February; and the floor to the depressed pit in the Mixing room was cut up during the first half of March, 2002.

The buried ductwork, which had contained residual uranium salts since the Vent Line Overflow incident in the late-1960s, was filled with foam and cut up during March of 2002. Certain managerial voices at Rocky Flats spoke to the treatment of this large-diameter duct as an irrelevant piece of equipment (do-anything-you-like-with-it) since all evidence pointed to but a few hundred grams of uranium remaining; but more conservative—and safer—opinions prevailed. The use of foam would “fix” whatever contamination might exist—whether it be the expected few hundred grams or the possible couple kilograms; and that fixation might prevent a criticality accident during this last phase of shutdown. After stripout, this duct was scanned in the hope of settling a controversy over three decades old. That controversy concerned just how much uranium salts actually remained distributed along that duct since 1969. The result of that scan was never revealed to this author.

### *Miscellaneous Steps Toward Shutdown*

Building 875, the filter plenum Building, built in response to the plant's fire in 1969, contained three different filter plenums. FP-501 used to serve the Cold area of the building and it was shut off in 1996. The smallest plenum, FP-503, served Building 875 itself and was shut off the same year. The filter plenum serving the Hot Area, however, (FP-502) was kept fully operational during all of the stripout work described above. It was the last to be shut off; and that happened in April of 2002. So, Building 875 remained in operation until that time.

The Storage Shed (Building 880) had contained a plethora of miscellaneous obsolete experimental equipment for a long time. Some of that had been jealously preserved for decades. All this useless equipment had been unceremoniously cleaned out and discarded by July of 1999. The then empty building did not remain so for long; it was almost immediately put to new use. The building supported decontamination and deactivation operations within Building 886 until it, too, was finally emptied one last time.

The Office Area of the building had been stripped of all windows and asbestos floor tiles by the beginning of the new millennium. This author visited the ghostly hulk in that state in the summer of 2001. For him, and probably him alone, it was a scene full of pathos. Halls once bristling with busy engineers and offices wherein the criticality safety of the plant had been ensured now echoed only hollow remembrances of those once-active days. All interior walls were demolished and removed by January of 2002. This process was made longer due to past use of asbestos in earlier paint jobs. The remaining interior walls were "hydrolized" with an

extremely high pressure water system which removed all (asbestos-contaminated) paint from these walls prior to final demolition. The Guard Post (Building 888) had been abandoned, demolished, and crated away by the end of 2001.

### *March 18, 2002*

The Rocky Flats plantsite was somewhat recognizable but strangely unfamiliar this sunny but cool spring morning. This author's daily access had ended many years earlier with only periodic visitations permitting some ongoing sense of plant closure; so he was little prepared for the ghostly scenes he would witness that day. The significance of the day was that that Monday was the day chosen to begin the physical destruction of the outside of the building. His host was Rock Neveau, the Radiological Engineer assigned to ensure governmental radiological standards were met before demolition could take place. Excitement was mixed with nostalgia as the pair drove eastward across plantsite.

Building 111—once the hub of the plant's top management—was a vacant lot, the first recognizable absence of a once-familiar building. Even the basement had been removed and the hole back-filled with earth. The drive east along Central Avenue revealed other absences. Building 123, this author's first "home" until Building 886 could be finished, was gone on the south side of Central Avenue. The Paint Shop was the first of the plant's several Maintenance Shop buildings to be leveled on the north. Even the huge reservoir which had contained the plant's heating oil was obvious by its absence. This very large tank had born the plant's catchy safety slogan:

"Plant Safety — Watch It Grow,"

for many years. Fences and other security measures once used to control access into the Protected Area (PA) on the plutonium side of the plantsite were still there but had shrunk considerably. Years of indoctrination taught that this Perimeter Secure Zone (PSZ) encircled a high-security portion of the plantsite; but these fundamentals were shaken by this scene of unrestricted access.<sup>57</sup>

Still, the passel of several still standing truly large buildings once enclosed by this PSZ—but heavily contaminated internally—raised serious doubt to this uninformed spectator as to the reasonableness of the projected closure date (2006) for the whole plant. On the other hand, however, modern techniques for decontamination and controlled demolition are truly remarkable and not necessarily revealed to simple-minded nuclear physicists. A few years into the new millenium, the target year of 2006 still seems achievable.

The above PSZ scene was directly north of Building 886; but once heads were turned to the south—to Building 886 itself—little more attention was paid to anything else that fateful day. Windows were boarded over; and a white sign draped across the north facade simply stated the obvious: “Building 886 Closed.”

A pair of wide-tread tractors with jointed girder arms hinged at shoulder and elbow also sported massive pinching fingers at the end of a swivelable wrist. Both mechanical arms sat poised for the day’s assault. The trailer attached to the east of the building, T 886 A, would be first. The four-office addition built about 1970 would follow shortly. The sheetmetal trailer seemed child’s play as thrust after thrust tore apart the building in short order. An unanticipated precaution was that water

from a fire hose was sprayed continuously on the accumulating pile of rubble as a means of dust control. One jaw cut as well as pinched; and the sight of steel I-beams from the trailer’s foundation cut in two as easily as a carrot was a memorable sight. Another tug upward pulled several of the cast-concrete footings right out of the ground. Less than three hours were required to raze the trailer and the four-office addition. The scene at lunch break found those two areas reduced to rubble and the northeast roof of the original building inclined to a bizarre angle. Figure 84 shows the heavy equipment used and the status of demolition ten days later.

Earlier in the morning of March 18th, a walk-through inside the building unveiled some equally startling scenes. Internal walls had been removed so “offices” no longer existed. The only remaining interior wall in the Cold Area was the load-bearing wall down the central Hallway. Even this wall had been partially destroyed in anticipation of demolition by a process called “hydrolizing” (described later) to remove asbestos-bearing paint; and the process removed mortar and the outer surface of the cinder block right along with the paint. Some cinder blocks on this load-bearing wall could actually be wiggled in place by hand; so much mortar had been hydrolized away. Because of this, the roof had to be stabilized another way. Plastic sheet draped from the ceiling roughly divided the once “Hot Area” from the Cold Area.

Room 101 presented a ghostly sight. The only light was that which filtered around the plywood door panels which replaced the sturdy Blast Doors of earlier years. The Elevated Platform was gone. The Walk-In Hood and the Horizontal Table had long ago left the room. Even the clutter was gone. The room bore little resemblance to its once-busy past.

<sup>57</sup>That perimeter had shrunk to surrounding one building elsewhere on plantsite.



*Fig. 84. Heavy demolition equipment had clawed away most of the Office Area by the end of March, 2002. The \$175,000 apparatus used to drill holes in walls of the Assembly Room for its eventual explosive fracturing can be seen on the roof.*

About half the floor had been sawed into blocks about one by two meters in size. Figure 85 shows this process in operation on March 4, 2002. These sawn chunks had been stacked near the south door; and, later that day, a fork lift truck was used to transfer these blocks into waiting cargo containers. Later, these cargo containers would be loaded onto flatbed railroad cars for transport to the Waste Isolation Pilot Plant (WIPP). The individual rectangles had each had lifting anchors embedded in them such that the still-useable 5-ton crane inside the building could be used to move the slabs about.

The Mixing Room was equally cold and naked. Tank, pumps, and plumbing had been removed years earlier. The Down Draft Room and the Fume Hood were but a

memory. The sheet metal pan ceiling had gotten slightly contaminated (plutonium) while removing the Down Draft Room and its associated glovebox; so the underside of this ceiling had been cleaned and painted over with an approved fixative. The roof's access opening, which had been used years earlier to remove the tanks, was still clearly visible overhead. Little light peeked through wall penetrations; and what other meager light existed was the gift of a few bare bulbs hanging here and there. The room was strangely dark and dreary. By mere coincidence, the room had been downgraded from a "contaminated area in excess of allowable discard limits" to free access that very day. This author was one of the first to enter the room without restrictions since shutdown began.



*Fig. 85. The floor of the Assembly Room was sawed into rectangular chunks and lifted using the Building's 5-ton crane. Workers and the environment had to be protected from possible low levels of radioactive contamination. This scene was dated March 4, 2002.*

The visitation inside the building was short-lived, however. The chewing action of the tractors gnawing away at the trailer coupled with billows of dust and dirt entering the structure prompted a hasty retreat from the building. This retreat was endorsed by the knowledge that the central load-bearing wall was so weakened.

The yard outside the building was a busy sight bustling with movement and cluttered with trucks and cargo carriers. Temporary wooden structures dotted the perimeter of the building. Collection areas of many descriptions could be found nearby. Perhaps two dozen workers were busily carrying out half a dozen different projects.

One of the most attention-getting projects was that atop the roof of the Assembly Room. There, a tall drilling rig, slightly resembling a miniature oil-drilling rig, was in the process for drilling 184 holes in the perimeter walls. Holes were 64 mm in diameter and were being drilled almost ten meters deep! These holes would, at a later date, be filled with a gelatinous explosive mix and that set off with a dynamite trigger. The explosion would not implode the building; but it would so weaken the walls that they could be knocked down easily. This plan was designed to prevent dust and dirt from moving very far from the collapsed building.

The drilling, itself, was an impressive operation. The drill device can be seen on the upper left skyline of the Assembly Room of Fig. 84. The drill advanced about a meter per minute; and this is all the more impressive when the amount of rebar in the structure is recalled. The machine is capable of twice that rate; but the slower rate was chosen because of the rebar. The hole pattern located two rows of holes around the perimeter of the walls. Both rows were closer to the inside of the walls with the two separated by, perhaps, a quarter of a meter. Holes in each row were about three-quarters meter apart. The impressive drilling machine cost \$176,000. One man operated this device.

The use of “Hydrolizing” as a means of removing asbestos and contamination has been mentioned above and is worthy of some description. The Hydrolize device projects a stream of water at almost 600 kg per square millimeter against the surface. The pattern is roughly circular; and about 20 liters of this high-pressure water per minute attacks the targeted surface. The resultant slurry is vacuumed up and filtered through a 50 micron filter medium. Solids are collected and stored in drums for eventual shipment to WIPP while the water is collected in large plastic reservoirs lined up in the old Storage Shed, Building 880. Coincidentally that day, a huge tanker truck backed up to the building to remove collected water.

Many surfaces had been Hydrolized weeks earlier. In the (no longer) Hot Area, the floor of the Pit Area of Room 103 had received the procedure; and this extended about a meter up the walls. Room 101 had also benefitted from the operation. The perimeter of the room had been Hydrolized at the joint between the floor and the wall.

The west wall close to the floor had warranted the procedure as had the south wall near the area of the Elevated Platform.

As this author left the site later in the day, he chanced to look upon his Visitor Badge. A moment of helpless resignation welled up as he realized that even his badge’s picture of himself seemed to reflect the current status of the CML. Both looked old and drawn, wrinkled, and maybe even a little bit tired.

Unmoved by nostalgia, the huge orange machines chewed and clawed at the Office Area on a daily basis. Their progress was from north to south. Front-end loaders kept up with this march scooping up debris into the beds of an endless stream of trucks. Concurrent with this activity, vertical holes in the walls of the Assembly Room had been completed; and the entire room was encased in a shroud of black plastic sheet and chain link fencing as depicted in Fig. 86. The plastic sheet would reduce dust dispersal; and the fencing would limit movement of concrete chunks. Somehow the black shroud, always associated with death and destruction, seemed fitting.

#### *April 13 and 14, 2002*

The explosive weakening had been scheduled for the previous day, Friday, April 12, 2002; but certain details forced a one-day delay. Holes were packed with gelled explosive and detonated with dynamite. Whether the packing took place before or after the black plastic shroud is not known. Few witnessed the weakening; but those few called it anti-climatic because the facility did not fall in upon itself. Still, the cloud of rubble ejected into the sky would have brought a silent tear to this author’s eye. The event was captured in Fig. 87 and, a second or two later, Fig. 88.



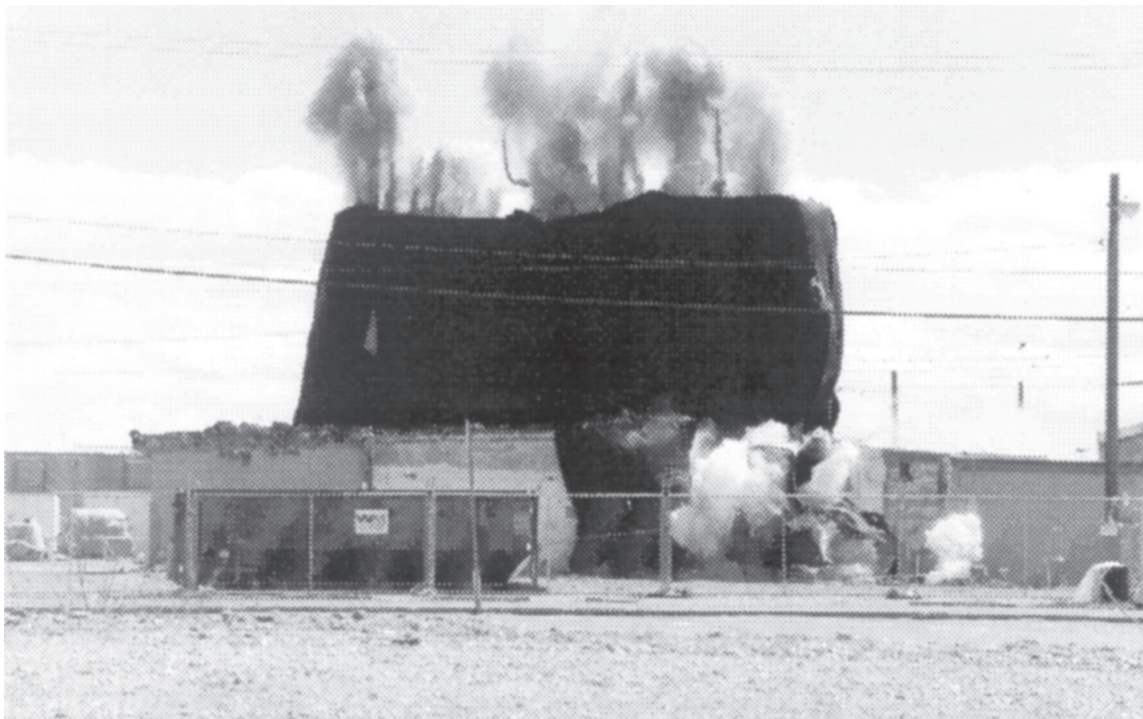


*Fig. 86. The Office Area was gone; and only the Assembly Room and the Vault Room remained standing on April 9, 2002. The Assembly Room was later explosively fractured on Saturday, April 13, 2002. It had been covered in chain link fencing to control concrete movement and a layer of black plastic to control dust and debris. The Hitachi tractor was called “the claw” by workers; but management preferred the term “processor.”*

One person who saw the event from a distance claimed to have seen a small segment of roof raise up into the air before settling back into place.

Evidently the Saturday fractured weakening of the shell may have been more successful than intended because workers at the plant arrived on Monday to quite a different skyline. The unstable shell had been knocked down by the orange machinery on Sunday as captured in Fig. 89. The date was April 14, 2002. The last vestigial remnant of the CML’s Assembly Room lay in a pile of broken concrete—guarded by a sentry of heavy earth-moving equipment. Only a pile of rubble remained as revealed in Fig. 90 on April 14, 2002.

This author paid another visit to the site on Thursday after the detonation. Much of the rubble had been scraped away. A third tractor, yellow in color, was fitted with a huge pulsating hammer was rented; and it broke up the concrete footings and other below grade concrete. Sections of buried trench remained in the ground; and the occasional exposed end clearly revealed the two pours of concrete which had been done in stages after the uranium solution spill of 1968 and before the cables were elevated to overhead trays. Interestingly, workers did not know about this spill and were grateful for advice about it. Because of that advice, the trench segments were removed with considerable added caution. Still, the skyline at the east end of the plant was forever changed.



*Fig. 87. The initial explosion sent directed jets of smoke and debris skyward; but the shroud still clung to the building.*



*Fig. 88. The power of the explosion soon caused the shroud to billow away from the non-weakened Assembly Room as clouds of smoke and concrete dust tumbled into the air. The date was April 13, 2002.*

*Fig. 89. Walls were easily knocked down on Sunday following the explosive weakening of Saturday, April 13, 2002. Close inspection suggest this was once the south wall because the moveable shield door can just be seen amidst the rubble near the claw of the “processor”.*



*Fig. 90. The Assembly Room was reduced to a pile of rubble the day following explosive fracturing. James W. Smith and Richard Seago, associated with the demolition project, seem proud of their accomplishment that Sunday.*



A formal closure of Building 886 took place the following week (April 25, 2002). A noon-time outdoor barbeque—including tents, tables, and windy-but-cool sunshine—was set out for any and all workers who had ever worked on any aspect of Building 886 shutdown. About 220 meals were ordered for demolition workers, decontamination personnel, waste disposal folks, their management, and anyone else who felt in some way associated with the project. It was a gala affair for everyone except this author. He marked the occasion by contributing a cake modeled into the shape of the cubical Assembly Room complete with the shield door on the south side. The cake was frosted a light tan similar to the actual color for many years. The symbolism that the cake was a yellow cake mix in honor of the color of uranyl nitrate solution was lost on almost everyone.

Festivities aside, a walk about the premises revealed a remaining mountain of rubble to the north; and a small depression where the footings and trenches of the Assembly Room had been to the south. Those trench segments had exhibited slightly elevated levels of reactivity when they had been removed a few days earlier; so they were stored a few meters away and covered over with plastic sheet. A few days later, they were loaded into a Cargo Carrier and disposed of as low-level contaminated waste to the Nevada Test Site. As a further precaution, the top 0.3 m of soil close to the trenches was also collected and will be treated like contaminated waste rubble.

All other soil, small chunks of rock and concrete, and other rubble were sampled to confirm the absence of radioactivity. This material was trucked to a landfill site near Erie, Colorado, a short distance north of the plantsite. Approximately 100 very large truck loads of debris have been delivered to this site from Building 886 alone. The closure of the CML has been

estimated to cost about \$20 million (mid-1990s to 2002). In contrast, the lab cost \$870,000 to build in 1964!

The remaining depression from footings and trenches was filled in using “clean” rubble. This is a collection of broken concrete and other debris from the demolition of other non-fissile buildings on plant site. Mounds of clean rubble were visible across Central Avenue and less than a kilometer away to the north.

Two items continued to perplex demolition workers. The thick shield door, which had hung across the southeast access to the Assembly Room, proved difficult to demolish; and yet it was far too massive to discard as a single piece. Its steel-plate casing resisted efforts to break up the shield door. By the end of April, no solution to this problem had been identified. The second problem area was the below-grade Holding Pit to the west of the original building. It was still continually wet due to the perpetual flooding of the floor. After all, the pit had been built right in the middle of an underground stream flowing through the plant; and this problem had plagued workers since the mid-1960s. The pit would have to be totally dry to accommodate a final detailed radiometric survey of the floor before the Holding Pit could be disposed of as non-radioactive waste. During the day’s walk through, this author suggested excavating around the perimeter of the pit to half a meter below the floor. This would require the underground water to flow away from the Pit, allowing the floor to dry. This suggestion was taken under advisement.

Ancillary buildings to Building 886 remained intact as of this late-April date. The air-handling building (Building 875) was still untouched. Its three filter plenums were shut down. The plenum (FP-502) which had served the Hot Area was tented in anticipation of eventual disassembly as contaminated equipment and disposal as radioactive waste. Filter Plenum FP-501

had served the Cold Area of Building 886 and remained uncontaminated. This two-stage housing was offered to the fledgling Cold War Museum whose organizers were in the early stage of collecting artifacts. The small Filter Plenum, FP-503, had served Building 875 itself; and it, too, remained uncontaminated.

The last major item in Building 875 was the huge Fire-Water-Suppression Tank within the building. This very large diameter tank was way too large to fit into any Cargo Carrier. The closure team was still working on options for disposal at this April date. The interior of the tank was just slightly more contaminated than discard levels would allow, complicating disposal. One state-of-the-art option under investigation was to spray the tank with a coating of black poly-urea plastic over a shrink-fit wrap of plastic sheet. This process, called "Instacote" may be considered a suitable "shipping container" for such mildly-contaminated items. The package would even be fitted with a two-way filter housing to prevent pressure and temperature changes during shipping from flexing the "container."

One other building remained standing. Storage Shed, Building 880, had been converted to an area for treating items containing low levels of radioactive contamination. It still housed the last slightly contaminated water from the Hydrolize process. It also contained about 60 drums of wet sludge from earlier Hydrolize activities. These drums were about two-thirds full with the sludge elevated above the bottom of the drum. A vertical standpipe enabled water to be pumped out of the bottom of the drum as it drained out of the sludge.

In summary, the end of April found Building 886 completely gone; but its footprint, a mound of rubble, and a couple ancillary buildings remained. Even these would be gone from the site within a few months.

## Epitaph

The summer of 1964 saw a lot of enthusiastic optimism at Rocky Flats and especially among those supporting the construction of a brand new Critical Mass Laboratory at the plant. Finally, confidence in criticality safety limits would be greatly enhanced through direct comparison against quality experimental data. That optimism must now be contrasted against the lonely depression and resignation inherent in the demolition of the facility in the spring of 2002. C. L. Schuske's once-hopeful dream is now collapsed into a nightmarish heap of rubble. In some sense, maybe it is better that he is no longer alive and forced to witness the demise of his dreams. Ironically, this book's longest chapter begins with many pages and photographs describing the several-month-long construction as massive walls of the Assembly Room were poured around an amazing complex of rebar; and that same chapter ends with a photographic record of the demise and demolition of the same structure. This author has been integrally affiliated with that facility during its 38 years of mostly productive existence; and perhaps he, along with Schuske, might be allowed a nostalgic lump in the throat.

Only the pragmatic revelation of unfolded history will prove whether or not the government was right to end experimental research in the field of nuclear criticality safety. If no accidental nuclear excursion ever happens anywhere in the world whose cause is traceable to a paucity of fundamental data which might have been generated at some CML, then they will have been right. If the dreadful opposite case must be recorded into history, then they must bare the burden of an unwise decision.

Schuske and his dream are both deceased; but both legacies will live on for decades to come.



## *Nuclear Fuels*

Fissile material was found in the CML in five different physical forms and two different isotopes. Isotopes were uranium-235 ( $^{235}\text{U}$ ) and plutonium-239 ( $^{239}\text{Pu}$ ). The latter was generically referred to as “weapon’s-grade” plutonium with respect to its isotopic composition while the former fell into two categories on that question. Uranium found in United States nuclear weapons was commonly 92% enriched  $^{235}\text{U}$ ; and that was the predominant form of uranium found in the CML. This isotopic distribution was often called “high-enriched” uranium. The other uranium composition was called “low-enriched” because the fissile isotope,  $^{235}\text{U}$ , was enriched from the naturally-occurring 0.7% to only 4.5%  $^{235}\text{U}$ . Low-enriched uranium was generally associated with nuclear reactor designs.

Sometime in the 1940s, high-enriched uranium earned the unusual descriptive phrase “Oralloy.” The word came from the source of the material—the Oak Ridge National Laboratory. It was, therefore, called “Oak Ridge Alloy;” and this got reduced to OR alloy, or Oralloy. Some old-timers in the industry may recall that this term, itself, was classified *secret*! Curiously, the word “plutonium” was also supposedly classified *secret* during World War II. That the name of an *element* should ever be classified seems peculiar these days. Still, early-day scientists working on atomic bomb projects occasionally needed to refer to the element in correspondence with one another; so the scientific community somehow agreed among themselves to use the simple ruse of using another element’s name. The element “copper” was

chosen. This really only led to complications when electrical wiring had to be mentioned which, of course, used the actual metal. Confusion was avoided by referring to the latter as “Honest-to-God copper.”

The plutonium metal existed in three different physical forms. One was nesting, thin-walled hemispherical metal shells such that nested sets could form thick hemispherical shells of certain specific inner and outer radii. Each even-numbered shell had an identical odd-numbered counterpart; so solid spheres and thick-walled spherical shells could be assembled. The largest shell had an outside radius of about 101.9 mm. Several dozen shells permitted a wide variety of geometries. A second form of plutonium metal consisted of machined metal cylinders with an average weight a little over 3 kg each (3.026 kg). A total of 125 cylinders were sealed in aluminum cans with steel lids for contamination control. These containers also protected the unstable metal from contact with the atmosphere. Plutonium is quite unsuited to exposure to ordinary air; and contact with moist air is even worse. All cylinders were nearly equilateral with a diameter about 30% larger than the height. The third form of plutonium metal consisted of routine production-line “ingots” temporarily diverted directly from the Rocky Flats weapons stream. Ordinarily, these ingots were the first stage of fabrication of the plant’s product. They were rectangular slabs a little over 10 mm thick and between 200 mm and 230 mm by between 250 mm and 305 mm. In this case, they were

diverted to the CML for experimental purposes. The largest array of these ingots studied at the CML contained almost 800 kg of this weapons-grade plutonium! This author was never privy to the country's total inventory of this exotic man-made element in the late 1960s (when these experiments were performed); but such a massive collection of plutonium metal placed at risk in one place and for one purpose seems unprecedented. That amount must surely have been a significant fraction of the world's supply at the time.

Uranium existed in three different physical forms also. Again, one was a set of nesting, thin-walled hemispherical metal shells such that nested sets could form thick hemispherical shells of certain specific inner and outer radii. Each even-numbered shell had an identical odd-numbered counterpart; so solid spheres and thick-walled spherical shells could be assembled. The largest shell had an outside radius of about 150 mm. In all, eighty shells permitted a wide variety of geometries. Uranium hemishells were quite similar in geometry to the plutonium ones except twice as thick (3-1/3 mm). About 260 kg of these precision-machined uranium metal parts spanned almost the full lifetime of the CML. A second form of uranium was the large holding (about 570 kg) of uranium solution in the chemical form of uranyl nitrate. This holding, too, lasted the full lifetime of the CML. It was delivered in 1964 and removed about 1996. The final physical form of uranium was about 2000 kg of low-enriched uranium oxide delivered in the 1970s as calcined  $\text{UO}_2$ . This loose powder was compacted into square briquettes such that seven layers of four briquettes nicely filled 152-mm cubical aluminum cans. Each can weighed an average of 15.127 kg.

About 130 cans were prepared, a little more than sufficient to construct a  $5 \times 5 \times 5$  array.

For each of these six nuclear fuels, subsections of this chapter describe the fuel in considerably greater detail, including how it was made. The name of the Senior Experimenter primarily associated with the fuel is also revealed. When the fuel arrived at the CML and how long it remained there is also discussed with all available accuracy and precision. (Surprisingly, readily available records do not always provide these dates; some detective work is sometimes required to obtain even estimates.) Any variations in the amount, composition, and/or physical form of the material over time is also discussed. This may prove important to someone validating a computer code against a specific experiment performed at a specific time. This "time-line" information may help pinpoint certain parameters inadequately described in earlier published documents. Impurity concentrations provide one example of this "time-line" approach. Impurity levels in the fissile metals are not expected to change over the lifetime of the fuel; however single measurements made to obtain a value for publication in a published paper would be subject to accuracy and precision uncertainties inherent in any single measurement of a single sample. Surely, a time-averaged value from several earlier programs using the same material provides a better estimate of the impurity levels. Similar arguments apply to impurity levels in fissile solutions. They could grow but would not be expected to decrease. Finally, methods employed to account for each material on some sort of periodic basis is described. These "inventory procedures" were necessary to ensure that no material had been surreptitiously diverted



away from the building since the last “inventory.” Anomalous events associated with any of the nuclear fuels are discussed in another chapter.

### ***High-Enriched Uranium Metal Nesting Hemishells***

*(History)*

Grover Tuck designed these experimental components. His major decision was the radial thickness of each shell. The balance, here, was the cost of machining many shells pitted against the possibly limited combination of available thick-walled geometries when several were nested. More shells permitted more possibilities and, therefore, more reactivity increments. Too few shells might mean that one nested assembly might be marginally small for a given experiment while the next larger might prove just too reactive to use. Tuck even considered allowing the radial thickness of shells to diminish inversely with increasing inside radius. This would tend to even out reactivity increments and might have been an acceptable choice. Nonetheless, he elected to retain a constant radial thickness sufficiently small to permit at least approximations to any desired spherical assembly and still remain within the allowed budget. One other consideration was that too-thin shells might lack durability during handling; one might easily bend out of shape and ruin the nesting capabilities both larger and smaller.

His final selection proved to be a very wise one. The entire complement of metal shells were made in early 1965 and first used in experimental studies that year. They were used on a large number of experimental programs over the next three decades; and they still continue to be available for experimentation. The full set

now resides at the Critical Experiments Facility at the Los Alamos National Laboratory in Los Alamos, New Mexico. Their plans for them are unknown at this time.

During his design contemplations, Tuck once mused aloud about a perplexing question associated with hemispherical shells. He wondered about the probability that a neutron leaving a random point on the surface of the smallest shell might escape further contact with the metal. This simple query prompted this author onto a six-month-long derivation of a formula which calculates the solid angle of any arbitrary point in space with respect to a circle. The problem seemed easy enough in principle; and, indeed, it is when the point happens to fall on the central normal of the circular opening. Away from that normal, however, the circle appears elliptical; and the eccentricity of that ellipse increases as the point moves further away from this normal. The derived formula in the published paper<sup>58</sup> calculates the solid angle at any point in space subtended by a circle. That solid angle is parametric in the angle away from the central normal and the distance between that point and the center of the circle. Though the problem seems simple on first thought, the formula contains little-known special functions such as Complete Elliptic Integrals of the First and Third Kinds and/or a pair of Heuman Lambda Functions. This is an example of how professional colleagues nurture one another in their careers.

Fabrication of these experimental parts followed standard production procedures then in use. Large slab-like ingots of high-purity enriched uranium metal were rolled into thick, flat plates of suitable thickness.

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<sup>58</sup>R. E. Rothe, “The Solid Angle at a Point Subtended by a Circle,” *Journal of the Franklin Institute*, Vol. 287, No. 6, June 1969.

These were annealed to relieve stresses introduced by rolling. The next step was to draw these into hemispheres by pressing into an outer die using an inner punch. Rough hemispheres were again annealed to relieve stresses introduced by forming. Finally, these oversized “bowls” were machined to final radial dimensions.

*(Physical Parameters)*

Eighty hemispherical shells were machined in all. Each was machined to a nominally 3-1/3 mm radial thickness less tolerances required for a tight slip-fit of adjacent parts. The only exception to this was the two smallest components which were machined hemispheres nominally 20 mm in radius and weighing 296 g each. Figure 91 shows eleven nesting parts viewed from above. The solid hemisphere

is to the lower right. The shell to its left fit over it and inside the larger shell to the left of the bottom row. The three slipped, in turn, inside the shell to the left of the middle row. Then, all four fit inside the shell to the right of that one and so on. All eleven parts shown here formed a hemisphere 53-1/3 mm in radius. It would have weighed 5719 g if the parts shown were odd numbered ones; 5725 g, if even. The total mass of all 80 nesting parts added to 256,071 g.

In addition to these 80 shells, Tuck had ordered five rods designed to slip-fit through pole holes drilled in each shell. These holes are discussed later. His goal was to have the option to plug a number of aligned pole holes with similar material in order to increase the effective density of an assembled uranium metal sphere. The five rods were different lengths of uranium



*Fig. 91. Eleven of eighty nesting enriched uranium hemispherical shells are shown. Even-numbered shells could form one hemisphere; odd-numbered, the other. Shells were black in color because of an oxide coating; and they were shiny because of a thin coat of grease used to control contamination.*

metal with a diameter suitable for an easy slip-fit through aligned pole holes. These rods, however, were never used for their intended purpose in an experiment. They never really seemed necessary; and the rods would have to be cut to suitable lengths as hemispheres of differing radial thicknesses were needed. Furthermore, these pole holes provided excellent means of fastening assemblies together during an experiment

Isotopic composition was determined during forming and machining operations according to routine Rocky Flats production procedures. These results were then merely reported along with the delivered product. Subsequent analyses could not be made of the metal itself without damaging the machined finish. The uranium was analyzed, however, in later years using the oxide rubbed off a surface during cleaning. Results are consistent with one another to well within the accuracy of analytical procedures. The “best values” argued for the isotopic composition of these components are:

$$^{234}\text{U} = 1.01 \pm 0.01 \text{ wt-}\%$$

$$^{235}\text{U} = 93.18 \pm 0.02 \text{ wt-}\%$$

$$^{236}\text{U} = 0.43 \pm 0.04 \text{ wt-}\%$$

$$^{238}\text{U} = 5.38 \pm 0.03 \text{ wt-}\%$$

No  $^{233}\text{U}$  was ever reported; this isotope was always found to be “less than the detectable limit.” Fortunately, all records of these measurements at the CML are archived at LANL. This collection does contain additional Analytical Laboratory measurements pertaining to isotopic composition throughout decades. Possibly, an improved average could be obtained from those data; but that effort was not deemed justified at this writing.

No measurement of metallic impurities within the fissile metal could be found during an exhaustive search of available records. However, because parts were

fabricated at Rocky Flats following normal plant procedures, a good estimate could be obtained from records of Rocky Flats production-stream data, if any could be found, from the late 1960s. This would yield at least nominal values for this missing information.

The bulk density of the uranium metal was probably the nominal  $18.664 \text{ mg/mm}^3$ , often quoted in textbooks for such material. A survey of documents pertaining to these specific parts uncovered one reference to a material density of  $18.675 \pm 0.05 \text{ mg/mm}^3$ ; but the source of this information is uncertain. The two are very close in value but not identical. Whether the larger or smaller figure is more accurate is not known at this date.

The effective density of an assembled configuration was reduced due to the necessary machining tolerances on each shell. The inside radius of any given component had to be sufficiently larger than the outside radius of the next smaller component to permit the two to slip-fit together. A typical such gap was about 0.1 mm. Those gaps plus five small holes drilled through each component (discussed later) reduced the overall effective density of an assembly. In one study involving 69 assembled configurations up to 186 kg of uranium, the average effective density ranged from  $18.06 \text{ mg/mm}^3$  to  $18.14 \text{ mg/mm}^3$ . A reasonable nominal effective density to assume for general discussion is  $18.1 \text{ mg/mm}^3$ .

Table II describes each hemishell precisely giving its inside radius, outside radius, and mass. These are the values measured at manufacture (1965). Odd numbered parts are given to the left, even, to the right. The right-hand-most column of each section gives the accumulated mass of that shell plus all smaller ones; but

**Table II. Physical Parameters of Enriched Uranium Hemishells Manufactured in 1965 for the Rocky Flats Critical Mass Laboratory.**

Odd-Numbered Hemishells					Even-Numbered Hemishells				
Part #	Inside Radius (mm)	Outside Radius (mm)	Mass (g)	Total Mass (g)	Part #	Inside Radius (mm)	Outside Radius (mm)	Mass (g)	Total Mass (g)
01	<sup>a</sup>	20.015	296	0	02	<sup>a</sup>	20.009	296	0
03	20.126	23.371	176	176	04	20.126	23.377	176	176
05	23.475	26.696	233	409	06	23.473	26.698	234	410
07	26.800	30.035	302	711	08	26.791	30.027	302	712
09	30.127	33.352	377	1088	10	30.123	33.351	376	1088
11	33.437	36.697	465	1553	12	33.44	36.698	466	1554
13	36.798	40.025	555	2108	14	36.801	40.024	554	2108
15	40.168	43.381	653	2761	16	40.162	43.376	652	2760
17	43.457	46.697	767	3528	18	43.463	46.698	766	3526
19	46.786	50.045	890	4418	20	46.783	50.039	890	4416
21	50.173	53.372	1005	5423	22	50.128	53.358	1013	5429
23	53.464	56.692	1147	6570	24	53.458	56.693	1150	6579
25	56.794	60.027	1288	7858	26	56.790	60.015	1286	7865
27	60.113	63.346	1445	9303	28	60.121	63.344	1440	9305
29	63.451	66.707	1612	10915	30	63.441	66.696	1612	10917
31	66.784	70.025	1779	12694	32	66.792	70.030	1777	12694
33	70.060	73.296	1949	14643	34	70.098	73.338	1951	14645
35	73.417	76.658	2134	16777	36	73.428	76.665	2130	16775
37	76.824	80.027	2349	19126	38	76.711	80.027	2342	19117
39	80.128	83.364	2527	21653	40	80.075	83.292	2511	21628
41	83.462	86.683	2722	24375	42	83.443	86.680	2741	24369
43	86.782	89.996	2945	27320	44	86.764	89.995	2953	27322
45	90.095	93.328	3188	30508	46	90.104	93.329	3179	30501
47	93.418	96.667	3442	33950	48	93.432	96.683	3450	33951
49	96.771	99.999	3656	37606	50	96.775	100.001	3658	37609
51	100.119	103.340	3912	41518	52	100.104	103.336	3918	41527
53	103.445	106.696	4207	45725	54	103.427	106.685	4208	45735
55	106.743	110.009	4464	50189	56	106.773	110.013	4461	50196
57	110.113	113.348	4733	54922	58	110.112	113.315	4729	54925
59	113.439	116.660	5003	59925	60	113.444	116.670	5025	59950
61	116.765	119.987	5323	65248	62	116.785	120.015	5326	65276
63	120.108	123.358	5660	70908	64	120.111	123.363	5650	70926
65	123.486	126.492	5509	76417	66	123.507	126.505	5495	76421
67	126.671	130.030	6495	82912	68	126.639	129.996	6492	82913
69	130.085	133.321	6599	89511	70	130.087	133.313	6598	89511
71	133.432	136.690	6982	96493	72	133.34	136.707	6973	96484
73	136.789	140.014	7262	103755	74	136.787	140.010	7244	103728
75	140.085	143.317	7619	111374	76	140.096	143.322	7613	111341
77	143.420	146.656	7984	119358	78	143.530	146.657	7952	119293
79	146.801	150.043	8415	127773	80	146.798	150.062	8413	127706

<sup>a</sup>This inside radius would be zero except that the cylindrical pole hole drilled through each component renders this parameter ill-defined.

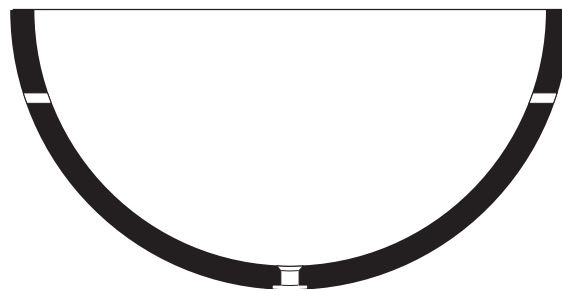
it does not include the inner-most hemisphere. Obviously, the sum of the two bottom entries (255,479 g) plus the two hemispheres (296 g each) gives the total inventory weight of uranium metal (256,071 g) in this set. Although these are masses at manufacture, subsequent weighings—even years later—revealed only small differences of seldom more than one gram, about the readability of a certified precision balance of the required capacity. Such weighings always followed a careful cleaning which included a solvent removal of residual grease and oils, removing any residual grease and oil from the five holes in each part, and a gentle soft-paper wiping of loose oxide. All 80 parts were weighted in 1997—32 years after manufacture—just prior to being given to the LANL for use in their Critical Experiments Facility. Other than being weighed at Rocky Flats, not much is known about these 1997 masses but results agree well with the 1965 masses. That such measurements were made with great care is not surprising. After all, this was an interagency transfer of accountable Special Nuclear Material (SNM).

Each hemishell had five holes drilled in it, one at the pole and four smaller ones in a plane parallel to the equatorial plane and a little below it. The pole hole was 7.14 mm in diameter with a tolerance of +0.13 mm and -0.05 mm. Both faces were counterbored to relieve sharp edges. The mass of enriched uranium removed amounted to about 3 g, including counterbores. The purpose of the pole hole was to receive a 6.35-mm-diameter rod of uranium or some other metal to align nested shells.

The four smaller holes were intended to be used only if two or more nested shells became stuck together through oxidation, vacuum, congealed grease, or any other

physical mechanism. Mild steel tools were made to fit the hands but have suitably small protrusions to fit the holes. Force applied in opposite direction would separate stuck shells. Happily, this worry proved unfounded as shells never stuck together. Each “pry hole” hole was 3.18 mm in diameter. They were drilled 90° apart azimuthally and parallel to the equatorial plane (not radial). They were located one-third of the outside radius down from this plane toward the pole. Each hole reduced the weight of a shell by about 0.5 g; 2 g for all four holes.

Figure 92 shows a cross section of these components. Although drawn from a construction drawing last revised in February of 1965, the figure accurately represents actual shells.



*Fig. 92. Enriched uranium hemishells were machined from construction drawings similar to this. The radial thickness was 3 mm less a very small tolerance to allow mating shells to nest easily. The pole hole and four pry holes (two at right angles to the pair shown) are discussed in the text. Tolerances were kept extremely small on these high-quality components.*

#### *(Use of the Shells)*

As machined, the metal was silvery in color; and small identification labels—including individual part numbers—had been printed near the equator. That silvery

color has never been seen by anyone at the CML. By the time the set had been manufactured and shipped to Building 886, an oxide coating had turned the surface black in color. For a few years, the black printing could still be distinguished; but those identification markings would be almost impossible to find today. The parts were always kept coated with a thin film of a petroleum jelly similar to Vaseline. This coating was intended to help prevent adjacent parts from sticking to one another by lubricating both surfaces. Another advantage of the coating was that it tended to contain any contamination that might otherwise abrade off a surface. The jelly also excluded any liquid in which an assembly might be immersed from leaking into interstitial spaces. In various experimental programs, these parts were immersed in a hydrogenous oil as well as uranyl nitrate solutions.

Between experiments, the uranium metal parts were stored in commercial pressure cookers similar to those used in household cooking of food. They are recalled to have been the “fourteen quart” size; but this is not certain. They were quite large. These sealed pots provided some protection against mechanical abuse as well as some additional contamination control. They also provided some materials safeguards in that wire seals could verify that contained parts had not been compromised since the seals were last installed. Nuclear criticality safety limits were established at 10.5 kg per pressure cooker; and this allowed some cookers to contain as many as seven parts. These parts were nested but with alternate odd numbered parts in separate cookers. The same was true for even numbered parts. For example, one cooker housed parts #1, #5, #9, #13, #17, #21, and #25 while a second contained #3, #7, #11, #15, #19, #23, and #27.

Two other pressure cookers housed the first fourteen even numbered parts. This “alternate nesting” was done to prevent adjacent parts from sticking together due to long-term storage in contact.

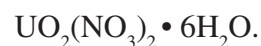
Monthly nuclear material accountability procedures were rather simple. Parts were not weighed each month as that would require degreasing and thorough cleaning; and this would contribute to both material degradation and increased risks due to handling. By the time periodic accountability became mandated by DOE, the serial numbers were becoming impossible to read. Even opening the cookers and counting parts was not deemed necessary when the wire seals were employed. The inventory procedure became as simple as counting pressure cookers and ensuring that their security seals were properly in place.

The complete set of components was given to the Critical Experiments Facility at the Los Alamos National Laboratory sometime in the 1990s. The intent was that this useful set would be used in many more experiments involving criticality safety; but the eventual use of the parts is not known.

### ***High-Enriched Uranyl Nitrate Solution***

*(Initial Receipt)*

The fissile liquid was manufactured as highly enriched  $^{235}\text{U}$  solution; and the uranium concentration was very close to the solution saturation limit. The solution was prepared in 1965 in Building 81 from a high-purity uranyl nitrate hexahydrate salt,



This salt was dissolved in dilute nitric acid to form the solution. It was then evaporated down to produce this high concentration.

That building had never before made solutions with such high concentrations; so even these experienced Chemical Engineers were treading new ground. This dense yellow liquid—almost a syrup—was shipped to the CML that summer. This author was assigned the responsibility for overseeing activities with this solution from that moment until he left Building 886 in the late-1990s—a span of over three decades. The solution was never used—or even moved—after the December, 1989, inventory measurement until it was removed in 1997.

This solution was shipped to the CML as “Uranium Feed Solution.” The first ten 55-gallon stainless steel drums were shipped during the summer of that year at the rate of 2 to 4 drums per day. Drums were, of course, Raschig ring filled for criticality safety. Interestingly, shipments came on canvas-enclosed trucks; and each drum was lowered to the ground on the truck’s tailgate and wheeled into the building—right through the office area—via a 2-wheeled hand cart. This method of delivery would hardly be considered today.

The technique for transferring solution from the drums into the already volume-calibrated tanks is not recalled. Those first drums were shipped in June and July (1965) at an estimated 106 liters each. The average concentration, over all ten drums, claimed was 483.4 gU/l. Thus, this initial delivery should have transferred 512,404 g of uranium; but parameters measured immediately upon receipt were 1030 liters (not 1060 liters) at an average concentration of 465 gU/l. That is, the measured receipt amounted to only 478,950 g of uranium. This shipper/receiver difference (almost 33.5 kg) was later traced to three factors: liquid held up in the drums, a badly calibrated slab tank in the manufacturer’s building, and concentration measurement

errors by the analytical laboratory. (That laboratory had never measured such high concentrations before. They employed a gamma-counting technique; and this method contained unrecognized self-shielding errors for such rich solutions.)

A final shipment (11th drum) came to the laboratory August 25, 1965. The sum of all shipments after small administrative adjustments finally led to a government-approved reconciliation of 569,711 g of uranium. This is the holding on record as of the fall of 1965. The uranium weight has been measured periodically since then for material accountability purposes. Even when the solution was finally removed from the CML in 1997, the amount shipped out was in good agreement with that initial inventory measurement—about three decades earlier—adjusted for many small removals and a few very small returns over this period. These very small perturbations to the huge overall inventory were either measured or accurately estimated.

This solution has a unique history that instills confidence in its long-term chemical stability. The same solution has been housed in the same set of tanks in the same building and used for the same purpose (criticality experiments) over its entire life. It served this purpose from 1965 to 1989. It had only passed back and forth between storage tanks and various experimental components over this entire time. It has been involved in about 1000 critical or critical approach experiments. All critical experiments involved very low power; so fission product inventory remained low. In addition to low power, the critical condition was seldom maintained very long. The only other significant operation performed with this solution during those decades was the occasional measurement of its uranium weight, done for material accountability purposes.

*(Inventory Measurements)*

These accountability measurements were performed triennially (once every three years) by CML staff. An accurate and precise inventory took two to three months to perform for such a large holding; and, of course, experiments with this material were not possible during inventory procedures. For that reason, DOE approved such a low frequency. The long measurement time was caused by the need to homogenize solutions in each of nine tanks for many hours, draw multiple samples for later analysis, perform routine tank maintenance such as replacing clouded plastic sight gauges, and a host of other details. The several routine inspection tasks mandated by the American National Standard governing use of Raschig rings (ANS-8.5) were also performed at this same time.

The uranium inventory weight,  $U$ , reported to DOE was the sum of uranium weights,  $U(t)$ , where  $t = 1, 2, 3, \dots, 9$  held in each of nine tanks. Each of these individual tank weights were determined by multiplying the measured concentration for that tank,  $C(t)$ , and the volume contained,  $V(t)$ . Concentration measurements were known to contain a possible measurement bias; but this bias,  $B(t)$ , was measured simultaneously with unknown solution concentrations. Combining all this, the solution inventory weight was:

$$U = \sum_{t=1}^9 U(t) = \sum_{t=1}^9 [C(t) - B(t)] \times V(t)$$

Even this complicated scheme was further complicated by a number of other factors. For one, small amounts of uranium were usually known to exist in very small quantities in unusual locations; and these had to be added to the total.

Furthermore, the volume measurement, itself, was not at all straightforward. Tanks

were far from simple right circular cylinders because of the thousands of glass Raschig rings contained within for criticality safety purposes. Even if the tanks were perfect right circular cylinders and did not contain these rings, they had complicated dished bottoms which would have made volume determinations by any straightforward calculation nearly impossible. For these reasons, then, each tank was volume-calibrated physically by the Chemistry Standards Laboratory. This was done by introducing a sequence of precisely-known volume increments,  $v^*$ , of some liquid. For each of these, the observed height,  $H(v)$ , was measured. Specifically, these volume increments were precisely 18.355 liters; and a number of these were needed to fill the tank to its top. This calibration effort was repeated a couple of times to provide enough data for a statistically significant curve fit throughout the tank. Such a calibration procedure yielded an almost linear (but not perfectly so) curve—at least over the supposedly linear portion of the tank (not through the dished bottom)—relating the observed height,  $H(t)$ , at inventory time to the contained volume of a number of known volume increments.

This raw calibration data was used to generate a linear regression fit which yielded a good estimate for the contained volume *at any height over the entire height* of the tank. It did not, however, provide the *best* measure of the contained volume at any *particular height* in the tank. The tank, after all, was *not* a perfect right circular cylinder all the way to the top even above the dished bottom. Factors causing a departure from this perfect geometry were the presence of side ports on the tank, possible minor imperfections introduced during construction of the tank, and a possibly non-uniform distribution of



Raschig rings within the tank. Nonetheless, this “good” data from the linear regression was engraved onto a scale mounted alongside the Sight Gauge. This scale would yield an acceptable measure of the contained volume at any height along the scale; but it did not allow the best measure of the volume contained at any particular height. A better measure of the volume at a specific height was obtained by returning to the raw calibration data. The two calibration increments that straddled the observed contents can be used to interpolate a more accurate volume. In more-mathematical terms, the *residuals* of the linear regression fit were used for interpolation at a specific point rather than the fit, itself.

Considerable effort was expended to minimize the overall uncertainty of the final inventory measurement. This happens when uncertainties of each component are about equal. Until the 1970s, uncertainties in concentration were several times larger than uncertainties in volume measurements. One improvement put in place to mitigate this imbalance was to reduce the uncertainty in the solution density by introducing a much more precise method of measurement. The switch to the more-precise volume determinations had reduced that uncertainty considerably. Then, other improvements in concentration determinations made the two components about equal.

The result of all this effort was that inventory measurements every three years were remarkably good. The new result was always compared against the previous measurement three years earlier “adjusted for known or estimated additions or removals.” Time after time, this comparison was within 600 to 800 grams of the expected value from the previous inventory. This is equivalent to an unbelievable

and surprising 0.1%—far better than the expected uncertainty of the physical measurement based on a calculation of the standard deviation. No scientific or statistical argument is offered as to why agreement was so exceptionally good. DOE never complained; and the CML staff was mystified. One anomalous decrease of over 6 kg occurred in the mid 1970s; and, for some unknown reason, was corrected by an approximately 7 kg increase during a 1980s-era measurement. No explanation is offered for this one-time decrease followed a decade later by a one-time recovery. Still, even these large changes were more in line with the mathematical standard deviation of the physical measurement which was greater than  $\pm 1\%$ .

One reason for such consistent triennial inventory measurements was that state-of-the-art improvements were constantly being implemented. For example, elsewhere on the plant site an “empty” tank—which had previously contained high concentration fissile solution—was volume-calibrated by introducing precisely known increments of nitric acid. The important point here is that the two liquids may easily have had significantly different densities. Even when the tank had been nominally flushed with a quick rinse of nitric acid, thousands of Raschig rings could holdup liquid of some unknown density between that of plutonium nitrate (often,  $1.5 \text{ mg/mm}^3$ ) and nitric acid (close to unity). The first increments of calibration fluid, then, could push ahead of it liquid with a different density than that in the bulk of the tank. This non-representative density solution would be that visible in the sight glass, while the rest of the tank contained only contaminated nitric acid. The two densities might well be different by a few percent.

At the CML, this problem was solved by using the fissile solution, itself, as the calibration medium. That is, the calibration fluid was the same liquid as that contained in a subset of tanks just before they were emptied for calibration purposes. Before starting the procedure several tanks containing the same concentration solution would be mixed together. Then the tank to be calibrated would be drained for a requisite period of time until deemed “drained.” Then, increments of the solution that had been present would be introduced to calibrate the tank. The density differential problem was eliminated altogether. To accomplish this, a “Tank Calibration Station” was designed and installed. A “prover” guaranteed a delivered volume of 18.355 liters per increment; and the set of data:  $(H_n, n \times 18.355\ell)$  was used to calibrate the tank. This station has been documented in the literature.<sup>59</sup>

Another useful device built into the solution handling system was a commercial unit that continuously provided an accurate measure of the density of whatever solution it contained—in this case, uranyl nitrate. The product is manufactured by a company named Micro Motion, located in Boulder, Colorado. Simply explained, the solution is forced to pass through a U-shaped tube which is set into vibration. The natural frequency of that vibration is a sensitive measure of the solution’s density. This “Densitometer” was added to the plumbing in the Mixing Room in time for the December, 1989, triennial inventory procedure. The device worked beautifully, as explained in the chapter on the CML Facility; but, unfortunately, that year’s

inventory was the last significant activity with the solution until its removal years later.

The same device can be used to record the mass of whatever fluid passes through it. That is possible because the mass of solution passing through this U-shaped tube causes a twist to the tube due to the Coriolis effect. The time difference between pick-off-coil signals on the inlet and outlet tubes due to the twist is directly proportional to the mass delivered. The CML had purchased two of these “Mass Flow Meters” years earlier and used them in a large number of critical experiments. Their precision came to be recognized as a few hundred grams out of as much as 1000 kg of uranyl nitrate pumped into an experiment. Indeed, the CML truly used state-of-the-art equipment in performing experiments as well as inventory measurements.

In spite of DOE’s ready acceptance of better-than-expected triennial inventory measurements, the government nervously desired more-frequent assurance that uranium solution was not being surreptitiously diverted. Together, DOE and this author worked out an additional quarterly inventory procedure. Quarterly results were completely independent of the triennial mass-based inventory and were ignored when the better inventory was performed. No comparisons were made between the two; and no justifications were ever needed to explain any differences. That questionable procedure simply called for multiplying an assumed weighted average concentration (the current book value) times the total measured volume contained within the nine tanks. Basically, the quarterly inventory was nothing more than a check on the *volume* of solution present. These tank holdings were not very accurate because the agreed-upon procedure called

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<sup>59</sup>R. E. Rothe, L. W. Doherty, and A. L. Johnston. “An In-Line Station for Volume Calibration of Raschig-Ring-Filled Storage Tanks for Fissile Solution.” Nuclear Technology, Vol. 28 (January 1976).

for recording tank readings without moving the solution. Differences between the indicated height and the true height were altogether likely; results were not trustworthy. Though easily performed in an hour or two, quarterly measurements yielded poor precision and unknown accuracy. This author never felt any comfort from them. Still they were easy to do and they appeared to appease DOE; so they were performed and reported.

*(Concentration Holdings)*

The CML has always maintained at least 1000 liters of high concentration uranyl nitrate solution. This solution was used in more critical experiments than any other. The initial 1965 receipt (465 gU/l) slowly degraded to 450.8 gU/l through use. Then, concentration drifted back up a little because exposed slabs of residual solution for the experiment in progress allowed some evaporation overnight. The solution concentration was intentionally decreased in 1972 to bring it into compliance with the newly-released (1971) American National Standard, the first version of ANSI/ANS-8.5. The Standard only addressed solutions up to 400 gU/l. Between 1972 and the mid-1990s, most of the productive life of the CML, this uranium concentration varied only a little around 370 gU/l.

In addition to this high concentration solution, two lesser concentrations were maintained for many years and used in selected programs. The first of these happened quite by accident. Workers from another group were brought into the building to volume calibrate an empty tank—this, in preparation for the first mass-based inventory. That group filled the tank with dilute nitric acid according to their well-rehearsed procedures used elsewhere throughout the plant. When finished with

this first pass, they asked this author to “...get rid of the acid so they could continue.” Only then, did anyone realize that no provisions had ever been made for the removal of bulk quantities of anything from these tanks. The tank farm was not connected to the plant’s waste liquid processing stream. The CML was stuck with a tank full of now-contaminated nitric acid and, in addition, no way to calibrate the tanks. This event, as much as any other, mothered the invention of the Tank Calibration Station (discussed above) and the use of uranyl nitrate solution itself as the calibration medium. Fortunately, the decision to reduce the highest concentration to below 400 gU/l happened about the same time; so this unwanted dilute acid was simply blended with a portion of the too-rich solution to create the first of these lower concentrations. This formed what came to be known as the Medium Concentration Solution. Roughly, 1000 liters of about 140 gU/l existed from 1972 through 1989.

The lowest concentration solution began as a small volume (a few hundred liters) of simply contaminated water. This water had been introduced specifically to rinse and flush out experimental apparatus. Throughout the 1970s and 1980s that holding probably varied between, say, 50 gU/l and 80 gU/l. It was occasionally used on experimental programs and was called the Low Concentration Solution. Both lower concentrations were blended into one (about 120 gU/l) just prior to the 1989 triennial mass-based precision inventory. Total solution volumes and tank farm capacities between 1965 and their removals in the mid-1990s are presented in Fig. 93. Variations in uranium solution concentrations over the same three decades are presented in Fig. 94.

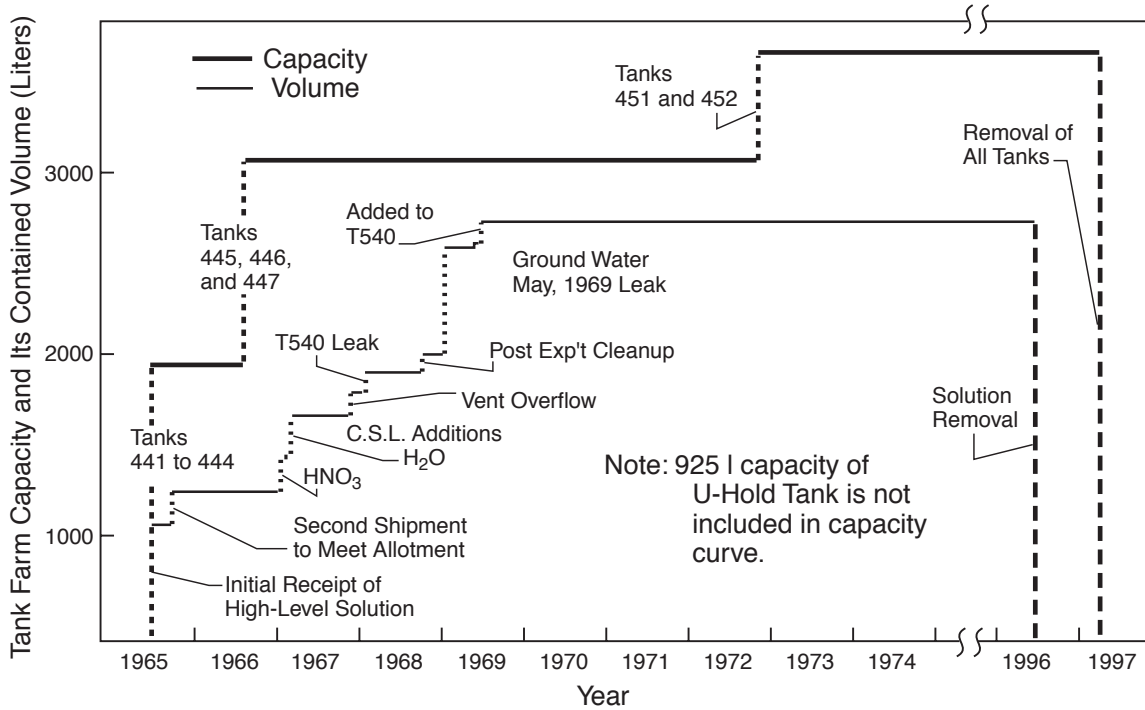


Fig. 93. Tank farm capacity grew over the years as more tanks were added to the farm. This is shown by the heavier lines. The volume of uranium solution actually contained also grew over the years for reasons pointed out at each upward jump. The solution was removed in 1996; so the contained volume fell to zero. The tanks were removed in 1997; so the capacity, too, fell to zero. There is a non-linear time break between 1974 and 1996. The 925-liter capacity of the so-called Uranium Solution Holding Tank in the outside below-grade pit is not included in the capacity curve.

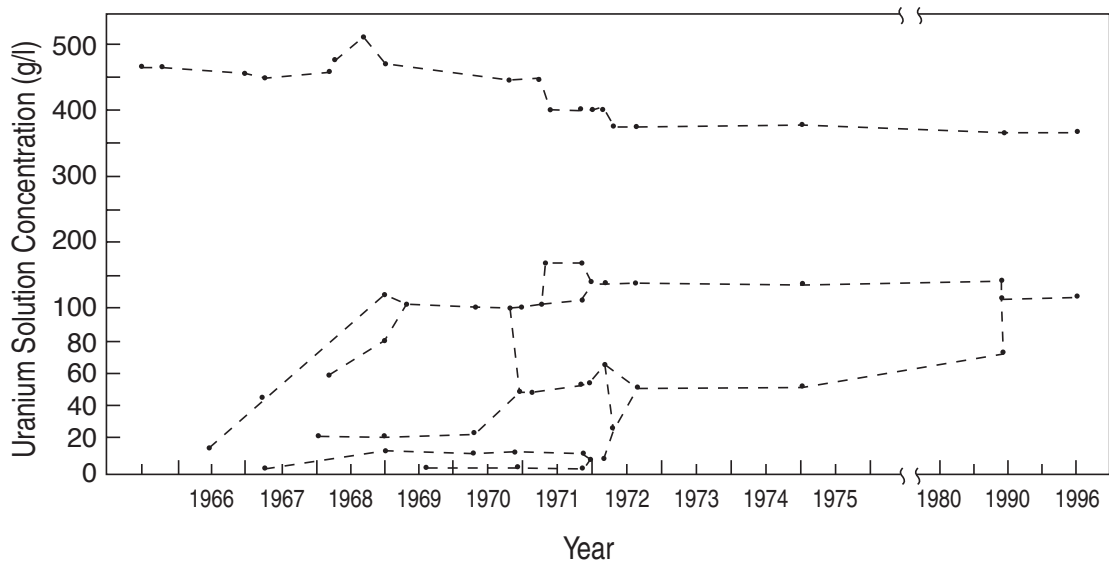


Fig. 94. Uranium solution concentrations varied over the years for a number of reasons. Evaporation tended to concentrate the solution in 1968; and a willful reduction to less than 400 mg/mm<sup>3</sup> was performed in the early 1970s. Two lower concentrations were inadvertently generated and maintained for over 20 years. They occasionally were useful in experimental programs. The two were combined in 1989, leaving only two concentrations. Dots represent actual measurements of the existing concentration. The time line is non-linear at the right beyond the break.

*(Solution Removal)*

The entire holding of all uranyl nitrate solution was finally removed from the CML facility in 1997. Ten liters at a time were transferred directly into type FL-10 shipping containers; and a number of these were loaded within a secure truck. It was trucked to Nuclear Fuels Service (NFS) in Irwin, Tennessee. A great many interstate shipments were required to complete the removal of about 3000 liters of solution. At NFS, the solution has already, as of the early 2000s, been converted into oxide in preparation for making reactor fuel elements. The oxide has probably already been down-blended in enrichment for this purpose, although whether or not this operation is completed is not known at this time. That would have been done at Lynchburg, Virginia.

*(Solution Properties)*

Physical properties of this “captive” solution have been reported in the open literature many times over the years. Each new report published that data for the specific program being discussed. Several programs using this solution spanned the three decades of productive use. Properties reported in the literature<sup>60</sup> for the first experimental program ever to use this uranium solution (in the late-1960s) identified a concentration of 450.8 gU/l, a density of 1.611 mg/mm<sup>3</sup>, an excess nitric normality of 0.72 N, and a fissile isotopic enrichment of 93.19 % <sup>235</sup>U. These properties, then, (along with an estimate of impurity concentrations) were measured a great many times during the lifetime of this solution within the CML. Typically,

<sup>60</sup>Robert E. Rothe. “Critical Measurements on an Enriched Uranium System.” *Nuclear Science and Engineering*, 35 (1969).

measurements were made as part of each experimental program and during inventory times. Long programs—spanning several months—might have two or three sets of multiple samples measured. Analyses for inventory purposes typically reported replicated results for *sixteen* samples for each of the three concentrations; and the same level of detailed analysis was applied to an identical number of standard solution concentrations prepared by the CSL to coincide with the concentrations on hand at the time.

Analytical methods used were the best available for the parameter measured. Uranium concentration was determined by Gravimetric Titration and, later, also by Potentiometric Titration. Both methods are precise to between 0.5% and 0.8%. In order to increase precision, solution density was measured using an extra-large (25 ml) temperature-compensated picnometer. This important parameter had a typical uncertainty of a few parts in ten thousand! The method used to determine nitric acid normality is not known to this author. Isotopic compositions were always measured by Mass Spectrometry. Impurity levels were measured by Photographic Emission Spectroscopy and Spark Source Mass Spectrometry. Sometimes, both may have been used. Impurity measurements are notoriously imprecise—often with uncertainties of factors of 2 or 3. More-prominent impurities were often measured again using the better ( $\pm 1\%$ ) Atomic Absorption technique.

Still, even a coarse estimate of impurity levels is important. It is needed to adjust uranium concentrations a little during the laboratory analysis procedure. In the Gravimetric Titration method, for example, solution is evaporated to dry salt (uranyl nitrate hexahydrate). This is calcined at a high temperature to drive off water of

hydration and the oxides of nitrogen. The result is uranium oxide, specifically,  $U_3O_8$  combined with the oxides of all impurity metals. This weight, then, equals the sought for weight of uranium oxide plus the weight of oxide states of all impurity elements. This latter correction was so small that errors of a factor of 2 or 3 in impurity content make little difference.

Another important reason for measuring impurities concerns their neutronic importance. Boron and cadmium would be strong thermal neutron absorbers; and beryllium could contribute additional neutrons through the (n, 2n) reaction.

Impurities measured over the decades belie the large expected uncertainty in the measurement. Surveys of analytical results culled over decades reveal few, if any, trends to increase one impurity or another; yet even successive measurements seldom agree with one another. Still, total impurities were present in the range of a few thousand parts per million parts of uranium; but little statistically significant growth is seen. The long-term stability of this quite pure solution allows an estimate on impurity estimates applicable to the entire three decades of use. Elemental impurities averaged over many years are expressed below in parts per million by weight relative to the uranium weight:

Al = $350 \pm 190$	B = $4.4 \pm 1.7$
Bi = $6.8 \pm 5.1$	Cd = $7.8 \pm 2.6$
Cu = $81 \pm 26$	Fe = $515 \pm 200$
Mg = $250 \pm 150$	Mn = $27 \pm 10$
Mo = $75 \pm 27$	Ni = $69 \pm 37$
Pb = $44 \pm 11$	Si = $43 \pm 20$
Sn = $280 \pm 190$	Zn = $230 \pm 100$

Neutron absorbers, boron and cadmium are small; and beryllium was not even detected. Results from one typical analytical report, selected at random, are included for comparison:

Al = 100	B = 2	Ca = 55
Cd = 10	Co = 2	Cr = 20
Cu = 10	K < 25	Mg = 200
Mn = 3	Mo = 100	Na = 10
Ni = 30	Pb = 3	Si = 2
Sn = 1	Ti = 1	

Decades of experience measuring chemical properties of this solution at Rocky Flats revealed a very tight linear relationship between density,  $\rho$  (mg/mm<sup>3</sup>), and concentration,  $c$  (gU/l). The mathematical relationship between the two is:

$$\rho = 0.001365 C + 1.001409.$$

This equation was developed, using the method of Least Squares, over a wide range of parameters over a span of two decades. Subsequent measurements, obtained over the next decade, were compared with this linear relationship and always found to be in excellent agreement. Figure 95 illustrates the early and subsequent data as well as the linear regression fit.

### *Nested Plutonium Metal Shells*

These metal parts were manufactured at Rocky Flats in the late 1960s. They were fabricated the same way uranium shells were—drawn from rolled slabs into hemispherical “hats,” stress relieved with heat, and machined to final dimensions. Rocky Flats was very experienced in this operation. These components were to be used in much the same kind of experiments as the only-slightly-older enriched uranium hemishells; and, since that design seemed quite practical, these parts were made the same way. D. C. Hunt was assigned the responsibility for maintaining this fuel. They were very similar to the nesting enriched uranium metal shells except that each was only half the radial thickness.

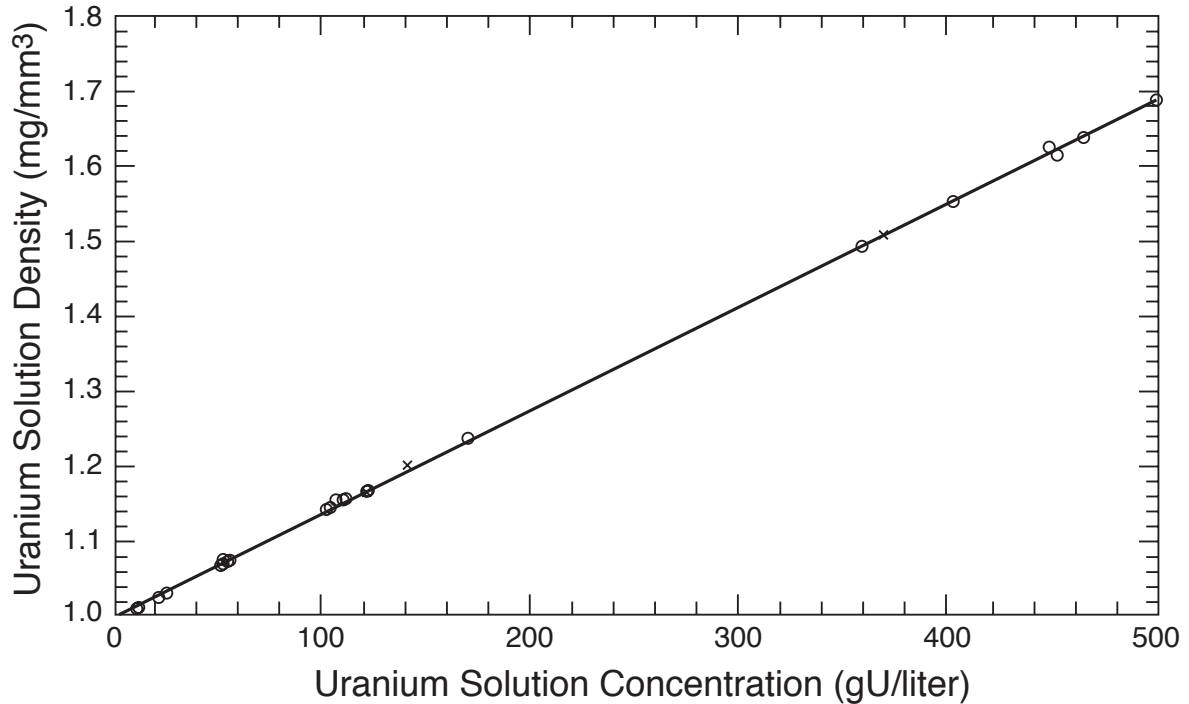


Fig. 95. The functional relationship between concentration and density for uranium solution in the CML was almost perfectly linear. The line is a linear regression fit to data spanning many years (open circles); and additional points are later measurements (x) to see if they fit the curve.

Hunt's concern here was that the reactivity difference between prompt and delayed critical, called a "dollar," is about three times smaller for plutonium than the other metal. For that reason, he opted for thinner shells. Such thin shells, only 1.667 mm in radial thickness, demanded careful handling for mechanical reasons; but that would also be necessary simply because they were plutonium.

The parts were stored between use in commercial pressure cookers much like the uranium shells. The cookers may have been a 10-quart size, smaller than the 14-quart cookers used for uranium. These pressure cookers were stored on shelves within the Down Draft Room described elsewhere. When a shell was needed, the appropriate cooker was taken from the shelf, placed on a clean sheet of paper laid

on the screen top of the Down Draft Table, the cover removed and held over the Table while another worker removed the needed component. The plutonium shell was then inserted through a guillotine door onto the floor of the adjacent glovebox. The pressure cooker's cover was then replaced and the still-clean cooker returned to the shelf.

Many details of this set of shells are not available for a number of reasons. Hunt is deceased. Inventory report forms, which had radial dimensions and individual masses for each component, were classified and are no longer available. This author has little recollection of the set because he was not the lead scientist in charge, although he did work with them on a number of experiments. Furthermore, the parts were removed from the CML early in the 1970s and returned to the Rocky Flats

production stream. Nonetheless, this author believes that every two successive plutonium shells had nominally the same radial dimensions as one from the uranium set. Perhaps, the naive thought was that some future experiment might contain mixtures of enriched uranium and plutonium metal hemishells in the same assembly. Whether or not that was in the back of Hunt's mind, no such commingled assembly was ever constructed. The two metals were always kept separated one from the other.

Only a few details are known about these plutonium hemishells. The metal was routine production material termed "weapon's grade" plutonium. The metal was in its alpha phase with a bulk density of  $19.74 \text{ mg/mm}^3$ . It was mostly  $^{239}\text{Pu}$  but contained 5.9%  $^{240}\text{Pu}$ ; other isotopic distributions are not known. Assembly densities, accounting for pole holes and pry-apart holes, exhibited a surprisingly wide range. They lay between  $16.34 \text{ mg/mm}^3$  and  $18.72 \text{ mg/mm}^3$  much larger than the nominal  $18.1 \text{ mg/mm}^3$  for uranium metal. The reason for such great variation is probably not fully accounted for by there being double the number of shells per unit radial thickness; but no other reason is confidently offered. No measurements of elemental impurities were ever made for these parts. A reasonable guess at this information would be to obtain similar data from typical production stream material being processed at the time of manufacture. Whether or not that information could even be obtained at this late date lies in serious question.

The metal parts are recalled to have remained more silver in color longer than the uranium set; but whether or not this is really true is uncertain. They really did not turn as black as the uranium ones did.

The pole holes for the plutonium parts were 6.85 mm in diameter, considerably

smaller than for uranium parts (7.14 mm). This author believes that four pry-apart holes existed in the body of the shell, too; but that is not certain. Their diameter and exact location is not recalled. The parts were covered with a thin coating of a lithium-silicon grease for contamination control and to minimize exposure to air. The grease had a density of  $0.972 \text{ mg/mm}^3$ .

Periodic accountability for these parts was also Hunt's responsibility. Details of how this was done is not recalled, although they were not weighed routinely. That would have required degreasing the parts and somehow weighing them within the glovebox. Quite possibly, merely counting the storage pressure cookers constituted adequate control in those early years. These cookers are recalled to have had braided wire security seals through their handles. These seals, intact, proved that the contents had not been accessed since the last inventory.

## ***Canned Plutonium Metal Cylinders***

### *(History)*

These fissile components were machined plutonium metal cylinders sealed within thin-walled aluminum cans having mild steel lids crimped in place much like a canned food product. The plutonium fit within this can quite closely. One could not sense any movement of the metal cylinder within the can when the can was gently rocked in the hand. After arriving at Rocky Flats, this "produce can" was, in turn, placed within a thick-walled stainless steel can fabricated in two halves and glued together. The produce can, however, fit quite loosely within the stainless steel outer container. A significant "rattle" was heard when the completed unit was shaken.



The plutonium metal cylinders had been fabricated at the Hanford facility in the early-1960s for the Lawrence Radiation Laboratory (LRL) at Livermore, California.<sup>61</sup> The plutonium was canned into the inner container at the time of manufacture; but these units were not placed into the stainless steel containers until many years later at Rocky Flats. The set of 130 such units were used in critical and subcritical experiments at LRL for more than four years; but that study was terminated in September, 1969. A few years later, the entire lot was shipped to Rocky Flats, still sealed in the aluminum cans, for continued use in criticality safety experiments. The 393 kg of plutonium metal were received at Rocky Flats in December 1973.

Seven additional units, dimensionally identical to the plutonium except made of uranium, were manufactured at Rocky Flats in the 1970s to serve as “substitution” cylinders for future experiments. The plan was to achieve criticality with an all-plutonium array and, then, repeat the experiment with a few substituted cylinders. None of these were ever used for this purpose, however, in any experiment. Five of these seven were about 93%-enriched <sup>235</sup>U with an average mass of  $2903 \pm 9$  g. The other two were depleted uranium, essentially all <sup>238</sup>U, with masses of 2856 g and 2970 g. The continued presence of these canned uranium cylinders in the building many years after the plutonium cylinders were removed (1983) is clearly recalled. Details about when and how they were eventually removed, however, are not recalled. They probably remained well into

the 1990s, although at one point early that decade, only four can be recalled. Two were enriched uranium; and both depleted uranium cylinders were still present. Whatever happened to the other three is no longer recalled.

Production needs for plutonium metal at Rocky Flats required half the inventory be returned to the production stream soon after the material arrived at RFP. National priorities superceded programmatic desires. They were never used in experiments at Rocky Flats. This left only 65 fissile units for further experimentation. The number was adequate to build a 4x4x4 array but too small for the 5x5x5 array possible with the initial number. The total plutonium holding in the building because of these cylinders, then, was reduced to only about 197 kg.

#### *(Properties)*

The average height and diameter for the full set of 130 cylinders was  $46.33 \pm 0.15$  mm and  $65.25 \pm 0.05$  mm, respectively. The density was  $19.53 \pm 0.08$  mg/mm<sup>3</sup>. The average plutonium mass of each cylinder was  $3.026$  kg  $\pm$  8 g. Similar parameters for the surviving 65 cylinders are not known; but they probably were not significantly different at all. The inner aluminum can measured 66.19 mm in diameter by 50.4 mm high; and the outer stainless steel can was 76.2 mm in diameter by 67.5 mm. Figure 96 shows a double cut-away drawing of a doubly-canned unit. The outer can is shown in section to the left and full to the right. Inside the outer can, the inner can is seen—again, in section to the left and the outside view of the inner can to the right. Table III gives the isotopic composition of the plutonium as well as three columns of impurities expressed in parts per million by weight.

<sup>61</sup>H. F. Finn, N. L. Pruvost, O. C. Kolar, and G. A. Pierce, “Summary of Experimentally Determined Plutonium Array Critical Configurations,” UCRL-51041, TID-4500, UC-46, May 10, 1971.

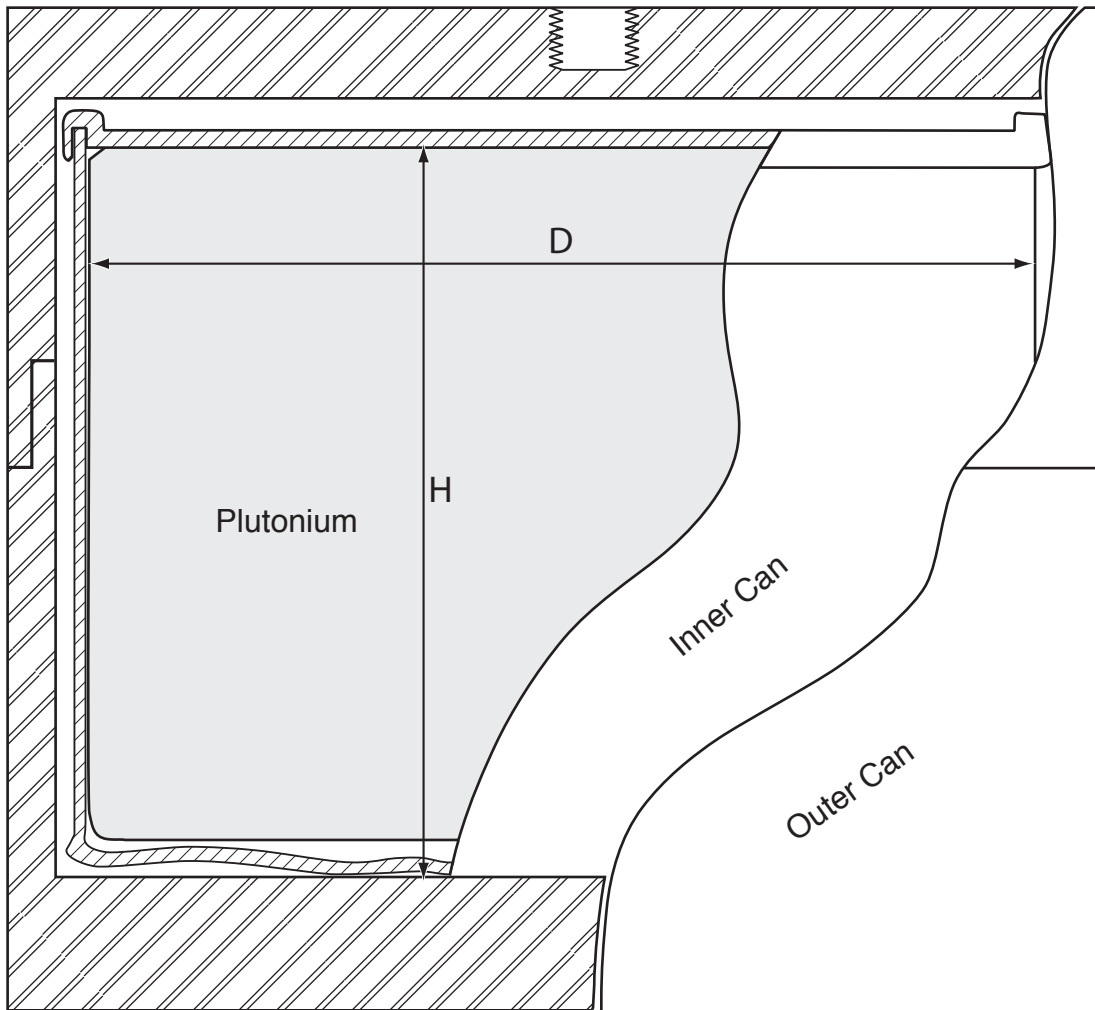


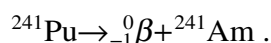
Fig. 96. Plutonium metal (shaded) fit closely within aluminum inner cans which had rolled steel lids (both: single cross hatch). These slipped rather loosely inside stainless steel cans (double cross hatch), composed of two parts glued together at a stepped joint.

<b>Table III. Plutonium Cylinder Isotopic Composition (wt%) and Elemental Impurities (ppm)</b>					
isotope	239	240	241	242	
weight-percent	93.56	5.97	0.46 <sup>a</sup>	0.01	
Ag	<1	Fe	35	Ni	50
Al	5	Mg	20	Pb	<1
B	1	C	180	Si	15
Ca	100	Mn	5	Sn	<2
Cr	20	Na	1	Ti	5
Cu	5	Total metallic: 265 ppm			

<sup>a</sup>Measured in July, 1965, and decaying with a 13.2-year half-life (see text).

*(Americium Buildup)*

The isotopic listing footnotes that  $^{241}\text{Pu}$  was decaying with a 13.2-year half-life. The result of this decay is the ingrowth of  $^{241}\text{Am}$  via the spontaneous beta decay process:



Americium was a problem because it is a strong gamma-ray emitter, adding to handling problems. The Americium content was never reported to this author's knowledge; but the assumption is made that Americium had been completely removed from the base plutonium sometime during the year preceding the cylinder's 1965 machining. The material was never again processed to remove Americium while in the form of these experimental components. The consequence of this ingrowth was that the fissile units became quite a severe external radiation hazard to the experimenters. Handling had to be streamlined and performed quickly—but, still, without dropping a cylinder. The time-honored safety principals of reduced exposure time, greater distance from the source, and increased shielding between personnel and that source were called into play wherever possible.

The material may have gone 18 to 20 years since last cleansed of  $^{241}\text{Am}$ . That amounts to about 1.4 half-lives of the decaying plutonium isotope, initially identified at 0.46 wt-%. A simple calculation suggests that  $^{241}\text{Am}$  may have been present at about 0.28 wt-%.

*(The Outer Can)*

The aluminum-canned plutonium metal cylinders were sealed a second time within a stainless steel outer container at Rocky Flats prior to any experimental use there.

This second canning was felt necessary to prevent contamination release in case an aluminum container split open if accidentally dropped. The two halves of the stainless steel can were glued together with a thin coat of a room-temperature-vulcanizing sealant called RTV Silicone. RTV is a silicone polymer containing fumed silica and is believed not to contain any strong neutron absorbers. Elemental compositions of the non-fissile materials associated with each cylinder are contained in Table IV.

These 65 parts were never modified further at Rocky Flats after being placed inside stainless steel containers. They were viewed as perfectly well-protected experimental components to be used in any of a number of planned experimental studies. In retrospect, this was naive thinking. Rocky Flats experiments would immerse these containers in water; and the sealant was expected to exclude water from the inner can and certainly from the plutonium, itself.

**Table IV. Elemental Compositions of Non-Fissile Materials in the Doubly-Canned Plutonium Units**

Element	Aluminum Can	Mild Steel Lid	Stainless Steel
Al	[96.05]		
C		0.08	0.03 max
Cr			18.0/20.0
Cu	0.25		
Fe	0.7	[99.2]	[65/74]
Mg	1.05		
Mn	1.25	0.37	2.0 max
Ni			8.0/12.0
P		0.015	
S		0.025	
Si	0.30	0.01 max	1.0 max
Sn		0.30 (*)	
Zn	0.25		
all others	0.15 max		
nominal alloy	3004	mild steel	304L

Square brackets represent values determined "by difference."

(\*) The tin was plated on the surface of the steel as tin-plate.

Use of this RTV sealant material was a foolish decision as evidenced from later developments. Thermal heat cycling and possible radiation damage degraded the glue over time and allowed small quantities of moisture to access the exterior of the inner can. In time, that little moisture even penetrated the steel-lid/aluminum-can interface. The plutonium metal began to corrode. The plutonium compound formed could not be contained completely within either container because of its much-reduced density. Sufficient compound formed over some unknown interval of time in one unit to split apart the once-glued-together stainless steel outer container. This disaster passed plutonium contamination to the floor of the experimental apparatus then in use. This unplanned incident is discussed in great detail in another section.

*(Storage Pots)*

The mass of each bare plutonium metal cylinder was never again measured at Rocky Flats. Therefore, material accountability procedures were *not* based on weight. Though not the Senior Experimenter in charge of this material, this author took part in several periodic accountability endeavors. He recalls that wire security seals had been entwined between the storage container and its handle for each water-filled and lead-lined storage container—often called a “pot.” Each contained only one doubly-canned plutonium metal cylinder. Accountability procedures for these plutonium components were simply the counting of storage pots and ensuring that each had an intact wire seal in place. Storage pots provided radiation safety by surrounding each unit with water to thermalize neutrons and lead to absorb gamma rays from the ever-increasing Americium.

The storage “pot” and components of the doubly-canned plutonium metal cylinders are nicely portrayed in Fig. 97. The water-filled “donut” having a rectangular cross section as well as a circular web at the bottom is the largest item in the photograph. Handles to left and right allowed the heavy container to be carried about. Small attachments at top and bottom served material safeguards purposes. A formed lead insert, seen to the lower left, slid inside the central cavity of the pot. The lid to the pot—also water-filled and lead lined—is shown to the right. The 3 kg plutonium metal cylinder contained in its aluminum can with a steel lid as the first encapsulation is seen to the far right at the bottom. Top and bottom sections of the thick-walled machined stainless steel outer can are seen near the middle of the bottom.

The storage pots attenuated radioactivity well; but they were cumbersome. Loading them onto higher shelves took some considerable strength and muscle control. Problems associated with the double containment of the machined plutonium metal are discussed at length in another chapter. In summary, water vapor penetrated all seals over time in a couple of cases and caused the inner container to rupture. In one case, the outer can became separated such that plutonium contamination spread all over the floor of an experimental apparatus. This was one of two serious contamination incidents in the CML’s history.

This absence of occasional weighings of these important items stems from hazards associated with handling such carcinogenic and pyrophoric material. When half were returned to production, only serial numbers of the items retained were noted. This record-keeping blemish is not important because individual cylinders were so similar to one another that such



*Fig. 97. The storage pot for plutonium metal cylinders was a water-filled and lead-lined “donut.” Water filled the pot (top left) and the lid (right). A lead insert (lower left) slipped inside the pot; and the bottom of the lid was lead covered as well. The aluminum-canned plutonium metal cylinder (lower right) fit loosely into the thick-walled stainless steel outer container (bottom center).*

small differences in dimensions and weight may be considered inconsequential. Each cylinder was considered a precise substitute for any other.

The cylinders probably were weighed again somewhere inside a Rocky Flats glovebox early in 1983; but this is not known for certain. An unfortunate event discussed in another chapter caused all 65 cylinders to be returned to production immediately—the same day as the event. Surely, these cylinders were weighed as they were removed from containment; but those weights were not reported back to the

CML. Many, but not all, of the cylinders were visually inspected by CML staff during this return to production. Speaking generally, most were in excellent condition as they were uncanned inside an inert atmosphere of a production glovebox; but a few of them showed that corrosion of the plutonium metal by moisture had started. In one case, the side of an aluminum can had split open but only a small amount of compound had begun to fill the outer container.

## ***Low-Enriched Uranium Oxide***

### *(History)*

The CML had a full program of critical experiments planned as this new laboratory grew to adolescence. It was an aggressive slate. Already-planned studies would use the enriched uranium and plutonium sets of nesting metal hemishells as well as the huge holding of uranyl nitrate solution. Plans were still under consideration to introduce some significant inventory of plutonium nitrate solution, too. Additional research work was neither sought nor desired.

The Nuclear Regulatory Commission (NRC) changed this status markedly. They needed a number of critical experiments to be performed using two different fissile fuels; and the Rocky Flats CML seemed to be the place to perform them. These experiments would enhance criticality safety of nuclear reactors throughout the United States. One fuel was uranyl nitrate solution; and the concentrations held at the CML worked well. Rocky Flats seemed quite suitable. C. L. Schuske was asked to accept an outside contract to do this additional work even though it might alter set plans.

The second reactor-related fuel was low-enriched uranium oxide. Rocky Flats, as a nuclear weapons plant, had no real interest in this material and, therefore, neither did the CML. Still, supporting the greater industry in a broader search for criticality safety would be a noble gesture—and a feather in the cap—for this still-young laboratory. Schuske discussed the dilemma with his staff; legitimate arguments existed on both sides. Eventually, the position was reached that the CML *could* stretch their planned programs without sacrificing too much. The contract income *would* improve budget issues

(even plantwide), and the national goodwill gesture *would* stand the CML in good light. The contract was written; and the course of the fledgling laboratory became redirected for the better part of a decade. That long-term overall duration of this “interruption,” first thought to last a year or two, was not anticipated at the onset.

### *(The Oxide)*

A number of black drums of a finely divided black material, looking very much like sifted dirt, arrived at the CML. Well in excess of 2000 kg of uranium oxide had been shipped to Building 886 from a company called National Lead of Ohio, later the Fernald Plant. The material was uranium oxide which had been calcined at high temperatures to a very dry uranium oxide. The vast majority of the material was  $U_3O_8$  although a careful analysis, by x-ray diffraction, of the material revealed a small component with an oxygen-to-uranium ratio of about 2.3. This could have been oxide in the form  $U_4O_9$ . Uranium oxides are very complicated and take many forms.

Most of the powder (93%) lay in the particle size range between  $1\mu$  and  $10\mu$ ; and 4.5% lay between  $10\mu$  and  $25\mu$ . The isotopic distribution measured for this oxide was  $95.43 \pm 0.02$  wt-%  $^{238}U$ ,  $4.46 \pm 0.02$  wt-%  $^{235}U$ ,  $0.08 \pm 0.01$  wt-%  $^{236}U$ , and  $0.03 \pm 0.00$  wt-%  $^{234}U$ . Four impurity elements were measured by the more-precise Atomic Absorption (AA) method with results given in parts per million by weight: Si (128), Cr (128), Fe (312), and Cu (185). Smaller impurities were: Mg (13), Al (37), P (50), K (25), Ca (15), Ni (16), and Zn (30). Strong neutron absorbers boron and cadmium were also measured by AA and found to be less than 0.3 and 2.0 ppm, respectively.

*(Can Preparation)*

At the CML, about 540 g powder was spooned into commercial polyethylene sandwich bags. These were sealed with a steel wire twist-tie and excess plastic cut away and discarded. Each bag was then compacted in a 2,500 kg hydraulic press to form a uranium oxide “briquet.” That is, each bag of loose oxide was compacted to a structurally-stand-alone “puck” compressed to a density of  $4.7 \pm 0.3 \text{ mg/mm}^3$ . This is about 57% of the crystal density of  $^{238}\text{UO}_2$ . Close to 4000 pucks were made. The press’s punch and die were machined to yield pucks 75 mm square with one corner rounded to fit the corner of a later container. Pucks were compressed to an average thickness of about 21 mm; but “spring back” after pressing caused the final thickness to vary some.

Compaction ruptured the plastic bag; but the finished puck had good mechanical rigidity as removed from the die. Pucks resembled a black shale-like rock which could be flaked apart with the aid of a screwdriver; but they did not fall apart of their own weight. Plastic bag fragments and wire tie remained embedded in the puck. The surface of the puck had a dull black sheen to it in places.

These pucks were to be positioned as explained later into deep-drawn, thin-walled, open-topped, Type 1100 aluminum cans. That type aluminum is known for its softness. Each can would become an experimental unit in subsequent studies. Each was 152.8 mm on a side but with rounded corners; and the aluminum was 1.5 mm thick. After loading with pucks, a lid of the same material, thickness, and 152.8 mm square would complete the cubical fissile unit. Before loading pucks, however, a 4 by 7 pattern of holes were drilled in two opposite side faces of the

empty can. These 6.3-mm-diameter holes would be used later for injecting water.

Each puck was slipped into a fresh plastic sandwich bag before being placed into the can. Four pucks filled each of seven layers forming a  $2 \times 2 \times 7$  arrangement of 28 pucks within each can. Seven times the nominal thickness of each puck (about 21 mm) just about filled the vertical height of a can. Accounting for plastic bags and surface irregularities on the pucks meant that each can was, in fact essentially completely filled with compacted uranium oxide. The lid was taped to the sides of the can to form the finished unit using a 50-mm-wide yellow vinyl tape. The second bags controlled water migration within these almost-rock-like pucks. Whatever water was to be injected later was at least constrained to exist within one quarter section of one of seven layers—that is, one twenty-eighth of a total can’s volume. Finally, very thin strips of mylar tape over the 28 holes prevented any loss or gain of moisture over time.

A very small amount of ordinary tap water was injected into these holes to adjust the H/U atomic ratio of the finished cans to a somewhat arbitrary hydrogen-to-uranium atomic ratio of 0.77. Several sources other than water contributed hydrogen and these were factored in when calculating the amount of water to be added. These included the shreds of the first plastic bag embedded in the puck, the second plastic bag surrounding individual pucks, and two kinds of tape. The initial, “dry,” oxide was known to have contained a little absorbed moisture. This had been determined by Thermo Gravimetric Analysis (TGA); and this, also, was subtracted from the amount to be intentionally injected into each puck.

When all preparations were completed each of over 125 experimental units possessed the following parameters:

H/U atomic ratio	0.768 ± 0.005
“Moist” Uranium oxide weight	15,129 ± 34 g
uranium oxide (no water included)	15,088 ± 39 g
absorbed water in “moist oxide”	41 ± 20 g
Water intentionally injected to produce H/U = 0.768	273 ± 4 g
Drilled aluminum can and lid (no tape)	526 ± 3 g
Plastic bags (both uses)	53 ± 2 g
Mylar tape over 28 holes	4 g
Vinyl tape for holding lid in place	3 g

A number of experiments were carried out at this H/U ratio. Then, additional water was injected into the pre-drilled holes to raise the moisture content for another series. That next series of experiments, then, was carried out with the H/U ratio increased to 1.25. No other changes were made to cans except for fresh Mylar tape which covered needle holes from the syringes used to inject water. These water additions sometimes flowed quickly into the shale-like puck; sometimes several moments were required for the water to seep slowly into harder pucks. Whatever amount of water was needed was divided by the number of holes in a can (28 on each of two sides—56 holes). Then, that number of milliliters of water was drawn into a large syringe for injection into the oxide.

This procedure ensured a reasonably homogeneous distribution of water throughout the entire can. Needles chosen for this purpose were long and thick and looked intimidating to any person naturally apprehensive about the medical use of needles. Many more experiments were performed at this second moisture content. Still later, a final injection of still more water was made for the final series of experiments. This elevated the cans to H/U = 2.03, their highest ratio. Cans were never changed after that. Similar procedures were followed for this elevation in moisture content.

Most cans were essentially identical to one another—nominally cubical except for small-radius rounded edges. Only the four lid-to-can edges were not rounded; and here was where the vinyl tape was located. A very few cans were intentionally made with a U-shaped cutout in one face. These vertical notches were designed to clear support rods for a special class of experiments described in other documents. These five or six cans weighed in the vicinity of 13 kg rather than 15 kg for the more-normal cans.

*(The Weight Change Phenomenon)*

All cans were weighed periodically over some sixteen months of the first study at the lowest H/U ratio. The cans exhibited a slow but continual increase in weight for almost every can. When first packaged, the total uranium oxide weight for the first 125 cans added to 1,998,590 g. The total weight gain during those months was 3914 g. This was only a weight gain of 0.2%; but the gain was undeniable. Not all cans gained at the same rate. The largest was 51 g; the smallest, 3 g. This was mystifying at first; but clever detective work proved productive.



The uranium within the cans was finally discovered to have been ever so slowly “burning.” It was oxidizing very slowly due to long-term exposure to ordinary air at room temperature. The *probable* explanation for this may be that the Stoichiometrically stable oxide of uranium is  $U_3O_8$  *only* at high temperatures. At room temperature, a more-stable oxide state may be  $UO_3$ . In this author’s simple view, the high-temperature oxide may then be described as three molecules only loosely associated with one another:  $UO_3 + UO_3 + UO_2$ . In this explanation, the third of these oxide states tends to add an additional oxygen atom—a process called “burning”—forming three room-temperature-stable oxides ( $UO_3$ ). In chemical terms,  $U_3O_8 + 1/2(O_2) \rightarrow U_3O_9 \rightarrow 3UO_3$ . Admittedly, this is a layman’s explanation of what *may* have been happening; it may easily be in error.

Inventory procedures for these oxide cans simply amounted to counting cans and identifying them by sequential numbers engraved onto each can. The occasional weighings were probably not performed for inventory purposes, especially considering the weight-gain problem just described.

#### *(Disposal)*

Experiments with the low-enriched uranium oxide ended in the early 1980s; but the packaged cans were not disposed of. Perhaps the notion lingered that further studies might someday be needed and continued storage posed no hardship. Sometime in the late-1980s, however, the decision was made to return these cans to somebody’s production stream; but whose? Other problems also arose.

Fernald really didn’t want the oxide back. The oxide had been so modified in form with shredded plastic and wire

embedded that it no longer suited their purpose. The material had been in a facility that once housed plutonium and even experienced a significant plutonium contamination incident. Could anyone assure the total absence of plutonium? Furthermore, many cans had been involved in critical experiments; and correspondingly higher-than-normal neutron fluxes may have formed some plutonium via the double-beta-decay process following neutron absorption of  $^{238}U$ . In truth, some small amount of plutonium almost certainly did exist. In time, the company was required to accept some of the returned material. This came to them in small shipments. By the time the third or fourth shipments had been prepared and transferred from Building 886 to Rocky Flats’ shipping building: Building 991, Fernald had been shut down for other reasons; and they could no longer receive material—happily or not. This turn of events, left some oxide in Room 102 of Building 886, some in Building 991 awaiting shipment somewhere; and some already returned to Fernald. The last of the compacted uranium oxide did not leave Building 886 until well into the mid-1990s.

#### ***Plutonium Nitrate Solution***

The initial thinking in 1964 was that the CML should have the capability of performing experiments with both plutonium and enriched uranium and that both elements shall be in both solid and solution form. Three out of four of these were realized. The existence of plutonium solution in the CML never came to fruition. It was not introduced initially more out of haste to get the CML up and running with enriched uranium than for any other reason.

The west side of the depressed pit area of the Mixing Room, Room 103, had been designed and set aside for plutonium solution. Similar designed space allowances had been made in the Assembly Room and the external Holding Pit. Many individuals protested, even in the mid-1960s, that the intentional co-mingling of uranium and plutonium solutions in the same room and in close proximity with one another would ultimately prove to have been an unwise choice. The contention was that any contamination found anywhere in the area would have to be attributed to the more hazardous element, plutonium, until absolutely proven otherwise. This proof would have to come from a pulse-height analysis of the alpha particle energy spectrum.

Perhaps the possible wisdom of this caution was recognized as the 1970s began. Possibly, Rocky Flats' production schedules could not permit diversion of even a small amount of plutonium solution for research purposes. For whatever reasons, the early years of the 1970s did not see plutonium solution in the CML.

Still, Schuske had not given up hope completely. Sometime during the early 1970s, he sent this author to the criticality facility at Hanford, Washington, to learn more about how to store and handle plutonium solution. Upon his return, a final serious thrust was made to implement this material as part of the CML's arsenal of research tools. A storage and handling system was designed and even engineered; but nothing further really developed. The CML never got its plutonium solution.

### ***Miscellaneous Materials***

The nuclear fuels discussed above were the bread-and-butter materials used at the CML in its continued quest for improved nuclear criticality safety at Rocky Flats and, if published results happen to apply to their concerns, to other nuclear facilities throughout the world. Still, other very special materials, also requiring accountability and control, were needed to operate the laboratory. These included external radiation sources and measurement standards. Amounts were extremely small; but they are discussed here for completeness.

The CML always maintained at least one external source of neutrons. Sometimes three or four might be on hand at one time. These "neutron sources" were small cylindrical objects about the size of a finger. They were used in conjunction with every experiment involving uranium. Characteristically, uranium does not generate a sufficient number of neutrons through normal decay to assure a true indication of real increases in reactivity. This is a statistical argument. A physical change to an experimental system could be made—which may have added significant amounts of reactivity—without changing the indicated neutron flux because of this inherently low neutron emission rate. Neutrons simply may not have been present in the region responsible for this increased reactivity. To preclude that problem, experiments involving uranium were required to be "bathed" in a sea of neutrons which could and would manifest any such reactivity increase by an indicated increase in the observed neutron flux. This sea of external neutrons was imposed over the experimental system by locating an external source of neutrons at a suitable place within the assembly under test.

These external neutron sources in the 1960s and early 1970s were small, encapsulated cylinders containing a mixture of polonium and beryllium. Radiation from the polonium released neutrons from the beryllium. The problem with these early-day sources were that they suffered a rather short half life (about 137 days). A source might be purchased with sufficient new strength to emit adequate numbers of neutrons through three or four half-lives; but this still meant that a new source would need to be obtained about yearly.

A much better solution to this requirement became available in the early 1970s. Prior to that, the new technology was not available. These sources were tiny bits of the isotope  $^{252}\text{Cf}$  doubly encapsulated in a sturdy housing. Initially, these were expensive. Costs to manufacture  $^{252}\text{Cf}$  were said to run \$10,000 per microgram. That amounts to a staggering \$10 billion per gram. Fortunately, the CML only required strengths of about 10  $\mu\text{g}$ . These new sources had a much longer half life, about 2-1/2 years, so only about half a dozen were required over the remaining two decades of the CML's productive life. A new source would be purchased about the time its predecessor had about a year's useful life left in it.

Soon after introduction, the cost per microgram dropped by a factor of one thousand. Generally speaking, a neutron source was thought to need an output of a few hundred thousand neutrons per second to be considered effective. Spent sources were discarded by intentionally placing them in a waste drum and discarding them along with routinely generated waste. This discard was always accomplished according to DOE-approved procedures and with some considerable documentation accompanying the drum in question.

The only other radiation source needed during experiments was a gamma-ray source. This was needed for one purpose only—to check the proper functioning of the one gamma-sensitive radiation detector mounted on the north wall of the Assembly Room. This detection device, as explained elsewhere, was used to monitor the growth of gamma rays in the room during critical experiments. The source, itself, consisted of a tiny bit of  $^{60}\text{Co}$  encapsulated onto the tip of a half-meter-long rod. The rod allowed the user to hold the source well away from the body to protect against unnecessary radiation dose. Throughout the entire three decades of experimentation, only two of these sources were needed.

The CML had installed a Well-Crystal Gamma Ray Spectrometer in Room 103 in the 1970s. This was an analytical device for laboratory measurements to determine the uranium concentration of unknown samples of any liquid containing uranium. The plan was to use this device for a first estimate of a newly blended solution concentration or contaminated waste waters. It would provide a quick estimate rather than wait several days for certified results from one of the plant's quality Analytical Laboratories. This device was neither certified nor subject to bias determination tests. It was never used for any concentration determination reported in open literature or for any inventory measurements.

A set of standard solutions, however, were prepared by the Rocky Flats Chemistry Standards Laboratory (CSL) for use in this device. About 20 standard solution concentrations spanned the concentration range from about zero to almost 500 gU/liter. A number were clustered in the range a few grams per liter and less; and these might be used to measure waste liquids. Several more were nicely distrib-

uted between a few and a few hundred grams per liter. They, of course, were used in conjunction with any blended concentration of useable uranium solution. Both the standard solutions and the unknown samples were pipetted into small glass vials. The volume of these was either 3 ml or 5 ml; that detail is forgotten. The glass vial was slid into a clear plastic tube which just slip-fit down the hole in the well-crystal.

In use, a number of standards close to the anticipated concentration of the unknown would be measured in the unit as a means of calibrating the counter. The greater the uranium content the greater the gamma rays detected. Then, the unknown—packaged just like the standards—would be counted in the device. That count rate, then, corresponded to some uranium concentration interpolated between the set of standard solutions.

The analytical unit worked well, but it was not used very often. The better capabilities of the certified Analytical Laboratory were really quite readily available; so they were preferred over these uncertified findings. Still, the set of about 20 uranium solution gamma-ray standards remained in the CML well into the 1990s.

When and how these gamma and neutron sources as well as the uranium solution standards were finally removed from Building 886 is not known to this author. They were most certainly gone from the facility by the late-1990s.

## **Building 986**

Experiments concerning nuclear criticality safety were, in some respects, receiving more nation-wide attention in the 1980s than the subject had elicited in earlier decades. Professionals from many laboratories—both nationally and interna-

tionally—were meeting to discuss the kinds of experiments the industry still needed. These included planned meetings as well as impromptu discussions—large groups and small. Others were writing papers on the subject. A resurgence of interest in criticality experimentation seemed imminent and just over the horizon.

Several factors appeared to contribute to this increased awareness. One question involved the “Area of Applicability.” How close did an experiment have to be—in geometry and/or composition—to a plant-related safety problem in order to apply a given bias, measured by the validation of that experiment against a calculational model? Could uranium data ever be applied to a plutonium situation? Could solution results at one concentration apply to plant problems at another? What was the correct way to apply a calculated bias? What was the best way to calculate a bias? When was that bias correction appropriate to apply? Perhaps more experiments were needed.

The sensitivity of many physical systems to reactivity changes was another driver for this renewed interest. Some systems might appear, even to the experienced eye, to be well subcritical; but closer analysis reveals them to be either critical or close to critical. Two examples illustrate this point. One is a classical calculational example. A large hypothetical array of well-subcritical simulated assemblies resting on imaginary shelves in a pretend storage vault was calculated by methods then in vogue and found, not at all surprisingly, to be predicted by the computer to be well-subcritical. The Safety Engineer decided to double the mass in one storage location, simulating an accidental double batching. He expected to calculate a neutron reproduction factor well in excess of unity because the simulated larger mass in that one location was super critical all by

itself. The calculated result, however, continued to show that the overall array remained well subcritical. The computer code mis-calculated a prompt critical situation! It wasn't the code's failing; the input data was in error. The error was that insufficient "neutrons" had been spread by the code operator over that one storage location code to allow proper indication of the appropriate reactivity increase. Not only were more experiments needed, code users had to learn how to avoid input pitfalls.

The second illustration derives from an experimental study performed at Rocky Flats in the 1980s. A 27-unit, nearly cubical, 3×3×3 array of about 3 kg plutonium metal cylinders were being immersed in water in this one study. Immersing 81 kg of plutonium metal in water within a fairly small volume is *not* something ever allowed in the plant; but this was experimental research. Throughout a small sequence of experiments, only the horizontal lattice spacings,  $\Delta x$  and  $\Delta y$ , varied. Vertically,  $\Delta z$  remained fixed. When  $\Delta x = \Delta y = 131.0$  mm, the water reflected massive array was well subcritical—perfectly safe. The horizontal spacing was next changed to  $\Delta x = \Delta y = 130.0$  mm, only one millimeter smaller; and criticality occurred half way up the array! A third experiment, at  $\Delta x = \Delta y = 130.5$  mm, attained criticality at the top of the top layer of plutonium metal. The last experiment in the mini-series was at  $\Delta x = \Delta y = 130.75$  mm; and criticality occurred several millimeters above the metal but far from an effectively infinite top reflection. The distinction between a clearly critical array and a well subcritical one was less than 0.2 mm in vertical spacing. This spacing was even approaching the mechanical ability to set these spacings.

More experiments are needed, code users have to avoid input pitfalls, and intuition as to what may or may not be critical can easily be in error.

These nation-wide concerns gave impetus to increasing the number of critical experiments at all of the nation's laboratories. The Rocky Flats CML would be included in that list. The problem was that the CML had been built in 1964 on the south side of the plant about central to buildings dealing with uranium and with plutonium. When the plant lost the uranium business, the CML simply lay south of plutonium buildings as well as south of the main road through the plant. Still later, when the government decided to enhance security as well as materials safeguards measures, the CML fell outside the Protected Security Zone (PSZ) which surrounded the Protected Area (PA). That is, Building 886—with many hundreds of kilograms of fissile material in its possession—lay in its own little island outside the PA. All the rest of the fissile material in any form throughout the entire plantsite lay securely within the plant's PSZ. Naturally, security and safeguards measures were enhanced in Building 886.

The Rocky Flats CML had visions of expanding. A second Assembly Room reserved for just experiments with plutonium was proposed. Construction of such new facilities outside the PA was out of the question. A new CML would simply have to be built inside the PSZ and subject to all its protection. A new facility presented the opportunity to improve upon designs of the 1960s. Two Assembly Rooms would support two storage areas each—one for metal the other, solution. State-of-the-art electronics would facilitate safer and easier-to-perform experiments; and ample office space for staff members yet unborn were drawn into the plans.

Engineering of Building 986, as this new Critical Mass Laboratory would be called, proceeded with flourish and confidence. Quite detailed drawings were prepared and discussed and an aura of certainty pervaded the heads of those concerned. A site on a hillside close to Building 991 was even selected. The hill would enhance safety by locating Solution Storage Rooms below the grade of the Assembly Rooms they served. An artist's rendering of the facility, perched atop its hill with many windows of an expansive office area gleaming, proudly announced its impending construction from a wall in the Control Room of the soon-to-be-replaced Building 886. Rocky Flats' Building 986 would be the centerpiece of the nation's criticality research facilities and the envy of all.

It never happened. Congressional funding was tight and the project delayed. Rocky Flats had its detractors; and their voices were heard. Challenges to methods of operation were openly expressed. The FBI raided the plant. Plant operations were "curtailed." The plant was driven into a posture of survival—a far cry from happy expansion. No, the closest Building 986 ever came to fruition was that lovely rendering by some talented artist; but even her watercolors dried up and went away.

## ***Physical Properties of Raschig Rings***

Raschig rings are small right circular cylindrical shells of a specific type of glass. They are a little taller than their diameter. They are small enough to easily fit the palm of a hand as Fig. 98 illustrates. They are made of a thick-walled glass containing a considerable amount of elemental boron, called “borosilicate” glass.

Raschig rings are extremely important in ensuring nuclear criticality safety of large volumes of fissile solution. In order to carry out that task effectively they must possess certain physical properties. These properties include sufficient mechanical strength, adequate boron content, chemical compatibility with the fluids in which they

will be immersed, and a number of other considerations. Not only must these rings have these properties at the time of installation, they must retain certain minimum levels throughout their life span as a fixed neutron absorber. If any of these properties were to fall significantly outside accepted boundaries, a nuclear criticality accident might ensue. Acceptable boundary conditions and parameter limitations are both identified and quantified in an American National Standard: ANSI/ANS-8.5. This document is re-approved or revised periodically to keep it current with latest technology and industry needs.



*Fig. 98. Raschig Rings are small, right circular, cylindrical, shells of borosilicate glass. The glass contains about 12.6 % boron oxide. Boron effectively absorbs neutrons preventing criticality. Modern rings since 1970 are tempered for strength and fire polished on the ends. The hand belongs to this author's Secretary for a quarter century, Carla Fisher.*

A marvelous and unique opportunity presented itself during the mid-1990s at Rocky Flats. That occurred because the CML was being decommissioned after decades of service. The opportunity was to measure any or all properties of Raschig rings on a set of well-used rings which had seen continuous service for over three decades in high concentrations of acidic fissile solution. That environment had been quite hostile toward the glass and could, conceivably, have affected some of these important parameters. Furthermore, the conditions of that service and the detailed nature of the fissile solution stored was fully known. Elsewhere throughout the industry, the genealogy of rings used or fissile solution in which they had been immersed or both was either unknown or uncertain. Only for these rings was the detailed history so well known and equally well documented.

The first task in decommissioning the CML's solution storage tank farm was to remove the large volume of chemically-pure, high-enriched, uranyl nitrate solution. That was accomplished in 1996. The removed liquid had been shipped elsewhere for future use; and this is discussed in another chapter. A year later, the next step was to empty the nine-tank farm of its 90,000 Raschig rings so the tanks, themselves, could be dismantled. That task, too, was easily accomplished; and that is when the wonderful opportunity presented itself.

The pedigree of the Raschig rings in the CML's tank farm was well known. They had never been changed since being installed in the 1960s—the first in 1964. Furthermore, these rings had been routinely sampled and inspected as required by the terms of the American National Standard ANSI/ANS-8.5. Good fortune continued; the high-enriched uranyl nitrate solution, introduced into the tanks

in 1965, had remained essentially unchanged until its eventual removal in 1996. Only very minor removals of small amounts and the eventual return of most of this liquid as well as very small amounts of solution lost during spills and leaks altered that initial receipt in any way at all. Finally, the solution, itself, was chemically pure with a minimal nitric acid content; and its chemical properties had been well measured over those three decades. What a fortuitous combination of circumstances!

Raschig rings installed into the first four tanks in 1964 were, admittedly, not “certified” as later required by the American National Standard because that document was not published until 1971. They could not have been certified because the basis for certification had not yet been written. The fact is, however, that the Raschig ring property requirements written into that first Standard were actually *based* upon the very same parameters measured on rings shipped to Rocky Flats during the early 1960s. These rings, then, were the prototype for the National Standard; so, as such, these initial rings in these tanks are essentially certain to be consistent with the Standard.

This unique opportunity might have been missed except that the United States Department of Energy (DOE) recognized the merit of an external suggestion to measure the properties of these well-used and well-documented Raschig rings and compare them with similar measurements on brand new rings. Those decommissioning the tanks were focused on that goal: decommissioning; and they lacked the background to assess the value of the knowledge they were ready to bag for ignominious disposal. DOE became convinced that both sets of measurements (new and used rings) could be compared against the required specifications of the Standard.



These comparisons could add considerable knowledge to the amount of conservatism inherent within the Standard. Based on the results of this comparison, authors of the next revision of the American National Standard might choose to adjust limiting parameters and/or modify other aspects of the document. That was one goal of the study which was funded by DOE. Unfortunately, DOE did not choose to publish the results; so, the peer-reviewed publication of these same results becomes another secondary goal of this history document.

### **The Raschig Ring Tests**

This opportunity was implemented by collecting samples of Raschig rings from the entire set removed from the tanks. A total of 119 thirty-gallon drums full of used rings were removed from the nine tanks. Of these, 110 were sent to the Nevada Test Site for long-term storage. One drum from each tank was set aside as the “sample.” Those nine drums were shipped to the Analytical Laboratories at the Los Alamos National Laboratory (LANL). There, selected rings from each drum were cleaned with ordinary tap water. To the ring’s credit, very little contamination remained on the Raschig rings even after just this simple procedure. Two different Analytical Laboratories at LANL were selected to perform parameter tests on these rings. One test measured the boron content; and the other, mechanical strength. In addition, the clarity of the glass, each ring’s weight, and the possibility of chips or other surface imperfections were noted.

These measurements were completed in May of 1998 and form the principal substance of this chapter. Mechanical strength results from this study are compared with similar results from a similar study conducted in 1995 at Rocky Flats. This earlier

study was on a set of brand new Raschig rings which had never been in any contact with any kind of solution. In summary, all results were very comforting. No decrease in mechanical strength was observed comparing results from both sets. This was true even after three decades of harsh service. At least three methods of measuring the boron content of borosilicate glass have emerged as nationally recognized techniques; and the study at LANL carefully compared results by different methods at different laboratories. Again, no decrease in the boron content of Raschig rings was observed even after thirty year’s service.

The conclusion is that Raschig rings may be an adequate means of safely storing large volumes of fissile solutions in harsh and corrosive environments. Raschig rings could continue to serve the nuclear industry by providing criticality safety in the storage of large volumes of fissile solution well into this millennium. Mechanical strength and chemical stability are much better than once thought. These strong declarations are substantiated below.

### ***Boron Content Tests***

No substantial evidence exists that the boron content of any properly manufactured lot of borosilicate glass Raschig rings would, could, or ever has changed with time or because of uses or environments to which the glass was exposed. Certain chemical compounds, notably hydrofluoric acid, may cause glass to dissolve and flush away over time; and this would certainly reduce the *amount* of boron present. Such dissolution, however, would uniformly change the entire mass of the whole ring; it would not alter the *relative ratios* between the several metallic oxides, most importantly silicon and boron,

in the remaining glass. No chemical mechanism has ever been proposed whereby boron, specifically, could be preferentially leached from borosilicate glass.

This claimed stability against boron leaching has been substantiated in routine laboratory measurements made at Rocky Flats over more than 25 years; and these tests spanned a wide variety of applications. These routine measurements were made periodically on samples of Raschig rings from over 200 Raschig-ring-filled tanks at Rocky Flats. They were made to ensure compliance with the requirements of the current version of the relevant American National Standard. Some of these requirements obviously pertain to boron content. Sampled rings came from ring-filled tanks containing a wide range of plutonium and uranium solutions. This includes fissile solutions with both high and low acidity in contact with the glass for many years. It includes chemically quite pure solutions to liquids heavily laden with insoluble precipitates and suspended solids. It includes liquids sometimes containing quite high levels of undesirable salts: phosphates, chlorides, fluorides, and other caustic compounds. Throughout all these years, no Raschig ring has ever experienced a validated loss of boron!

This same dramatic stability was also borne out by the LANL measurements made in 1998 on nine sets of Raschig ring samples from the Rocky Flats CML. These rings had seen continuous service for about 32 years! At installation, they contained  $12.6 \pm 0.3$  wt-% boron oxide. They were measured again at LANL—along with a sample of NBS standard glass (NBS-SRM 93A). This latter standard glass is certified to contain precisely 12.5% boron oxide and, so, formed a “bias correction” to the procedure. The LANL measurements were

found to *underestimate* the boron content by +0.31%. Adding this small bias to the LANL measurements of the 32-year-old rings, the column labeled “normalized” in Table V, showed an average boron oxide content—over three decades later—of  $12.58 \pm 0.17$  wt-%. This phenomenal agreement (12.6% new vs 12.58% three decades later) exists in spite of measurements being done at different laboratories and by a variety of methods. The Table also shows that the ratio of boron isotopes remains unaffected by use. Details of these measurements are contained in the yet-to-be-published paper in the hands of DOE; but the conclusions are still clear: Raschig Rings do not selectively lose boron through long-term use. Even without applying the bias correction, used rings were not statistically different from new ones at one standard deviation:  $12.6 \pm 0.3$  vs.  $12.27 \pm 0.15$ .

The lower limit for the boron content of Raschig rings as specified in the earliest American National Standard dealing with such rings is 11.8 wt-% boron oxide.

**Table V. Boron Oxide Contents of Raschig Rings from the Rocky Flats Critical Mass Laboratory After More Than Three Decades Service in a Corrosive Environment as Measured By an Independent Laboratory.**

Tank Sampled	Boron Oxide (wt %)		$B^{10}/B^{11}$ Ratio
	Reported	Normalized	
441	12.31	12.62	0.2347
442	12.11	12.42	0.2360
443	12.45	12.76	0.2355
444	12.11	12.42	0.2359
445	12.25	12.56	0.2333
446	12.27	12.58	0.2329
447	12.59	12.90	0.2322
451	12.06	12.37	0.2364
452	12.33	12.62	0.2351
Avg.	12.27	12.58	0.2350
Std. Dev.	0.15	0.15	0.0018
New Ring	12.27	12.58	0.2380
NBS Std.	12.19	normalized	0.2371

No one today can even recall where the apparently arbitrary lower limit ever came from; and calculational evidence exists that it could be lowered significantly with little impact on safety. Still, the Standard's lower limit is so much lower than any measurement ever made on any ring—new or old—that boron content might never need to be measured after the first time; and even that first determination would be just to ensure that borosilicate glass, rather than boron-free glass, had been used to fabricate the ring. The hope is that authors of future revisions of the relevant American National Standard may choose to reexamine the required frequency of boron measurements in greater detail and relax considerably those requirements.

Boron content of borosilicate glasses may be determined from three different parameters in the analytical laboratory. These are, of course, all related to one another. First, the boron oxide, a chemical compound, content could be measured. Next would be a determination of elemental boron. Finally, a direct measurement of the  $^{10}\text{B}$  isotope, alone and of itself, would provide the needed data. Only this last method requires no further analyses at all because the only important isotope in the glass for nuclear criticality safety purposes is  $^{10}\text{B}$ . Both other parameters would require additional laboratory procedures to measure the isotopic ratio,  $^{10}\text{B}/^{11}\text{B}$ . The first, of course, assumes the oxide state of boron is precisely  $\text{B}_2\text{O}_3$ , although other oxide compounds are not at all common.

The conclusion here is that Raschig rings have never failed a legitimate test for boron content. This is true for brand new rings as well as those which have seen long-term service in contact with corrosive and otherwise hostile fissile solutions such as plutonium and enriched uranium. Not only have they not failed the test; but they

have shown no tendency to change in any way. True, some acids, notably hydrofluoric, may dissolve away glass (and therefore boron); but the boron content never leaches out of the glass preferentially.

One other simple study on the boron content of Raschig rings was carried out in early July of 1970 at the Rocky Flats CML. This study also supports the conclusions of all other studies. This early measurement took place before the first version of the American National Standard; so the measurements are believed to have been done purely out of scientific curiosity. The test is not statistically conclusive because the numbers of rings tested were quite small. Still, three sets of three rings each were measured; and each had a different exposure history to the high concentration uranyl nitrate at the CML. One had been exposed to about 450 gU/l solution for about 4-1/2 years; and another set had exposure to the same solution but for only 2 years. The third set was brand new rings never exposed to any solution at all. Results of these nine measurements of each parameter are presented in Table VI.

**Table VI. Boron Oxide Content of Nine Selected Raschig Rings from Tanks at the Rocky Flats Critical Mass Laboratory After Various Lengths of Exposure to Corrosive Uranyl Nitrate Solution**

Exposure to Solution	Boron Oxide Content	$\text{B}^{10}/\text{B}^{11}$ Ratio
new	12.59	0.241
	12.46	0.241
	12.77	0.241
2 years	12.67	0.242
	12.63	0.242
	12.94	0.242
4-1/2 years	13.40	0.242
	13.12	0.242
	13.30	0.242

<sup>a</sup>Rings presumed to conform to manufacturer's specification of  $12.60 \pm 0.3$  wt-% and an isotopic ratio of at least 0.240.

Even a casual inspection of the data reveal no degradation in boron oxide content. In fact, the apparent *increase* in boron concentration with use might suggest some time-dependent bias in the measurement method.

### ***Mechanical Strength Tests***

Borosilicate glass Raschig rings of the design produced since the 1960s are extremely strong. This has been proven a number of times over the years. This includes measurements performed both at Rocky Flats and at LANL in the 1990s. Rings easily handle the rigors of industrial applications with little breakage. These rigors include the *static* weight of a sometimes tall column of Raschig rings stacked above them as well as *dynamic* forces imposed as rings are caused to contact one another during use. This dynamic action may occur as solution moves vigorously into or out of a tank such that adjacent rings, not rigidly locked against their neighbors, may “bang” into one another under the force of turbulent solution flow. Earlier designs of Raschig rings, prior to 1960, were not so strong; but tempered and fire-polished ones produced since then are remarkably so.

Industrial applications of glass as a neutron poison for fissile solutions should determine a Raschig ring’s necessary mechanical strength requirements. Nuclear safety is not a consideration during the ring loading process because no fissile material is present. The starting point of a Raschig ring’s industrial life begins *after* the glass has been placed into a tank. This truth was not recognized when the American National Standard was first written in 1971. It contained *requirements* (not just suggestions) designed to ensure strength during

loading. That shortcoming persisted as part of the Standard through the 1986 version. Requirements for strength during ring loading operations has been removed in the 1996 edition.

Experiments in the 1990s on both old-but-unused and also on well-used rings show that there is little tendency to diminish this remarkable mechanical strength with either age alone or age combined with exposure to harsh and acidic fissile solutions. Both static and dynamic mechanical strength tests were performed in the 1990s; and these were especially tailored to reflect the mechanical environment actually encountered by a Raschig ring during its use as a neutron absorber. Static tests recognized that the weight of rings above exposed bottom rings to a crushing load. Dynamic tests recognized that the sometimes vigorous movement of solution within a tank could cause adjacent rings to vibrate and rattle against one another.

Different tests were designed to model different geometrical orientations rings might experience relative to one another. These orientations were called “styles.” For each style, loadings were increased incrementally until the rings broke. For example, Raschig rings were oriented end to end, end to barrel, barrel to barrel with ring axes parallel, and barrel to barrel with axes orthogonal. Another orientation—anticipated to be one of the weakest—found the end of one cylindrical ring oriented at 45° and pressing into the open end of an adjacent ring. This one orientation would subject one ring to forces tending to spread it apart rather than crush it.

Tests were performed at Rocky Flats on a set of unused rings in 1995 using equipment designed for metallurgical testing. They were performed under the capable

leadership of Sharon A. Bokan in her metallurgical laboratory at Rocky Flats, although all tests were designed by this author. The instrument used for the static testing was an Instron Testing Machine, Model Number 1125. One or two rings were placed on a fixed lower table and an upper ram was lowered gently into contact. Then, increasing force was applied in a measurable way until the glass shattered. The glass was arranged in seven different styles of either one or two Raschig rings.

The instrument used for dynamic testing was a Manlabs (Sharpe) Impact Tester, Model Number CIM-24. Rings to be tested were laid horizontally. One end butted against a rigid end stop; and the test consisted of inflicting a horizontal impulsive blow upon the other end. The magnitude of this measured blow was increased until one or more rings broke. Five styles of two or three rings were studied in the dynamic tests. Clear shields surrounded both instruments to prevent injury from flying glass.

Unused rings from several sources were selected for the 1995 study. These rings came from the Rocky Flats Warehouse, a private collection of never-used rings in the author's collection, long-term storage at another government facility, and other sources.

Results from the static mechanical strength study reveal remarkable strength. In fact, two test cases never broke at all in spite of about 9000 kg of force exerted. A survey of the data shows that all other styles, excepting those which never broke, withstood about 700 kg before fracturing. If rings had been stacked one on top of another, this weight corresponds to a stack of rings over 170 stories tall! Even the very weakest ring in this test broke at 165 kg—equivalent to a 40-story-tall building. Production tanks are not anywhere near that tall at any nuclear facility.

Results from the dynamic mechanical strength study also reveal surprising strength, although not quite as impressive as the static strength. A survey of the data shows that all styles withstood, on the average, a little over 2 kg-m of impulsive loading before breaking. Expressing this in everyday terms, average rings would break when a conventional bowling ball was dropped on them from a height of over a quarter of a meter.

For the 1998 LANL study, ten different batches of rings were tested. Nine were rings taken from Rocky Flats tanks. The tenth was another set of brand new rings. Only three rings were broken for each of the ten batches; and this small number is recognized to constitute low statistical significance. Only two styles were remeasured at LANL on the three-decade-old well-used rings removed from CML tanks. This reduced effort was a concession to limited budget. The styles chosen were the weaker ones found in the earlier study. Both styles measured static mechanical strength; no dynamic tests were repeated in 1998. The equipment used at Rocky Flats was no longer available; so similar (but not identical) equipment was employed at LANL. Tests were performed on an MTS hydraulic test system using a closure rate of 0.2032 mm per minute to apply the desired breaking force. A running maximum load indicator was used to record the actual failure load of the rings under test.

In 1995, average fracture forces for these two styles were 504 kg and 462 kg, respectively. Results of this 1998 LANL mechanical strength study revealed breaking forces for these weakest styles were  $535 \pm 172$  kg and  $457 \pm 53$  kg, respectively. The two pair of averages are essentially indistinguishable one from the other. Interestingly, the weakest ring in the combined studies was one brand new ring

which broke at 165 kg. Another observation from these LANL tests is that little difference appears to exist between brand new and well-used rings.

Ample justification existed for questioning the National Standard's mechanical strength requirements surrounding Raschig rings even prior to these studies. The American National Standard not only specified a questionable method (called the Tumble Test); it also specified an arbitrary frequency for this periodic determination. Both flaws are discussed in the next subsection. These measurements in the 1990s proved that required frequencies were unnecessarily high. Those frequencies persisted through the 1986 version. This overly conservative frequency—as often as twice yearly for many tanks—led to many expensive, unnecessary, and potentially hazardous ring-change operations at Rocky Flats. In the late 1970s, for example, 19 tanks had their rings changed in one year; and six were the result of failure to pass the faulty mechanical strength test. Between 1967 and 1980, 15 tanks out of 97 cases had to have their rings changed because of the failure to pass this same inappropriate test. Unfortunately, both the method and frequency had been written into the Standard and, so, was mandated. Both the method used and the frequency of these ring inspection operations has been modified in the 1996 version the Standard.

*(The Tumble Test)*

The mechanical strength test required by the National Standard was called the “Tumble Test.” It was truly ill-conceived and in no way approximated the actual use of Raschig rings. Many aspects of the Test were completely arbitrary and bore no resemblance to real-life conditions. An arbitrarily large metal drum, about a quar-

ter meter in diameter, received an arbitrary number (10) of rings to be tested. The drum was caused to rotate an arbitrary number of times at an arbitrary rotational frequency with an inner blade sweeping the rings to an arbitrary height before they would fall and crash into other rings and/or the floor of the drum.

Application of this testing procedure at Rocky Flats quickly revealed that the required ten rings was too large a sample. It was not safe to withdraw that large a sample from the lower reaches of a tank under test for fear rings above those being removed might slide under gravity to fill the void. This removal procedure was a manual task; and the operator's hands were exposed to potential crushing as well as contaminated cuts or puncture wounds. This safety issue was resolved in an arbitrary way. The number of rings withdrawn was reduced from ten to an arbitrary four. In practice, four rings could almost always be removed without allowing those above the void to shift downward. Those four sample rings were co-mingled with six brand new rings. Physical implications of this equally arbitrary decision to Test results were never considered.

The Tumble Test was recognized early on, even by its authors, to be extremely harsh; so an occasional broken ring was to be expected. If a tank “failed” the Test, all Raschig rings within that tank would have to be changed out for completely new certified rings. Complete changes of Raschig rings within an in-service process tank were costly, time-consuming, potentially hazardous, and created considerable contaminated waste materials. Combining these truths prompted Test authors to permit one ring to break during the procedure without “failing” the Test. This, too, was a perfectly arbitrary decision tied in no way on any understanding of safety.

The six new rings were not considered part of the test lot; so breakage data pertained to only the four sample rings from the tank.

The conclusion of this Tumble Test, then, was that a tank was considered to have “passed” the Test if only one out of four test rings broke (25%). If the results of this Test were applied to the subject tank under study—a reasonable scientific protocol, twenty-five percent of the rings within an in-service process tank could break during use and still be considered to provide needed criticality safety. This is obviously false! Breakage of a quarter of a tank’s Raschig rings would surely lead to a nuclear criticality accident when fissile solution were next admitted into the returned-to-service tank.

The Tumble Test lacked any intelligent tie between the pass/fail criteria for the Test and an acceptable pass/fail criteria for glass strength in actual service. It was both arbitrary and capricious. Common sense directed the Test’s replacement with a more-suitable measure.

### ***Other Worthwhile Tests***

Other mechanical strength tests have been performed at Rocky Flats over the years. Better methods were used than the one unfortunately written into the Standard (the Tumble Test). Results from these other tests are quite consistent with the 1995 Rocky Flats studies as well as those repeated at LANL in 1998. Back in 1977, A. L. Watson compared several Raschig ring tests for mechanical strength.<sup>62</sup> One of his better tests was called the “Crush Point-Loading Test.” It subjected Raschig rings to a number of discrete

crushing loads. Rings were drawn from five different fabrication types or heat-treatment histories, although the exact meanings of all five is not certain decades later. The distinction between them is probably not important because test results seem to be statistically indistinguishable from one another. Some were described as “High Fire-Polished” rings and probably were also tempered whereas “Regular Tempered” rings may or may not have been fire-polished. Another set was labeled “Rejected Lot #287” and is believed to be an entire shipment of brand new Raschig rings that had failed the harsh test required by the Standard. This probably was an improper rejection of perfectly good rings.

Watson’s Crush Test also revealed amazing strength for the glass. The weakest ring broke under a load of 409 kg. The weakest *class* of rings had a weighted average about 10% greater. Interestingly, the class of rings rejected by the Standard’s Tumble Test were just about as strong as the tempered and fire-polished rings. Even acid-etched rings withstood crushing from a column of rings equal in height to a 300-story-tall building!

### **Conclusion**

Raschig ring filled tanks are a practical and efficient way of storing fissile solutions with great confidence in their ability to ensure nuclear criticality safety. Evidence now shows that they can serve this important function for a long time with very little maintenance and only occasional periodic inspections. Raschig rings were introduced in the 1950s for this nuclear safety purpose; and natural early conservatism, initially introduced to compensate for the lack of knowledge about long-term suitability, became implanted in the first relevant American National Standard in

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<sup>62</sup>A. L. Watson, “Durability Study of Borosilicate Glass Raschig Rings,” Rockwell International, Rocky Flats Plant, January 1977. CRD77-002.

1971. In subsequent years, both in-plant experience and a number of specifically-designed experiments cast serious question about two certain overly-conservative aspects of that Standard. This was a difficult error to correct because the aura and prestige of an American National Standard is difficult to overcome. These conservative limits persisted through the 1979 and 1986 versions. A first step in righting some of these overly-conservative limitations was taken with the latest version of that Standard, published in 1996. Many—but not all—were removed from the 1986 version and replaced with more reasonable limits without any appreciable decrease in safety at all. Authors of the next version of ANSI/ANS-8.5 are encouraged to seriously consider points discussed in this chapter when revising the then-current version of the Standard in the area of strength and chemical stability.



## ***Safety, Security, and Safeguards***

Safety is an important aspect of the industrial world. This sounds trite but warrants recognition. Human safety is paramount; but the prevention of loss of or damage to equipment is also important. Such safety considerations apply to every industry. Additionally, protection of sensitive information and certain materials is nearly unique to the nuclear industry as well. The very nature of the nuclear arena imposes risks and responsibilities. The physical danger of injury or loss of life through nuclear accidents is an ever-present concern. Small-sized explosions, enormous bursts of radiation, and widespread contamination are potential risks. Coupled to those safety-related concerns, however, are the associated requirements to protect these materials from mis-use, unauthorized access, or outright theft.

Aspects of these measures are discussed in this chapter which closes with a thorough discussion of how written documents and their approvals tended to foster good worker attitudes toward safer and more secure working conditions.

### **Alarms**

All public buildings need certain safety alarms to ensure public safety in emergency situations. This general safety consideration certainly applied to Building 886. Buildings containing nuclear materials, however, require additional alarms to alert personnel to certain other potential hazards. These include both airborne and surface contamination as well as the possibility of a nuclear criticality accident.

Building 886 was well covered for these nuclear safety concerns along with more common safety alarms.

### ***Criticality Alarm***

Any facility housing even a modest amount of fissile material bares a risk of an accidental prompt nuclear criticality accident—also called a “nuclear excursion.” Such an accident could be life-threatening to near-by persons; and immediate appropriate response is always required to mitigate injury and damage. The enriched uranium solution, alone, housed in the CML contained enough fissionable material to form over 500 simultaneous critical configurations. Building 886 warranted a well-designed alarm system.

The building’s Criticality Alarm system—colloquially called the “Crit Alarm,” consisted of multiple radiation detection chambers strategically placed throughout the Hot Area. Signals from these were coupled to an alarm-response panel connected, in turn, to an audible signal generator that sounded throughout the whole building when activated. The sound was an obnoxious wail that could never be mistaken for anything other than its intended purpose. Workers were well-trained that their response was an immediate and quick-but-orderly evacuation of the building to some designated point. The alarm signal was also transmitted to other emergency-response buildings on plantsite; and these personnel were always required to respond to any activation of the alarm.

At one time, there were three detection chambers which could initiate the alarm; but that number later increased to six. This happened when Building 875, the new Filter Plenum Building, was built in 1970. It, too, was capable of a criticality accident and needed to be monitored. The three additional detectors were placed in that building and the underground tunnel connecting it to Building 886. The initial three had been gathered side-by-side in the Hallway (Room 108) in the Hot Area of the main building. These were sensitive enough to detect neutrons from an accident anywhere in the building except that the thick walls of the Assembly Room (Room 101) may have shielded detectors from a minimum-level accident in that room. Consequently, an alternate scheme was adopted for that one room; and this is described later.

The alarm signal, itself, always required at least two of the six detection circuits be activated to initiate an alarm. Otherwise, accidental activation could occur with annoying frequency. Electrical noise signals, accidental movement of the detection chambers or their wires, and any number of other situations could cause a single channel to activate at any time. Instruments were quite sensitive. Requiring redundant channels activate minimized this potential. Any true nuclear accident capable of setting off one detection channel would certainly set off others—probably all six—as well. Even a moderate-sized accident in Building 886 might well set off alarms even in neighboring buildings.

The Assembly Room had to be monitored for this accident potential, too. That had to be done in a different fashion because of the room's thick walls. Indeed, the functional purpose of the room was to attain criticality; and the distinction between radiation levels extant at an

experiment performed intentionally at some “high” power level and that resulting from the lowest possible criticality accident might be difficult to distinguish. The plant-wide standard design criticality accident detection system might well have been set off by almost every experiment. This room was the only location on plant site where the same, raspy, Criticality Alarm wail was triggered by something other than that plant-standard design.

In that room, every critical approach experiment was routinely monitored by a number of radiation detection chambers, including both neutron- and gamma-sensitive devices. These were part of the routine approach toward criticality anyway and were intended to provide data about the experiment in progress. Most had built-in “trip” points which would close a circuit if a preset upper limit were exceeded. From the experiment's point of view, these trip points would merely shut down the experiment. These trip points, however, could provide that needed Criticality Alarm protection in Room 101. These trip points were wired into the building's overall Criticality Alarm system such that activation of any one of these trip point circuits would automatically activate the loud wail. While not a Criticality Alarm in the plant-wide sense of the phrase, the resulting sound was indistinguishable from one and was always treated as such.

### ***Building Alarm***

This protection of the Assembly Room was called the “Building Alarm.” That may not have been the most descriptive name; but, whatever it was called, it served its purpose well. The Building Alarm had to be eligible for activation throughout an experiment; but it was normally desensitized at all other times to preclude false

activations and unnecessary evacuations. The important step of sensitizing the building's Building Alarm at the onset of an experiment was ensured by including this as the final step in the Prerun Checklist of important safety items. An important observation is that, whenever the Building Alarm was desensitized, that one room was left without Criticality Alarm coverage.

Whether or not it was safe to leave this room unprotected required a continual knowledge about the absence or presence of fissile material there. Some experimental programs required fissile material be left unattended overnight in its last experimental configuration. One experimental study, for example, had 81 kg of plutonium metal confined within a small space within the Assembly Room. This had to be left overnight between successive daytime experiments because unnecessary exposure to radiation would result from daily disassembly. Furthermore, the room always contained a few waste drums for the collection of contaminated waste; and these drums would contain at least a few grams of fissile material. Building Alarm coverage probably should have been in effect during either situation at non-experimental hours; but whether or not that was always practiced is not recalled for certain. If something were to have happened to cause a criticality during these times, even that serious event might have gone undetected. The building's six alarms might have been shielded against the radiation burst by the thick walls; but whether or not that is true is not known with confidence. Fortunately, no circumstance ever developed to highlight this possible safety oversight.

An argument could be made that coverage was unnecessary because the fissile material was isolated from human contact; but others may point out that an earthquake—however unlikely in

Colorado—still might have caused material to shift. The first group could counter that with the observation that the room, itself, was *designed* to contain all consequences of a nuclear criticality accident. At this point, all arguments remain speculation.

Unlike the plant-standard Criticality Alarm design, then, criticality detection coverage in Room 101 of Building 886 was obtained from a number of electronic devices with built-in trip points; and this was called the Building Alarm. Redundant trips were *not* required to activate the Building Alarm because it was the Experimenter's responsibility to keep the instruments operating well below their trip points. Actually, some radiation-sensitive ionization chambers had two trip points built into their circuitry. The lower would initiate a SCRAM of the experiment but not sound the Building Alarm. The higher would cause both a SCRAM and initiate the Building Alarm's evacuation wail. These electronic instruments included:

(1) A pair of neutron-sensitive ionization chambers connected to a pair of low-current measuring devices. These were called the "Linear Picoammeters" because their electrical output current was linearly proportional to the instantaneous neutron population. The lower trip was set at 100% of full scale while the one which activated the Building Alarm occurred at 130%.

(2) The Log N device was another neutron-sensitive ionization chamber designed to read out both the logarithm of the instantaneous neutron flux as well as its time-rate-of-change of that flux. The former was especially useful in light of the anticipated exponential growth of the flux for a slightly super critical configuration. The natural logarithm of exponential growth produces a straight line; and the linear drawing of an inked trace from a recording pen was especially easy to

identify—the edge of a sheet of paper could prove linearity. This trip point for the logarithm of the neutron flux was set two or three orders of magnitude greater than any normally encountered during an experiment. The second function of this device indicated the instantaneous “reactor period” associated with the experiment in progress. It helped the experimental team remain within certain operational limits. This trip point would be generated if the neutron flux ever increased by a factor of  $e$  in less than 15 seconds.

(3) Still another electronic instrument measured the logarithm of the instantaneous gamma ray flux. This instrument’s lower trip, which only initiated a SCRAM, was usually a couple of decades above any normally experienced during an experiment. The upper trip—two decades greater—added the evacuation wail.

The CML never had a criticality accident; but it did have an embarrassing number of accidental activations of the Building Alarm. These happened during experiments or instrument testing procedures. Occasionally, for example, an experimenter would inadvertently switch the range selector switch on one of the instruments to too sensitive a range; and this would initiate a Building Alarm. Another time, the Instrument Technician squatted to inspect an instrument mounted low in the rack. His knee accidently depressed the instrument’s “test” button. This sent a test pulse through the instrument and caused the alarm to sound. He was embarrassed. On still other occasions, simple electronic noise signals superimposed on top of normal, very low, currents (in the picoAmpere range) caused the same effect. Fortunately, incidents of false activation happened infrequently over three decades as presented in Table VII for one ten-year-long interval. They did provide a good test

**Table VII. Accidental Criticality/Building Alarm Trips During One Ten-Year Interval**

Date	Description of Occurrence
10/18/76	Accidental bump of the “Test” button on the log gamma picoameter panel.
3/15/78	Technician was checking instruments while Building Alarm was inadvertently left ON.
5/5/78	The Cf <sup>252</sup> neutron source was brought too close to certain electronic instruments.
8/3/78	Misinterpretation of the building’s Criticality Alarm. An evacuation was ordered but no alarm had sounded.
1/17/79	Inductive coupling of transient electronic noise signal into instrument.
9/26/78	Electronic failure traced to a loose nut inside a coaxial cable that created a noise pulse.
11/23/82	Human error in making a range change on a console electronic instrument.
7/25/84	The Building Alarm was inadvertently left ON during a test of console instrumentation.
2/11/85	Accidental trip of Building’s Alarm during testing of portable alarm system.
10/4/85	Failure within an electronic console instrument. An internal circuit failed in one of the linear neutron picoammeters.

of the building’s Criticality Alarm system and personnel response to it. Aside from these unplanned incidents, the entire system was intentionally tested at least annually. This is discussed further later.

The same signal that triggered the Building Alarm automatically shut down any experiment in progress at the time; the equipment was designed to do that. This was not true of the building’s six plant-standard Criticality Alarm detectors; they just sounded the alarm. If the actual Criticality Alarm—as distinct from the Building Alarm—ever were to have sounded during an experiment, the Experimenters, themselves, had to physically initiate the SCRAM before beginning their required evacuation response.

They were well-trained to do this and never failed in that response on the few occasions it was put to test.

### ***Response to Criticality or Building Alarms***

Proper response to either alarm was an immediate, though orderly, total evacuation of the building. Classified documents could even be left unattended; and workers could exit the building even wearing possibly contaminated clothing. Immediate evacuation was considered that important! Evacuees congregated at a designated location out-of-doors and some distance away from the building. That Assembly Area was in the opposite direction (north) from the anticipated location of the accident, presumed to have been somewhere in the Hot Area. Typically, it was directly across Central Avenue just to the north of the office area on Building 886. That site was chosen because it was in the radiation “shadow” of the building. That is, the several walls of the building would also attenuate radiation streaming from the source of the accident.

One humorous event is associated with the deeply indoctrinated need to evacuate the building promptly in the event of a Criticality Alarm. This involves a talented craftsman affiliated with the Pipe Shop. The unfortunate fellow’s name was Roy Ward. After leaving the Hot Area, he entered the men’s restroom to use the seated facilities there. He was well settled within a locked stall when the Criticality Alarm sounded. His trained response was an immediate evacuation to the Assembly Area; but this was in conflict with certain bodily functions. Somewhat harassed, Mr. Ward reported to the Assembly Area but was a couple minutes late. His earlier anguish was betrayed by the fact that he had bitten his smoking pipe in half when the alarm first sounded.

Top plant management always responded to the Assembly Area, even if the event was a planned exercise. Personnel safety was that highly regarded. At the Assembly Area, other response personnel would account for all persons and monitor any suspected of having received a radiation dose. If necessary, injured or contaminated persons would be transported elsewhere according to other plant-wide procedures. These safety procedures were never needed; but they were often practiced.

Naturally, some employees with offices in the building may have been out of the building at the time of the alarm. They would not be present in the Assembly Area congregation. A simple-but-clever expedient was used to account for these persons. A metal plate was fabricated with a number of electrical, bat-handle type, toggle switches adjacent to names of individuals belonging in the building. The switches were not connected to anything electrical; the slant of the bat handle was simply used as the indicator. As a person entered the building the bat-handle was inclined toward the building. As they left, the switch was reversed—pointing away from the building—showing they were “out.” The number of switches was large enough to cover all employees routinely assigned to the building as well as frequent visitors such as Radiation Monitors, janitorial personnel, and Maintenance workers.

The toggle switch board mounted to the Guard Post through which people entered and left the building. This was also the evacuation route; so those inside the building necessarily passed by the toggle board. As they exited enroute to the Assembly Area, each person would flick their switch to show “out.” Velcro adhesive cloth strips held the plate to the wall; and this author was assigned the responsibility of pulling the board from its strips as he

exited the building in response to an alarm. Infrequent visitors were logged into and out of the building through the same Guard Post as a security measure anyhow; so that log plus the toggle switch board became a record of all persons expected to be in the building at the time of the alarm. This personnel accountability procedure was simple but effective. It worked well and never introduced confusion.

The physical location of the Assembly Area was moved a few times during the three decades; but it generally remained in the same general vicinity. One safety theory postulated that the Assembly Area should be indoors to protect evacuees from possible airborne contamination. This was tried using Building 865, northwest on Building 886, as the Assembly Area; but that location required an evacuation route through a possible radiation stream if the accident had occurred in Room 103. That proposal did not last more than a few years. Fortunately, no activation of that loud, raspy wail was ever in response to an actual criticality accident.

### ***“SAAM” and “CAM” Alarms***

A number of other alarms and safety messages were employed in Building 886. One of these was the Selective Air Alpha Monitor, often called the “SAAM” alarm. This was a device that detected airborne contamination. It continually sucked room air through a porous piece of filter paper. The paper was continuously monitored by solid-state alpha-particle detectors such that radiation streaming from entrapped airborne plutonium or uranium contaminants would be detected. If a preset level were exceeded, the SAAM Alarm would sound. The audible sound was an almost musical tone varying sinusoidally in pitch and somewhat reminiscent of a European police car. Building 886 had only two

SAAMs: one in Room 102, the other in the filter plenum building (Building 875). In response to this alarm, personnel were required to don respirators which were required to be always “at the ready” when in the Hot Area. This alarm sounded very seldom, although it did happen on rare occasions.

Breathing air within the Hot Area was also continuously monitored by a number of Air Head sampling stations. These were called Continuous Air Monitors (CAM) and similar to the SAAMS except that they did not sound any alarm. Filter papers were changed daily at the end of a day and counted for alpha activity. Comparing results spanning several days allowed slow build-ups to be seen easily. Several Air Heads were distributed throughout the Hot Area: two in Room 101, one in Room 102, and three in Room 103. The last might be more prone to airborne contamination because a small leak might go undetected for a few days such that a few drops of fissile liquid could dry before becoming airborne. Air Head information was retained in another building (Building 123) on plantsite for many years; but data for Building 886 has probably been lost long ago. No significant problems with airborne contamination were ever encountered anyway.

### ***Fire Alarm***

Fire-related problems throughout plantsite—including Building 886—were easily reported in a number of ways. The alarm could be reported to the Fire Department by activating any manual Fire Alarm station in the building. One could telephone a plant-wide emergency response number, 2911, a logical extension of the now-familiar 911 emergency phone number in common use. Additionally, any

problem could always be telephoned directly into the Rocky Flats Fire Department (Building 334) or the plant's Dispatcher's Office, 2444, via normal telephone use. All three of these numbers could be used to report a fire or any other real or imagined emergency. The manual station caused the Fire Alarm bell to sound automatically; but telephone reporting would not. The alarm, itself, was a raspy, metallic gong sounding a few times per second. It was loud enough to be heard anywhere within the building.

A worker's response to a Fire Alarm differed from that of a Criticality Alarm. Immediate evacuation of the building was not required, although this standing order could be countermanded via the public address system. To this author's recollection, that never happened. Every worker in the Cold Area, upon hearing the Fire Alarm, was to have their half-mask respirator "at the ready." That is, their currently certified respirator was to be somewhere on or near their desk, ready to put on if instructed to do so. Workers in the Hot Area were to put on their respirators and proceed to a place where they could respond to instructions from persons in the Cold Area. This author cannot recall this procedure ever being put to test either.

Building 886 was also protected by Heat Detection heads mounted in ceilings of every room with several heads in larger rooms. All sensors in both the Cold and Hot areas automatically reported activation directly to the Fire Department. In the Cold Area, activation would trigger a sprinkler system; and the water spray was expected to extinguish any fire. The passage of water through the dedicated fire-water fire suppression system caused one other fire-related alarm to sound. This was a metallic "dinging" physically caused by flowing water making a wheel turn within

a piece of commercial hardware. This "fire water flow" alarm was not very loud but could be heard in the Mechanical Room (Room 111).

Sprinkler protection in the Hot Area, on the other hand, was not allowed for two reasons. Fissile material (plutonium more than uranium) is corroded with water; and, second, water introduces a potential criticality hazard due to the introduction of unwanted neutron moderation and reflection. Water posed too great a risk. This area was protected just with Heat Detectors. In later years, this area was securely locked off-hours and rapid response to any fire reporting may have been difficult. Fortunately, this perceived weakness was never put to test because no fires ever occurred in Building 886.

At one time, sprinkler protection in the Control Room (Room 112) was questioned because the water spray would almost certainly ruin a lot of expensive electronic equipment. The room was engineered for replacement using Halon, a gaseous fire suppressant; but whether or not this conversion was ever actually accomplished is not recalled.

No fire ever occurred anywhere in Building 886 or its auxiliary buildings, although alarms and people's responses to them were tested periodically.

Rocky Flats conducted a program of doubtful merit (this author's opinion) during the 1980s. This was to train ordinary employees in certain emergency response activities. Accordingly, physicists associated with the CML became members of the "Fire Brigade" and the "Bomb Search Squad." Monthly training and practices probably did add to the student's knowledge and understanding of these scenarios; but it is doubtful how well these people would have responded in a true emergency. This author views his training

as a member of the Fire Brigade as more useful in his planned emergency response to a home situation rather than any plant-related activity. Fortunately, neither training ever actually was put to test.

### ***Public Address System***

Plant-wide warnings and other safety messages could be heard over the building's Public Address system. This system continuously played soft music as an indicator that it was always operational; but the music could be interrupted for important safety or security announcements. These interruptions could come from the plant-wide Dispatchers Office, a few other safety-related buildings, or Building 886 directly. Local activation would momentarily override background music.

Interruptions from outside the building usually contained information of general interest to the plant as well as comments directed specifically to Building 886. Local announcements might acknowledge that an uncleared person was about to enter the building. This would serve as an alert to people inside the building to protect and/or secure classified documents. It could also be used to announce building meetings such as Safety Meetings or professional discussions in Schuske's office with technical visitors from off plant site. Finally, it was also used to call people to the office when needed or to alert them to a telephone call. The ability to make building-wide announcements from a microphone in the Main Office was never abused with frivolous proclamations.

### ***Life Safety Disaster Warning***

The building's Public Address system was used for one other general type of safety warning. This was called the Life Safety Disaster Warning system—or LSDW. This would be used to warn the entire plant or specific buildings of impending safety issues. This might include natural disasters, terrorist attacks or threats, contamination incidents affecting a large population of the plant, bomb threats, and a host of other similar situations. It was also used for less-threatening conditions. When used in this mode, the plant-wide Public Address system would be interrupted by a series of short beeps; and this would be followed by a verbal announcement of general interest to the plant population.

In summary, the set of alarms and methods of communicating important information throughout the building in a timely manner was quite sufficient and functioned well for decades.

## **Protective Clothing**

### ***Cold Area***

Ordinary street clothing<sup>62</sup> was worn while employees worked in offices and other rooms within the Cold Area. As the

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<sup>62</sup>Interestingly, this dress code for casual street wear was subject to the country's fashion-conscious public. Gentlemen of the 1960s and early '70s usually wore a white dress shirt and a tie as slide rules and manual typewriters were manipulated in Building 86. Suits were not worn except for special visitors and more-formal occasions. The bow tie was in vogue for several years. Dress slacks completed the professional appearance. Women wore professional-looking dresses. As years passed, everyone's dress became less formal. Ties disappeared and shirt collars were left open. Women even wore dress slacks to work. Comfort replaced formality at Rocky Flats just as it seemed to do nationwide.



name implies, that portion of the building was free of contamination and shown to be so by periodic surveys described later. Only rarely was any contamination discovered somewhere in the Cold Area; and even this was always traced to being tracked there from the Hot Area by one of the workers.

Maintenance workers wore company-supplied coveralls which were either freshly laundered or had been shown by careful survey to be free of fissile contamination. In earlier years, this clothing was the same white coveralls worn in the Hot Area; but, by the early 1990s, color-coded clothing became the vogue. These were green, gray, blue, orange, and perhaps a few other colors. Green was worn by analytical laboratory personnel; blue was associated with beryllium work. Gray was the color worn by maintenance workers before they changed into clothing suitable for work in a hot area.

### ***Hot Area—The Casual Visitor***

Apparel was different in the Hot Area. Contamination was known to exist in certain areas and was possible about anywhere. Considerable effort was expended to keep this area as free as possible of contamination; but the *potential* for contamination was sufficiently high that precautionary measures were introduced early on.

The “casual visitor” was distinguished from the worker who knowingly was to work with fissile material; and the two will be discussed separately. Persons entering the Hot Area just to “look and not touch” were required to wear freshly-laundered canvas shoe covers—called “booties”—over their street shoes. These shoe covers had an elastic band that held them against the upper part of the shoe and a gritty

bottom that ensured good non-slip traction. A knee-length white fabric smock, sometimes called a lab coat, was worn to protect street clothing from casual contact with hidden contamination; and this buttoned down the front. Safety glasses were required. Most workers had their own plain or prescription glasses, although some visitors had to wear inexpensive plastic safety glasses. These were not very comfortable but were deemed adequate. Finally, the visitor had to wear a half-mask respirator suspended around the neck. A good practice (not always followed) was to wear this respirator with the rubber face piece against the chest. That would prevent undetected contamination from collecting in the portion of the mask later to be placed over the face and mouth if the mask’s use were suddenly required.

The same casual visitor exited the Hot Area at the Airlock (Room 108). A trained person called a “Radiation Monitor” would survey the visitor’s smock, personal clothing, hands, face, and feet for contamination. Any items carried with them were also surveyed for contamination. This practice proved quite effective. Almost never did any visitor or their hand-carried items pick up any contamination; and, if they did, it was quickly detected and dealt with. Canvas shoe covers were, perhaps, the one item most often found to have unexpected contamination. With safety glasses removed and both respirators and shoe covers placed into drums headed for plant laundry, the casual visitor was free to walk about the plant site and carry on with other business.

No cases are known where this practice failed such that undetected contamination was carried away from the building. Everyone recognized the important need to prevent contamination spread.

### ***Hot Area—The Worker***

Persons handling fissile material directly dressed quite differently. White fabric coveralls were worn over company-owned white underclothes (t-shirts and underwear). Company-issued steel-toed safety shoes were worn over white sox. This apparel was put on in the men's restroom immediately adjacent to the Air Lock. Sometimes, depending on the nature of the work to be done, a white cloth cap was worn over the hair. White was probably selected for all this clothing because it showed quickly evidence of dirt and smudges which might carry contamination with them. This dress mode persisted on into the early 1990s.

The worker was now almost ready to enter the Hot Area. First, the same canvas shoe covers worn by visitors had to be worn over company-owned shoes. A respirator was also required. This could be the same kind of half-mask used by the casual visitor; or the nature of the work might call for use of a full-face respirator. Respirator and shoe covers would be put on in the Airlock. Latex rubber surgeon's gloves were used to protect the hands from contamination. Some applications called for one pair of these gloves to be taped over the sleeves of the coveralls with a second pair slipped over the first. These gloves were put on before entering the Hot Area. The worker was now ready to enter the Hot Area and commence the day's activities. Once inside it, gloves were changed often at the direction of the Radiation Monitor.

Occasionally, this enhanced-protection procedure for working with fissile material was allowed to be circumvented by scientists within the CML. This was only done because of their long-standing experience with the fissile materials coupled with their knowledge of the contamination character-

istics of the materials to be handled. For example, the enriched uranium metal was so well coated with a thin coat of petroleum jelly that shells could be handled for short periods of time wearing the same smocks worn by casual visitors. Only latex surgeon's gloves would be worn additionally to protect the hands from direct contamination. This was not a good practice; but no contamination incidents stem from the occasional practice.

Exiting procedures from the Hot Area were quite similar for both the fissile material worker as well as the visitor. Contamination simply had to be contained within the Hot Area. When contamination was detected on the company-owned clothing, the affected worker was stripped of outer clothing right in the Airlock. When this was necessary, the clothing would be removed inside out to contain the contamination and prevent it from spreading. All workers were required to take a shower before putting on street clothing. This was so whether the work day continued or the worker went home.

Humorously, the CML facility was built with no thought that any worker in the Hot Area would possibly be female. This oversight seems incredulous in light of today's social thinking. Still, women had to change clothes and shower before leaving the building. On these rare occasions, the affected woman would be given private and exclusive use of the men's restroom and its shower. A "guard" would be posted at the door to prevent accidental entry by the male population accustomed to ready access to the facilities whenever the need arose.

These early-day procedures worked remarkably well. Radiation Monitors were dedicated persons; and the workers, themselves, were motivated to leave contamination at the plantsite. No one hurried the careful surveys of exposed

body parts and clothing. All of these precautions changed markedly over the life span of the Rocky Flats Plant. Procedures described above were common, at least in Building 886, through the early 1990s. Much-improved procedures came into common practice plantwide after that; and these are discussed a bit later.

In retrospect, some early actions performed by this author would certainly have been done differently in light of present-day thinking. For example, he once allowed himself to be lowered one-and-a-half meters into a meter-diameter tank for the purpose of scraping several millimeters of concentrated uranyl nitrate solution from the bottom of the tank down into its SCRAM tank. The sides of the tank were also heavily contaminated but not puddled with liquid. He used a Teflon blade to do this scraping. For this tricky task requiring good balance, he wore company-owned white fabric overalls with white under-clothing. Cloth fabric would easily absorb any contamination splashed onto it. Safety shoes were covered with booties and an additional plastic bag slipped over the feet (knowing they would be disposed of as contaminated waste). He wore two pair of rubber gloves and a half-mask respirator. He could even smell nitric acid fumes through the respirator. The whole operation took only about 10 minutes; and he worked very carefully. Happily, he emerged from this balancing operation losing only the plastic bags over the shoes and the rubber gloves. Today's more-cautious procedures would not allow this operation. Extra operator caution is now seldom used to replace physical protection.

Today's decontamination worker at Rocky Flats dresses outwardly much different. The clothing is called "Anti-Contamination," or Anti-C, protection. The white outer clothing is

made of Tyvex, a plastic material that does not absorb liquids. The face and entire head is completely covered. Breathing is done either through "supplied air" or "self-contained-breathing-apparatus." In the latter, the worker carries the air supply with him and must leave the work area before the supply runs low. In the former, air is pumped into the suit from a compressor unit in a safe area. Later variations of this breathing apparatus were termed "Air Purifying Respirator" (APR) and "Powered Air Purifying Respirator" (PAPR). Working under these conditions is tedious and hot. This author has very limited experience with modern Anti-Contamination clothing and procedures. A photograph of modern Hot Area workers is shown in Fig. 99.

## **Radiation and Contamination Safety**

### ***Contamination***

Any building containing fissile material is susceptible to many forms of worrisome contamination. Solid surfaces can become contaminated and require cleaning. People and clothing can become contaminated and carry that problem off plantsite if not detected properly. Breathing air can collect airborne contamination requiring use of respiratory protection. Air discharged up the exhaust stack to the environment must be monitored to prove to a questioning public the safety of the air they breath. Land surrounding the plant had to be monitored for the same reasons.

All these responsibilities fell generally under the domain of one important organization at Rocky Flats. Called by several names over half a century of service, thousands of industrial workers owe their continued health and comfort in retirement



*Fig. 99. Modern Anti-Contamination clothing does not expose any part of the body to the immediate environment; and the outer layer is non-absorbent. Two Radiation Monitors appear to flank production workers. The scene is the Pit Area of Room 103 in September of 2001.*

years to these person's daily diligence. A few labels were: Health Physicist, Radiation Monitor, Monitor, Radiation Protection Technologist (RPT), Radiation Control Technician (RCT), and Radiological Engineer. These men and women were assigned to every building handling fissile materials in proportion to the number of workers at risk. Building 886 had one person assigned to it most of the time. Heavy work loads sometimes found an additional helper in the building. Although others preceded him, one man served the building in this capacity for a couple of decades. His name is Gilbert (Gil) Garcia; and this author personally acknowledges his devotion to his profession as well as his personal friendship.

Tools of their trade were many—both simple and sophisticated. Radiation surveys of skin, clothing, and personal belongings in search of contamination were accomplished with a sensitive meter responsive to alpha radiation. All fissile materials give off alpha radiation; and this portable device was set low enough to detect even very low levels of contamination. The meter itself, called a Ludlum 12-1A, was usually worn around the Monitor's waist with the detection surface at the end of a meter-long electronic cable. Secondly, solid surfaces could be rubbed with small circles of filter paper smearing a portion of any contamination onto the paper. Then, these disks could be inserted into a device to measure the level of contamination, if any, on the surface

smear. These, too, were alpha-sensitive instruments. Third, Monitors were responsible for obtaining and logging results from many air sampling stations such as “Selective Alpha Air Monitors” (SAAMs) and “Continuous Air Monitors” (CAMs), discussed earlier. Next, Monitors were also responsible for the periodic counting of air samples from the exhaust stacks. Finally, Monitors took gamma and neutron surveys of all areas within the Hot Area.

Workers, themselves, had some responsibility for and opportunity to remain contamination free. They could check themselves on either of two kinds of instruments available within the Hot Area. One was a waist-high sheet metal box called a “Combo” or, more colloquially, a “tin monitor.” It housed a probe that could be used for detecting alpha contamination on both sides of the hands. The probe was attached to a long cable also; so it could be used to check clothing and belongings. A lower second probe could be used to check for contamination on the bottoms of canvas shoe covers (booties). Two of these were found in the Hot Area of Building 886—one in the Airlock, the other could be moved about to wherever it might prove most useful. The second instrument was called an “Alpha Met.” It was similar to the hand probe on the above Combo. Several were mounted to walls and other hardware throughout the Hot Area. One could check one’s own hands for possible contamination right at the work site. Both devices had a visual readout of the contamination level. The first also had audible readout. Neither device was ever used in lieu of a trained Radiation Monitor; but both were useful for periodic interim safety checks while work was in progress.

One other concept in the war against the spread of contamination was the “Step-Off Pad.” This was a region of floor space, painted yellow, where the Radiation Monitor stood on the “cold” side while the

suspect worker remained on the “hot” side. The monitor would carefully scan skin and clothing for contamination before asking the worker to lift his/her feet, one at a time, to survey the soles of the shoe covers worn. If the torso was free of contamination, “cold” shoe covers would step across the step-off pad into the “cold” portion while a contaminated shoe cover had to be changed before making that step. The vision of sometimes heavyside workers encumbered with anti-contamination clothing, a respirator, and other paraphernalia awkwardly balancing on one foot while changing a bootie was sometimes quite humorous.

## ***Radiation***

Most fissile materials are emitters of natural radiation irrespective of any contamination issues. This radiation constitutes a potential hazard to human tissue. All personnel were monitored as a means of establishing practices that could reduce these exposures to a minimum. Toward this goal, workers wore badges capable of detecting a wide spectrum of radiation. These were worn whenever they were present in a building containing fissile material. These badges were called “film badges” because they contained small pieces of photographic film which would cloud over if exposed to certain radiation. The badge also contained a button of sulfur and bits of other metals which would become activated upon exposure to high levels of neutron radiation. Later models of these badges housed a number of thermoluminescent devices (TLDs). All in all, the badge was a clever design of radiation-sensitive materials; and it was capable of detecting both accumulated doses of low-level radiation as well as huge bursts of radiation. The former served day-to-day exposures and allowed a detailed history to be developed for each employee.

The latter might be the result of an accidental prompt nuclear criticality accident. If that ever were to have happened, the badge would have been an invaluable tool in reconstructing radiation doses following the accident. Fortunately, this was never called for.

Post-accident analysis of radiation levels following a criticality accident would be aided by specially designed high-burst radiation dosimeters. These would be hung around anywhere such an accident might occur. They would be ignored most of the time because their intentional response was only to radiation levels of 10 Rad or more. They would only prove useful in response to a criticality accident. Other facilities throughout the United States used a design called the Hurst Dosimeter (spelling uncertain). The need for such a design plantwide at Rocky Flats was recognized during the 1980s; and Dr. Robert E. Miles of the CML designed a dosimeter for use there. Building 886 only used his design during the last few years of productive operation. Mile's design is called the "Fixed Nuclear Accident Dosimeter" (FNAD); and dozens of these units still exist throughout plantsite. A photograph of one is shown in Fig. 100. His initial design work was aided by one series of experiments performed at the CML. These were part of a routine experimental study except that special instrumentation was placed throughout the Assembly Room and the experiment was run at about an order of magnitude greater power level than normal and criticality was maintained for longer than usual.

Gamma radiation while working with plutonium was an annoying nuisance. "Fresh" plutonium as used elsewhere on plantsite was comparatively low in gamma emissions. Older plutonium presented a greater problem. On occasion in Building 886, workers with older plutonium metal<sup>64</sup>

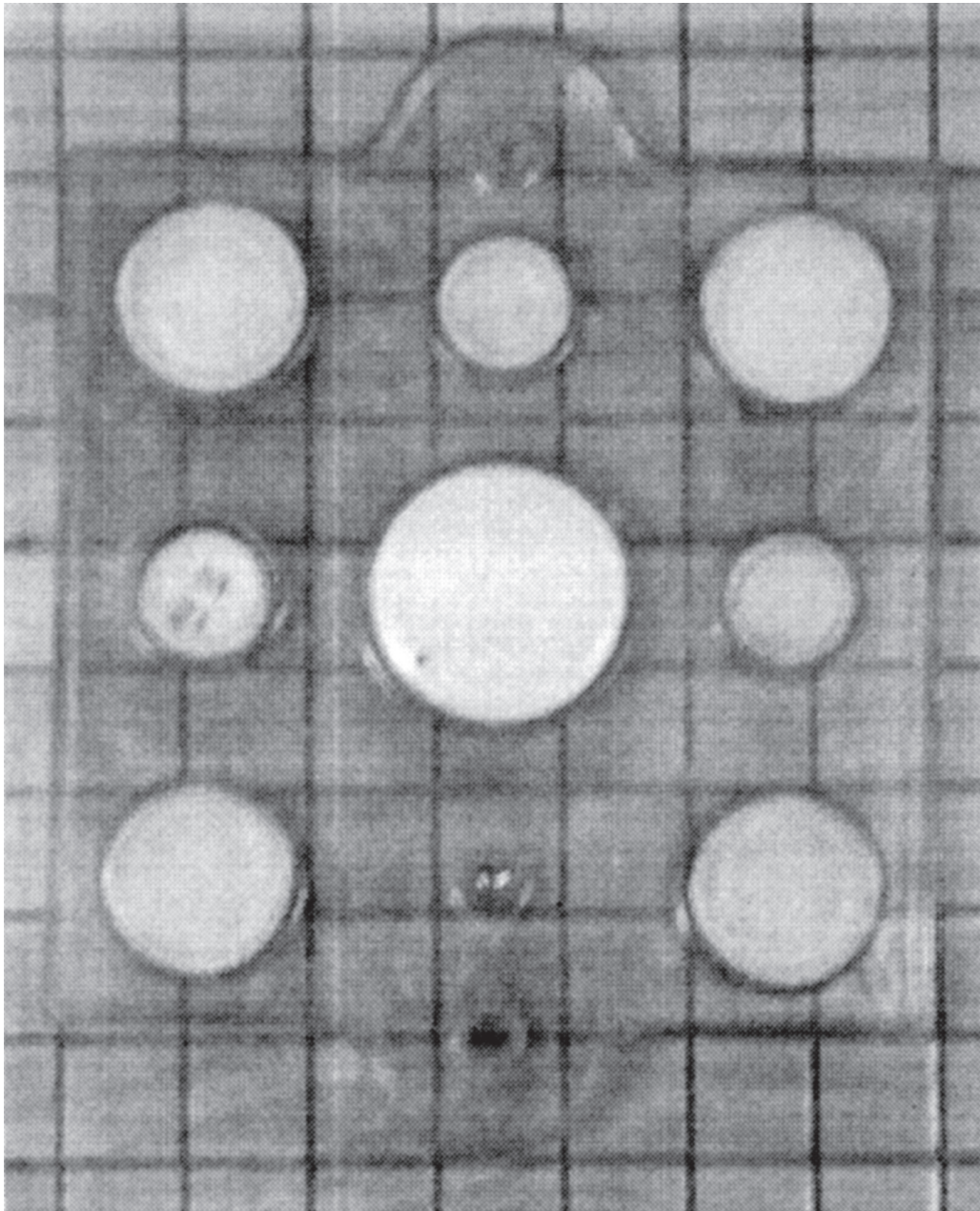
wore additional "wrist badges." These were strapped to the wrist much like a wrist watch and contained TLDs. They measured the radiation dose to the hands of the worker. Occasionally, a TLD would be taped to a worker's forehead as well; and this measured the dose to the eyes and brain. These extra precautions were more intended to prove that important parts of the worker's body had *not* received radiation than to casually measure the amount of radiation impinging onto important body parts.

Although nuclear workers are allowed to receive certain small amounts of radiation, according to government guidelines, to various vital organs and appendages, the goal throughout the plant was to keep the total exposure very much below even these low limits. This became known as the "ALARA Principle." The acronym means: As Low As Reasonably Achievable. This concept was quickly adopted plant wide with considerable enthusiasm. Even on into the early 2000s, this principle has become personified in plant publications as two persons named Al and Lara. Access roads into the plant boast series of signs reminiscent of the nostalgic Berma Shave signs so common half a century ago. Signs entering and exiting the plant entertain with the words:

"Al and Lara Say  
(Submit your suggestion)  
At our site...  
"This very day...  
We plan the work...  
Reduce your dose...  
To get it right."  
Make it pay."  
Alara  
Alara

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<sup>64</sup>Plutonium inbreeds Americium as it ages; so older plutonium is a strong emitter of gamma radiation. By 1983, the plutonium metal used in experiments was almost 20 years old.



*Fig. 100. Fixed Nuclear Accident Dosimeters (FNAD) still hang in many places throughout plantsite. They are not needed unless a criticality accident occurs because it is designed to measure only very large doses of radiation. The outline of the device may be hard to discern against the cross-hatched background.*

To this author's knowledge, no worker in Building 886 ever received doses greater than a few percent of these already low limits.

Experimenters in the 1970s and early 1980s sometimes wore flexible aprons containing lead when working with the older plutonium. This was to attenuate the gamma radiation from the fissile metal. These aprons hung around the neck and tied behind the back. The aprons protected major internal and reproductive organs within the body. Flexible arm-length

gloves, also containing lead, were sometimes worn, too. These minimized dose to the fingers. Large plutonium arrays were assembled behind a three-sided lead-lined plastic shield assembly; and this further reduced radiation incident upon the body of workers. Figure 101 illustrates these radiation protection steps. The photograph was taken in May of 1974; and the metal was kept almost another nine years before being returned to the production stream. The Americium content was quite high by 1983.



*Fig. 101. The author is properly dressed for handling canned plutonium metal containing a considerable amount of Americium because of its age. Older plutonium becomes a strong gamma ray emitter. The glove and apron contain lead yet remain flexible. His film badge is worn inside the apron and the wrist badge under the glove. A half-mask respirator (not seen) hangs from his neck with the face seal against his chest. Glasses are safety glasses. Storage containers (foreground) for the plutonium are water-filled and lead-lined inside. Over 60 kg of plutonium have been assembled behind the three-sided shield in the middle of the photograph.*



Gamma radiation was often measured by Radiation Monitors using an instrument named a Victoreen 440. Aside from older plutonium, other sources of gamma radiation made this safety a necessary precaution. In Building 886, for example, the uranium solution would sometimes exhibit elevated levels of gamma radiation following a particularly long critical experiment or one operated at a higher-than-normal power level. In these experiments, the solution would accumulate increased amounts of radioactive fission byproducts. These isotopes were short-lived heavy gamma emitters. Fortunately, the same instrument always showed a decreased gamma ray flux to an acceptable level by the following day.

#### *Bio-Assay*

Plantwide, many other measures were taken to monitor radiation workers; and this included those in Building 886. Workers were subject to periodic measures of radioactivity in both urine and fecal samples. A day's urine production, for example, would be boiled to dryness and the residue counted for radioisotopes.

Each fissile worker also had regularly scheduled lung tests to measure any fissile material breathed into their lungs. This was a pleasant test because workers were encouraged to fall asleep while lying on a comfortable bed in a quiet and darkened room listening to soft music for about half an hour. During their rest time, large gamma ray detectors (sodium-iodide and, later, germanium) rested lightly on their chest. The room was constructed of steel recovered from pre-World War II navel vessels (with lead, tin, and zinc plated onto inside surfaces) to eliminate any radiation derived from radioactive fall-out; and the thick walls shielded the detectors from

cosmic and terrestrial radiation. Finally, special, freshly laundered—and radiation-free—loose-fitting clothing was worn to make the rest even more comfortable. This device detected the presence of fissile material down to a very few nanoCuries. This procedure was called a “Lung Count;” and the standard quip was that the worker only had two. No worker in Building 886 is believed to have received any measurable “lung burden” based on this test. Plantwide, precautions against internal contamination were carefully thought out; and test measurements to detect the same were very sensitive.

Occasionally, a worker might sustain a laceration of the skin within a potentially contaminated area. Rocky Flats was well-equipped for this event. Devices called “Wound Counters” could be inserted right into the cut or puncture and measure the possible presence of fissile material. Workers had a good sense of medical coverage for any medical emergency at the plant.

#### ***Public Safety***

From a public perspective, still other measures were taken to protect the community as well as plant workers. Even through the first decade of the new millennium, the plant remains surrounded by a curious arrangement of technological gadgets. These mechanical devices are designed to sample continuously air, water, and soil in the vicinity of the plant site. Such environmental safeguards inform everyone of any small amount of contamination which might escape the plant's boundary.

## Industrial and Nuclear Safety

### *Industrial Safety*

Many alarms and safety precautions discussed elsewhere in this chapter are unique to the nuclear industry. A number of other safety measures at Rocky Flats, however, are common to every industry which employs human beings as workers.

Entering a new job at Rocky Flats opened this author's eyes to a whole new outlook on the issue of Industrial Safety. He had come directly from an academic environment (experimental nuclear research at the university level) where safety was always *presumed* to exist; it was never *talked* about. Naturally, each PhD candidate cared for his/her own well-being and would never intentionally perform any unsafe act. Still, nagging cuts and bruises from "unanticipated accidents" were explained away as unavoidable occurrences. The different approach to safety at the new job proved this explanation false.

Workers at Rocky Flats actually *talked* about safety. Building 886 even conducted monthly Safety Meetings. Plant management issued safety directives; and clever slogans about safety appeared all over plant site. Printed forms, called a "Work Permit", had to be filled out before even the simplest maintenance task could be started. This was a whole new outlook on one aspect of life previously taken for granted by this fresh, young PhD. He mused over this new-found philosophy for a while but soon came to appreciate the unexpected worth of a good attitude and work ethic toward industrial safety.

Signs on the entrance road proudly announced the number of million man-hours worked without a disabling accident. The number "10,000,000" seemed impressive; but the numbers grew. Every few

weeks in the mid-1960s a larger number was posted: "15,000,000," "18,000,000," "22,000,000!" Maybe this attitude toward safety had a point. In time, the sign read: "24,000,000 Man-Hours Worked Since the Last Disabling Injury." The plant was actually buzzing over the possibility of achieving 25,000,000. People talked about it. The plant newspaper boasted about it. Plant management issued congratulations and encouraged continued diligence. A new telephone extension was even created for anyone to phone for recorded safety messages and the latest data on the plant's growing record. That telephone number was "25-GO!" (x2546). That extension is still operational three-and-a-half-decades later. The author phoned it just after composing the preceding sentence and heard safety messages.

Sadly, the string was broken at 24,295,542 man-hours. The goal was never achieved. A puncture wound in July had led to a day off three months later. The plant had to start over.

A plantwide contest for a safety slogan captured the imagination of the entire population. From the hundreds of entries, the winner was:

*"Plant Safety. Watch it Grow"*

This catchy slogan—replete with multiple meanings—is still remembered many decades after its use. It had been emblazoned on the curved wall of the plant's huge cylindrical tank used for storing fuel oil.

Building 886 fell into the spirit. Monthly Safety Meetings always included findings from a two-person safety audit team. Before the meeting, this team of two had walked around the building searching for questionable safety situations. Almost everyone participated in this routine; and dozens of fresh eyes in the course of a year gave fresh perspective to each audit.

One team might focus on possibly frayed electrical connections. Another might emphasize how ladders are stored and whether or not the ladders, themselves, were properly certified. Tripping hazards, pinch points, top-heavy storage, and a myriad of other easily overlooked safety concerns were identified. Typically, Work Orders to avert an accident were written almost on the spot in response to these findings. Few people grumbled about having to pause in their professional tasks to attend Safety Meetings.

### ***Nuclear Safety***

Still another monthly safety review in Building 886 was the periodic comparison of practices involving fissile material against the written requirements of posted “Criticality Limits.” Any deviation from these limits could result in the offender being assigned a “Criticality Infraction.” Such infractions were taken seriously by upper plant management, the offender’s immediate management, and the offender himself/herself. Flagrant or willful violations could result in termination from the plant or, at least, reassignment to work not involving fissile material. Fortunately, this never happened within the CML and almost never happened throughout the entire plantsite. Some Limits were posted at the work site where they most applied; but all Limits, posted or not, were considered binding on the fissile material user.

Crit Limits were taken seriously because a criticality accident is a serious event. Three consequences include a (small) explosive yield, an instantaneous high burst of penetrating radiation, and the creation of a huge inventory of long-lived radioactive byproducts. If an accident were to occur, people were trained in specific and immediate responses which have been

discussed earlier and will not be repeated here.

Rocky Flats—and Building 886 in particular—had a good attitude toward both industrial safety and nuclear safety. Perhaps this attitude is reflected in the proud right to declare that nowhere on plant site has a nuclear criticality accident ever happened during almost a half a century. Few other plants can boast such a record. The almost 25,000,000 man-hours worked between disabling injuries is the second longest in the nation’s industrial history—an admirable record.

### **Safety of Experiments**

Experiments involving fissile materials received additional safety attention. In addition to expected safety features which would have existed in any building handling fissile materials, critical experiments—by their very nature—demanded a number of additional safety considerations. These experiments would penetrate well into delayed criticality; and, yet, they had to remain well-below prompt criticality. Exceeding the later would constitute a nuclear accident (a prompt criticality excursion). The thin, narrow, band between the two physical states is colloquially called a “dollar.” Experiments at Rocky Flats were conducted between a “few cents” to “several cents” into delayed criticality. Still, the relatively close proximity to prompt criticality demanded enhanced safety measures.

These measures included more-detailed inspections, certification of operating conditions, certification of personnel, an in-depth review by a multi-faceted committee, another internal safety review by personnel of the CML, and a number of other features. This whole process became so complicated that an unofficial

Experiment Safety Check List was devised to ensure nothing got overlooked. This list was not required in any document; but it did remind the Senior Experimenter in charge to address all requirements. The Check List proved so useful that it became a self-imposed requirement through an internal CML document. The actual status of experimental preparations would be compared against this list before the first experiment began.

The proper approval of the Experimental Plan was the first item on this list. Over a dozen signatures were required for that approval; and these included high-level plant management. Moreover, that Plan had to contain a detailed description of equipment and instruments to be used and procedures to be followed in all phases of the experiment. It further identified the acceptable range of parameters and specified limits to these. The Plan also showed that the worst credible accident produced fewer fissions than the facility's Maximum Credible Accident (MCA) specified in another document, the Safety Analysis Review (SAR). The Plan also demonstrated that the temperature coefficient of reactivity was, indeed, negative. This means that, as the fissile assembly heats up thermally, reactivity will tend to decrease—rather than increase—as components expand. It also contained a copy of the Pre-Run Check Sheet. This was a one-page document that had to be filled out and signed each day before the day's experiments could proceed.

The Check List went on to verify that experimental equipment had been load-tested and shown to function properly in all respects. This included during reactivity additions at a wide range of rates, reactivity removal, and proper response to a SCRAM signal. Equipment so tested included the Horizontal Split Table, the Solution Base,

vertical-standing concrete reflector panels, tanks and other apparatus which would later contain fissile solution, and an endless variety of other items. In addition to load testing, seismic considerations had to be considered, too. Each electronic instrument was subject to a Quality Assurance (QA) program; and the list reminded the Experimenter in charge to verify that status. The Senior Experimenter was also reminded to show that the CML Facility, itself, was current on its required annual leak rate measurement as well as all 6-month and 12-month instrument checks.

Two safety reviews were required by different sets of individuals with any findings addressed and satisfied in writing. The first was an inspection by the entire scientific staff of the CML. They were looking for weaknesses which could be corrected before the larger, more diversified, committee—the Nuclear Safety Committee—was invited to critique the planned program. This committee will be discussed more later. Their membership spanned a widely diversified arena of safety disciplines; and they took their charge seriously.

Finally, the Safety Check List prompted the Senior Experimenter to verify that all persons participating in subsequent critical approach experiments were fully trained and certified. This certification is discussed in depth later; and it was renewed annually. Both Senior Experimenters and Experimenters were certified separately.

## Documentation

All this safety<sup>65</sup> naturally must be supported by documents. These papers set the standards for all aspects of safety. They were well-written, periodically reviewed, often updated, and religiously followed. They served their purpose well.

## Safety Analysis Review

The very first of these safety-related documents, both in fundamental importance as well as date, was the facility's Safety Analysis Review (SAR). This 130-page-thick volume was written in the form of an unclassified addendum<sup>66</sup> to a still-classified report, RFP-334. The document was reviewed and updated annually; and a fresh page of signatures attested to the reviewers. The latest revision was dated in 1988. The document contained twelve chapters and five appendices. The body of the text occupied the first 97 pages. The first few chapters defined the objective of the facility, described its program, listed administrative controls, described the physical plant, and discussed the handling of fissile materials. The avowed objective of the experimental programs was stated as:

The experimental program at Rocky Flats consists of critical and subcritical measurements of various forms of fissile material ranging from powered oxides to solutions and metals. The experimental cores range from fully reflected to essentially bare. All experiments are run at essentially zero power.

<sup>65</sup>As this page is being written in draft form, the United States of America stands in mourning. The date is September 11, 2001. Terrorist attacks have taken place against the World Trade Centers as well as the Pentagon Building. The world is stunned. Irony befits this discussion about safety.

<sup>66</sup>“Addendum to RFP 334. Safety Review of The Rocky Flats Nuclear Safety Facility.” DOE Contract #DE-AC04-76DPO3533. Original issue: October, 1964. Last revision: August 1988.

The SAR's chapter on Administrative Controls defined the requirements of persons conducting these experiments, called for the preparation of an Experimental Plan, mandated daily pre-run checks and door interlocking, and specified the use of an external neutron source for uranium experiments. It also delineated the method to be used to ensure safety of critical approaches: the reciprocal multiplication technique. The next six chapters—two-thirds of the SAR—was devoted to the establishment of a Maximum Credible Accident (MCA) for the facility. This was discussed from many points of view and yielded a quite reasonable estimate of the magnitude of this kind of nuclear accident.

Two MCAs were calculated. The one for plutonium metal came to  $9.27 \times 10^{18}$  fissions with a “high explosive equivalent” of  $1.8 \times 10^{-3}$  pounds of explosive—one-third of a single stick of dynamite. Many people express explosive yield in those terms. The uranium MCA came to  $1.8 \times 10^{18}$  fissions with an explosive equivalent of  $3.6 \times 10^{-5}$  pounds of explosive. Either fission burst, while not enormous, would/could be lethal to persons close to the accident even though the high explosive yields were really quite small. They might break nearby glass and lift ceiling tiles; but neither would damage the building otherwise.

The first Appendix answered questions raised about the facility and often referenced the document itself for those answers. Another Appendix defined and established the Nuclear Criticality Safety Committee (NCSC)—also called the Nuclear Safety Committee (NSC). They were an important facet in the safety features of critical experiments and are discussed later. The final Appendix, added in February, 1975, introduced the Filter Plenum Building, Building 875.

### **Technical Specifications**

This document, “Technical Specifications for the Rocky Flats Critical Mass Laboratory,” formed the primary governing agreement between the United States government and the CML for the performance, control, and limitation of critical experiments. The original document was dated August, 1973; and the latest revision bore the date July, 1989. The last version contained 31 pages, divided into six sections, and shows the approval signatures of well over a dozen persons.

The Technical Specifications, colloquially called “Tech Specs,” were preceded by two earlier documents. The first, dated July 30, 1969, was titled: “Rules Governing the Hand-Stacking and Critical Approaches.” This document was only one page long and listed but ten rules. The next predecessor was titled: “Operating Limits for the Rocky Flats Nuclear Safety Laboratory.” No date is known for the original; but a revision carries the date December, 1972. This document was 14 pages long and contained *no* approval signatures!

The design of the Technical Specifications document was highly organized making any limit easy to find and clearly delineated. Discussion about each level of each parameter is broken into four clearly identified factors:

- “Applicability” When and where the limit is to be applied
- “Objective” What aspect of safety is protected by this limit
- “Specification” A precise statement of the limit
- “Basis” A justification for why the limit is as stated and why it is adequate

A number of parameters are given limits; and, furthermore, three levels of limits for each are identified. Each level is designed to be protected by the more-conservative (safer) limit above it. That is, the hierarchy becomes:  $L_1 > L_2 > L_3$ . That hierarchy of limits is defined as follows:

(1) The least conservative limit is called the Safety Limit (SL). This is the point at which physical damage to apparatus might be expected or which might lead to a release of fission fragments beyond acceptable limits if the SL were to be exceeded. The Safety Limit for the CML stated:

“No critical or critical-approach experiment will be allowed to achieve prompt criticality.”

(2) The next level, more conservative than the Safety Limit, is called the Limiting Safety System Setting (LSSS). This is a somewhat arbitrary point designed to prevent any experiment from ever approaching the Safety Limit. The LSSS helped keep experiments well removed from the SL. The LSSS for the CML was specified for each fissile element—uranium and plutonium. The e-folding time for any uranium experiment shall not become shorter than 5 seconds; and the e-folding time for any plutonium experiment shall not be shorter than 10 seconds.

(3) The most conservative point designed to prevent experiments from ever approaching even the LSSS was called the Limiting Conditions for Operation (LCO). LCOs existed for several parameters; and these included the shortest reactor period and maximum power level. The LCO for the reactor period was 10 seconds for uranium and 13 seconds for plutonium experiments. The power level of any near-zero power critical assembly is difficult to measure. It could not sensibly be specified in Watts or milliWatts, the usual

unit of power; exactly how to express this LCO was the subject of lengthy discussions. In the end, the LCO representing maximum power level was expressed in terms of neutron flux. The limit was that the quasi-DC current exhibited by the ionization chamber neutron detectors shall not exceed  $10^{-6}$  A or six decades above ambient background at the beginning of the experiment. This was recognized to be an arbitrary representation of the power level.

The policy at the CML was to stay well away from any of these limits. Exceeding any limit in the Tech Specs could be embarrassing, might lead to professional employment consequences, or could even prove fatal. To ward off these unwelcome consequences, self-imposed even-more-conservative limits were placed on each of these parameters in order to safeguard the most-conservative limit in the document itself. The reactor period<sup>67</sup> for uranium serves as one example. The previous paragraphs identified the SL as *not* being prompt critical. That state might be associated with a reactor period of zero. The LSSS is 5 seconds; and the LCO is 10 seconds. Scientists at the CML set the instrument measuring this period at 15 seconds (meaning a SCRAM trip would occur) well before the LCO could be exceeded. Experimenters, themselves, even protected this trip point by limiting the e-folding time to longer than 60 seconds; and this was written into most Experimental Plans. In actual practice, Experimenters, themselves, generally sought to keep neutron reactor periods longer than three minutes (180 seconds). Expressed visually, these reactor period limits, in seconds, are:

$$\begin{aligned} \text{SL} &= 0 < \text{LSSS} = 5 < \text{LCO} = 10 < \\ &\text{Instrument SCRAM} = 15 < \\ &\text{Experimental Plan} = 60 < \text{in practice} = 180 \end{aligned}$$

<sup>67</sup>Shorter reactor periods are closer to accident conditions than longer ones.

One technical detail related to reactor period must be understood. The time-averaged reactor period is different from the instantaneous period. The instantaneous value changes markedly because so few neutrons are involved such that the statistics of events are just not good enough. The instantaneous period appears, at these low statistics, to vacillate between plus/minus a few seconds while the average period recorded on strip chart recorders tries to draw a straight line. The recorder trace is, at best, a coarse estimate of a few-second average of the true instantaneous period. No instrumentation can ever accurately measure the instantaneous period. The truth of this contention is shown in actual experiments when the neutron population has grown by several decades. Then, the “noise” of the instantaneous period quiets down markedly. Reactor period specifications given in the Technical Specifications are assumed to represent time-averaged values; however, the closer any critical system gets to prompt criticality, the more important the instantaneous period becomes.

The Technical Specification document covered many other aspects of experiments at the CML. The document specified minimum instrumentation allowed for experiments. It also discussed hand assembly operations and mandated that an external neutron source must be used with uranium experiments. The whole subject of reactivity removal was also addressed. This included routine removal of reactivity as well as SCRAM initiators and mechanisms. The existence of a Manual SCRAM capability was set forth by this document. The leak rate allowed for the Assembly Room was specified in the Tech Specs (2 vol% per hour over 6 hours from an initial overpressure of 1.6 psi).

Emergency Power and radiation monitoring of effluents and a number of other concepts were discussed.

The requirement that “at least two certified Experimenters one of whom must be a Senior Experimenter” must be in control of every experiment was contained in the Tech Specs. This document also specified the need for an Experimental Plan. The Technical Specifications were reviewed annually, at least during the last several years of operation. It was last reviewed on July 24, 1989 and this update was signed by Dr. James Wu.

### ***Experimental Plans***

An Experimental Plan was written for each new experimental program. That Plan was reviewed and approved by a host of persons. These included other scientists within the CML, several layers of management associated with the CML, the Manager of Criticality Engineering who approved all operations other than the actual approach to criticality,<sup>68</sup> and one representative of the Nuclear Safety Committee (NSC). Each member of the NSC was associated with a different safety discipline. Mechanical Engineers examined the structural integrity of planned apparatus, Chemical Engineers looked at the compatibility of materials relative to the fissile fuel used, Radiation Safety personnel considered radiation and contamination aspects of proposed operation, experienced workers with fissile material in other buildings evaluated planned handling and storage procedures, and even Waste Management personnel considered that side of the new study.

The Nuclear Safety Committee was taken quite seriously. No operations could

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<sup>68</sup>At this point, the terms of the Plan took over and allowed criticality to be attained.

begin until all their questions had been properly resolved. After carefully reading the Experimental Plan, at least one tour of the actual site of the planned study ensured first-hand that all aspects were understood before any signatures appeared on the document. Membership on the committee was carefully selected to ensure management-level persons with considerable experience handling fissile materials were included. Generally, the highest level of management was not selected because their first-hand experience with hands-on operations might not be as complete. The NSC’s review was considered a valuable final overview of the entire planned program; and their suggestions were happily received and implemented.

Typically, an Experimental Plan contained between 20 to 30 pages with the approval page (discussed above) in the front. The format of a Plan was fairly constant from program to program although this was nowhere decreed; the Plan merely had to include all necessary details. In one example,<sup>69</sup> an Introduction described the experimental program in one paragraph and specified the purpose behind the study. The next section discussed fissile materials to be used. Maximum values of parameters (solution concentration, total volume, largest shell diameter, etc.) were specified; but any lesser amount was permitted. The Plan was to serve more as a “maximum envelope” for parameters and less as a specific statement of explicit experiments to be done. Another section described the apparatus to be used. The precise item was described if there was no chance it would change; but, again, ranges were given if appropriate. In the example case, the tank was well defined; but many

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<sup>69</sup>“Experimental Plan for the Poison Tube Tank Experiment”, 26 pages, May 1983.



absorber rod materials were allowed whether or not that material had been planned for use. Ways to monitor the experiment was another important section. The method(s) used to determine solution height were described in the Plan but stated broadly to allow some flexibility. The radiation detection instrumentation package was also described without reference to specific brand names. The Plan defined the envelope of procedures; these served as an operational envelope. Limits on reactor period, reactivity increments allowed between reciprocal multiplication graphed data points, load limits (weight), and a number of other Limits and Controls were described in the Plan. It also defined the SCRAM device(s) to be used in considerable detail. Most Plans contained a broad statement designed to allow maximum flexibility within the experiment without compromising safety. Finally, a copy of the PreRun Check Sheet for that experimental program covered by the Plan was included in an Appendix. The check sheet for this illustrative example used throughout this paragraph is shown in one of the figures in the chapter on Normal Operations. Whenever relevant, an additional daily safety check sheet was prepared for the hand-assembly phase of some program.

### ***Experimental Audits***

During subsequent day-to-day performance of experiments under this Plan, periodic but unannounced safety audits of experimental operations were conducted by one of the other two Senior Experimenters. He would inform the Senior Experimenter in charge of the study that an audit would be performed that day. Then, the auditor would follow along as any or all activities associated with the experiment were carried out. One audit might follow the

entire day's operation or simply the critical approach phase. Another might oversee the manual assembly activity where fissile metal was being built into an array to be flooded later that day. These audits were documented in the Control Console Log Book with the page number circled in red to highlight it. Audits were terse entries; and seldom were findings written which required corrective action. This does not mean audits were frivolous whitewashes of the day's operations; instead, experimental programs were routinely conducted in a serious and orderly fashion.

### ***Procedures For the CML***

A self-imposed document setting forth good practices within the CML, itself, was titled "Procedures For The Critical Mass Laboratory". This was first written in 1980 and revised annually. The last complete revision was dated July, 1989, and was 42 pages long with seven additional Appendices. It was only approved by the top manager in Building 886. Violations of its policies carried no penalties beyond a discussion with management; they were not reportable above that.

The document contained chapters on experimental operations, non-experimental operations, accountability of nuclear materials, source handling procedures (see next section), shipping, receiving, and storing nuclear materials about plantsite, CML training and certification, performing chemical analyses in the building, and the annual required leak rate measurement.

The chapter on experimental operations contained sections on planning an experiment, hand stacking (also called manual assembly) operations, Control Console key sign-out and sign-in procedures, when, how, and why safety interlocks could be bypassed, requirements for

access into the Hot Area of the building, and Control Room rules during a critical approach experiment.

The chapter on non-experimental operations contained sections on access controls into the Hot Area and building tours, waste and contamination control, safety inspections and audits, and procedures to be followed when making modifications to building or equipment. This last section contained reference to the use of Work Permits and Welding Permits. Both these forms had to be filled out on the site of the work to be done with both workers and building personnel present. They covered a number of routine safety considerations.

*(Miscellaneous Procedures)*

The seven appendices spanned many safety issues. Each was a separate procedure document merely collected into one existing manual. (1) The first laid out the rules for guaranteeing that a minimum of two persons would always occupy the Hot Area. Its title was “Material Safeguards Procedures (Two-Man Rule) for Building 886.” The first issue was written in June, 1977, with two revisions in 1982,

two more in 1983, and one each in 1984, 1986, 1988, and 1989. The last was dated July, 1989. (2) The second appendix delineated the Quality Assurance program for Control Console instrumentation. Its title was “Reactor Control Console Quality Assurance Program.” The first issue was dated April, 1984, and the document, 17 pages long, was last updated in July, 1989. (3) The third addressed source handling, storage, and transportation. Its title was “Procedures for the Use, Storage, and Transportation of Radioactive Sources in Building 886”. It was first written in 1981 with four revisions until the last in 1989. It was 10 pages long. Table VIII lists the four neutron sources and two gamma ray sources owned by the CML in 1989. (5) The next appendix discussed personnel certification. It spelled out how to employ Tamper Indicating Devices (TID), discussed later, which were part of the ongoing Nuclear Materials Safeguards program at the plant. (6) Another appendix identified procedures for the collection and disposition of (non-fissile) hazardous waste materials. (7) The last appendix promoted good housekeeping procedures within the CML.

**Table VIII. External Sources Contained in Building 886 in July of 1989**

Registry Number	Manufacturer's Number	Isotope	Radiation	Source Strength		
				Strength at (Date)	n/sec (10 <sup>7</sup> )	half-life (years)
S-082		Co-60	gamma	14.0 mCi (1965)	—	5.27
S-083	NS-28	Cf-252	neutron	5.9 mCi (3/71)	3.3	2.6
S-297	SRCF-134	Cf-252	neutron	7.0 mCi (11/76)	3.9	2.6
S-363	SN-112	Cf-252	neutron	0.225 mCi (~1977)	0.13	2.6
S-475	F-621	Co-60	gamma	10.28 mCi (8/84)	—	5.27
S-507	SRCF-147	Cf-252	neutron	7.32 mCi (7/85)	4.16	2.6

Encapsulation: All sources used for critical mass measurements are doubly-encapsulated stainless steel enclosures except for source S-082, whose encapsulation is not known, and source S-363, which was used for another program, whose encapsulation also is not known.

## ***Emergency Procedures***

Another highly emphasized procedure manual at the CML was that considering responses to a wide variety of emergencies. These included both natural disasters and man-made situations. The training and certification of experimental personnel (discussed next) always stressed this topic. A separate test was given to determine a candidate's understanding of these procedures. The document was titled: "Building-Specific Emergency Responses for Personnel in Building 886 and T886A." The words "Building-Specific" were added to distinguish this document from a similar one with a similar title which applied to all buildings and all personnel on plantsite. The original issue of this Building-Specific manual was dated October, 1969; and it was revised fairly often. The last revision was dated July 26, 1989. It was a 15-page-long document. Earlier versions of the document did not carry the extra words "Building-Specific."

A copy of this manual as well as a number of other manuals already discussed above were always available to anyone. They stood in a wall-mounted rack along one wall of the east/west hallway at the north end of the building. These safety manuals were taken quite seriously by all persons in Building 886 whether or not they were associated with the CML.

Each emergency response was written succinctly and clearly so the user did not have to wade through a lot of verbiage when responding to an emergency. The emergency scenarios covered included: a criticality accident, a contamination incident, a fire or explosion, medical problems (such as a heart attack, broken bones, etc.), natural disasters such as floods, high winds, etc., civil disturbances such as terrorist action or a bomb threat, and finally actions of a disgruntled employee.

The manual contained five appendices. One was a set of schematic drawings of the building with all of safety features (fire extinguishers, radiation safety equipment, public address speakers, and a host of other components) clearly located and named. This was carefully kept up to date as changes were made. The second appendix described shut down procedures to be followed. These included times when experiments were in progress as well as other times. The third identified utility (water, gas, steam, electrical, etc.) shutoff locations. Another appendix was simply a "Call List" giving home and plant telephone numbers for a number of people who might need to respond to a given emergency. The last appendix was a Threat Response check list. The idea is that a person receiving a threat over the telephone might be too rattled to ask the right questions. This list guided him/her with best advice.

## ***Experimenter Training***

Critical experiments, more so than less hazardous work, require a certain high level of knowledge, skill, and experience. Those personnel characteristics had been tacitly assumed in the early years of the CML. People were hired because of their schooling, interviewed before being hired to determine skills, and trained by more-experienced researchers to obtain experience. This approach worked well; but it lacked any documented formality. Early on, the AEC simply trusted that the Contractor would hire qualified people; and the Contractor fulfilled this trust more out of common sense than any compliance with government orders.

This looseness in staffing experiments manifested itself in the late 1960s by the credentials of those performing the earliest experiments. Aside from Grover Tuck,

Doug Hunt and this author who had been hired for this purpose, others became involved in experiments simply because they showed an interest and had, according to Schuske's opinion, adequate knowledge, skills, and experience. That is the avenue by which Bruce B. Ernst came to lead the unofficially titled "Christmas Tree Study." Ernst was a Criticality Engineer and not hired to perform experiments. Another example involves E. E. (Tim) Hicks, also an Engineer. Hicks led a very short study about partially reflected slabs of uranyl nitrate solution.

By the early 1970s, the need for increased formality was recognized. The terms "Senior Experimenter" as distinguished from "Experimenter" were coined. Senior Experimenters emerged as those holding doctor's degrees (Hunt and this author) or a PhD-degree equivalent (Tuck). They were also required to have had experience through leading programs prior to the definition. All others persons associated with the CML became simply Experimenters. The entire group was also divided between the CML and Criticality Engineering; and the Engineering group was no longer allowed to cross over into performing experiments.

Training leading to recertification was undertaken every three years. This took a couple of forms. Often, a college-level syllabus on nuclear fission, criticality, and nuclear reactor theory would be constructed. Then, members of the CML would lecture one another in the areas they were strongest. These classes would last several hours a week and were, in no way, taken lightly. On one occasion, a series of televised lectures from a scientist associated with the nuclear reactor at St. Vrain in Colorado were religiously watched. That year, a visit to the reactor while yet under construction proved very valuable.

C. L. Schuske followed the course work with an examination on the material covered. Often, his questions were tailored to pertain directly to Rocky Flats situations. The written exam usually took a full day to complete. Schuske would also give an oral examination to each person one at a time; and this discussion usually lasted about an hour. All examinations, both written and oral, were maintained on file. DOE auditors would review the tests, the responses, and the grading during their next visit to the CML. Interested persons can still review these certification packages for each person in the CML. These records exist for the years 1970 through 1990. They are contained in the Rocky Flats collection (A-1996-051) at the LANL Archives in Box 33, Folders 3 through 9 and Box 34, Folders 1 through 25. This collection includes written exams, oral exams, and emergency exams. One example set of exams, taken close to the end of 1985, is presented in the Appendix at the end of this chapter.

## **Nuclear Materials Safeguards**

The protection of nuclear materials at the CML increased significantly in a wide variety of ways during the lifetime of the facility. It grew from being a bit too lax in the late 1960s to being perhaps a little too extreme in the 1990s. This is the author's personal opinion only; and readers are free to differ. Others more in tune with world tensions over these decades were responsible for initiating new procedures. The possible merit of current safeguards procedures will not be discussed here. The point is moot in the new millennium because all fissile material is gone and the building stood as a hollow shell of itself until demolition.

All doors to and within the Hot Area were *not even locked* during the first half-decade of the facility. Key locks had been built into doors; but they were never used. Access was free and unrestricted because Cold War tensions had not yet filtered down to this level. People were assumed to shy away from occupying these rooms—with their perceived hazards and required clothing—unless they actually had a *need* to be there. One reason for not locking doors was that quick access to nuclear materials was thought to be required for safety reasons under some circumstances—fire, smoke, a leak in solution plumbing, etc. This safety goal appeared to take precedence over the supposedly meager and perceived hypothetical threat of unwanted intervention.

Sometime in the early 1970s, the decision to lock these rooms was made. This author unsuccessfully—and quite naively—argued that door locks were unnecessary for several reasons. His flimsy arguments fell on deaf ears. Soon in fact, combination locks were added to all four doors to enhance security even further. These four included the one leading into the Hot Area Hallway (Room 108) from the Airlock (Room 104) as well as those leading into the Assembly Room (Room 101) and both material storage rooms (Rooms 102 and 103).

Materials safeguards measures escalated even more as world tensions increased. In time, procedures called for a “Two-Man Rule” routine. Toward that goal, *three* locks on each door were used. They were configured such that each of two had to be unlocked by *different* persons in order for anyone to gain access into the room. The third lock was the original key lock; and it could be unlocked by anyone after the first two had been opened. The door itself was locked by the combination

lock; but a covered faceplate, also called a Hasp Hider, obscured the combination lock’s numbers. Obviously, the combination could not be dialed even if known. The faceplate was locked in place over the combination lock by a second lock, a key-operated padlock. Persons knowing the door’s combination could never possess the padlock’s key; and the holder of the key did not know the combination. Compliance with this was administrative only; but it worked well. At first, the Manager of Nuclear Safety (as the group was called for many years) would sign out the padlock key only to persons known not to have knowledge of the combination. The person allowed to hold the padlock key was not authorized access to the safe which contained the secret combinations. These combinations were changed periodically. Remembering all these secret combinations was not an easy task. Fortunately, the same combination applied to all four doors’ combination locks. This satisfied the Two-Man Rule requirement concerning access but trusted one person to ensure compliance.

Safeguards concerns increased still more through the early 1990s, leading to several additional enhancements of security measures. The key for the padlock was locked in a small cage located in the Airlock instead of being in the possession of one person (the Manager). This cage was locked shut by a second combination lock; and persons knowing that combination could *not* be one of those having access to the other combination lock. Thus, each person of the Two-Man Rule had to know a combination. The cage improvement was implemented in the belief was that an administratively handled key could be too easily stolen or copied or otherwise fall into the hands of the person knowing the door’s combination.

The two combinations were obviously different from one another; and they were changed monthly. Combinations were treated as classified information.

Five additional safeguards enhancements are recalled. (1) One was to install a sheet of 9.5-mm-thick armor-plate hardened steel over the door from the Hallway into the Assemble Room. (2) The second enhancement was to install a steel grid door in front of the door between the Airlock and the Hallway. This door was similar to a jail cell and was colloquially called a “monkey cage.” It was fabricated of thick steel bar stock in horizontal layers formed into a grid by vertical steel bars. The grid was perhaps 100 mm by 200 mm. This door, also, was locked with *two* pair of locks (one high on the door, the other, low) which also required two persons to access. (3) The third improvement was that the clear glass in the original door could be covered over from the inside with a moveable opaque shield. The purpose was to prevent a potential thief from seeing into the Hot Area. The shield could be lowered during the working day to allow quick vision into the Hot Area. (4) Another safeguards enhancement was to install radiometric scanners on either side of the doorway leading out of the Hot Area. The purpose of this was to detect any pilfered fissile material through its gamma radiation. (5) The final enhancement was the fabrication of a large, heavy, concrete block that rested just outside the south side of the Assembly Room. It prevented the Shield door from being opened. Invaders would have to bring a fork-lift truck with them to remove this massive constraint before they might attempt to blow the door open with explosives.

At one point, then, conditions for accessing the entire Hot Area had become pretty elaborate. Eighteen locks of different types had to be unlocked to open five doors. Two armed guards were mandated<sup>70</sup> as well as the two members of the CML to comply with the Two-Man Rule. Then, two or more workers needing to enter the Hot Area would also be standing by. In addition, one or two Radiation Monitors were often present in the Airlock. With that scenario, the Airlock sometimes proved to be a little undersized. These procedures were cumbersome but they ensured materials safeguards.

All persons entering the Hot Area were required to record their presence on a specially-designed log form. Furthermore, a telephone call-in procedure was instituted for access through the door between the Airlock and the Hallway. Here, one member of the entry team was required to telephone the plant’s Dispatching Office just prior to access and to say a specific code word. That word had to be worked into the conversation. Hearing that word, security forces would *not* respond when the door’s opening automatically registered on their monitors. Another equally secret code word was to be used if this access was being made under duress. Then, security forces *would* respond *en masse*. Both words were changed periodically to complicate nefarious detection and use. Some code words were awkward to work into a routine telephone conversation. When everyone finally left the Hot Area at the end of the day, each person was required to document their exit on the same log form used earlier to record their entrance.

The physical ability to lock the Assembly Room (Room 101) in the same fashion as the material storage

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<sup>70</sup>Truly, their machine guns lent a Hollywood aura to each entrance. Guards remained close at hand as long as personnel worked within the Hot Area.

rooms was always available; but it was only required when that room contained unattended fissile material. Whenever the Assembly Room was devoid of these materials; the door was allowed to be left unlocked. Many times, however, experiments were “set up” one day and reactivity added remotely to achieve criticality the next. This involved a manual assembly of the fuels in a configuration that would remain well-subcritical. In these cases, this door would be double-locked overnight just like the other doors in the Hot Area. On a few other occasions, the critical experiment, itself, left the fuel questionably irradiated with short-lived fission fragments. Radiation Monitors sometimes recommended the fuel be allowed to decay overnight to safer levels. Their advice was always heeded; and the door would be left double-locked.

Considering the complexity of all these operations and their labor intensiveness, the cost of actually getting any work accomplished within a nuclear facility is high. Arguments could be offered suggesting these procedures might constitute “overkill.” That point is not argued here. The fact remains that no fissile material was ever diverted from Building 886.

The year 1992 introduced a new wrinkle adding additional safeguards to fissile material on plantsite. This was called the Personnel Security Assurance Program (PSAP). Its objective was to ensure that all persons in any way associated with fissile material shall be trustworthy individuals and free of habits that might make them vulnerable to blackmail or intimidation. Affected workers were anyone with “hands on” accessibility to

nuclear materials. This included production workers, truck drivers, guards, and a host of other persons. By the mid 1990s, about 15% of the plant participated in PSAP. Employees under this umbrella are subject to random drug testing, although each one will receive one or more tests in a year. This author was not affected by PSAP. It was being introduced to the plant about the time he was retiring.

The protection of nuclear materials against theft was aided by the addition of radiometric scanners outside the building sometime in the 1980s. The gates into the Material Access Area (MAA) were monitored by such devices. They could detect fissile material carried out by an individual or transported by truck. The sensitivity of these devices is not known to this author and probably best left not discussed anyway; but even the movement of waste drums bearing unknown quantities of uranium were communicated to the Guard Post to preclude surprise triggering of the detectors. A second radiometric scanner was constructed at the exit from the Hot Area; but this has already been discussed elsewhere.

Nuclear materials, often referred to as SNM (Special Nuclear Material) needed to be well-controlled. They are dangerous due to potential criticality, attractive to terrorists, carcinogenic, pyrophoric, as well as expensive. The CML had a significant holding of two elements in four forms. These were given identification numbers, called Material Balance Areas (MBAs), as shown below with the responsible Senior Experimenter from the CML to the far right:

<u>MBA</u>	<u>Fissile Material and Chemical Form</u>	<u>Responsibility</u>
0385-71	93% enriched uranyl nitrate solution	R. E. Rothe
0385-72	93% enriched uranium metal	G. Tuck
0385-73	plutonium metal (shells and cylinders)	D. C. Hunt
0385-74	low-enriched (4.5%) uranium oxide	G. Tuck

The last of the plutonium metal had been removed from the facility in early 1983 as described elsewhere in this book; so that identification number fell into disuse. Later, upon the death of Grover Tuck and Doug Hunt's accepting a new position elsewhere, this author took over sole responsibility for all remaining SNM.

The manual which addressed all activities with respect to these important materials was called "Accountability Procedure Manual for Nuclear Materials in the Critical Mass Laboratory." Although the document may have been preceded by one or more less-formal procedure documents, the first version of this specific manual was dated February, 1972. It was periodically reviewed and revised as necessary after that. The last changes were dated April, 1985; and the last review was dated May, 1987. The manual was only 9 pages long and was approved only by the Manager of the Nuclear Safety Facility, the Director of Plant Security, and the Manager of SNM Accountability.

All SNM was stored and used inside the Hot Area; and safeguards to protect this area have already been discussed in detail. In addition to these procedures, each container of fissile material was somehow "locked out" using devices called "Tamper Indicating Devices" (TIDs). TIDs were lengths of braided wire with one end embedded in a lead seal. The wire would then be passed through the handle of some closed container not to be tampered with and looped back toward the seal. Next, that other end could then be passed through a hole in the lead seal and crimped shut. Crimping prevented one from withdrawing the wire. If the TID was found intact, that provided evidence that the contents of the container had not been accessed. The only way to access the material was to intentionally destroy the TID by cutting the wire.

The lead crimping tool was considered a classified item and was stored in a safe. This precluded someone from breaking the seal, removing the SNM, and then resealing the container as though nothing had happened. The seal left a unique marking on the crimped lead; and this prevented one from merely smashing the lead with a hammer.

TIDs were used in a variety of ways depending on the container being protected. Pressure cookers containing enriched uranium metal had a TID through the mating handles on one side of the cooker. The water-filled storage pots housing plutonium cylinders had a TID spanning the lid but attached to the body. TIDs were used on the uranium solution system too; but, here, a bit of creativity was needed. These TIDs passed through the handle of any valve which could be opened to allow solution to exit the storage tank farm. Waste drums were locked out, too, by passing a TID through a hole drilled in the bolt used to seal a full waste drum. In-use waste drums had other types of closers; and these, also, were subject to TID control. Exactly how TIDs were to be used was not mandated; so some creativity was not only allowed but encouraged.

The Accountability Procedure Manual also contained a lengthy discussion of how fissile material was to be shipped. This included onsite as well as offsite shipments. DOE-approved shipping containers were to be used; and these had to be labeled inside and out. SNM was to be transferred under the control of several documents (forms). These included the Nuclear Materials Transfer Report and the Drum Transfer Receipt. An armed guard would accompany all transfers; and a Courier Receipt was required to document that. All of these paper forms had multiple copies. One copy went to the shipper,



another to the receiver, and still another was mailed to the department in charge of SNM on plantsite. Paperwork was prevalent; but no fissile material was ever lost or diverted leaving Building 886. Finally, the Guard Post just outside Building 886 had to be informed that the movement of SNM would set off radiometric scanners installed to preclude the nefarious theft of these materials.

The Manual also contained a separate section dealing with the opening of the south door of Room 101. This was especially sensitive because the door opened directly from a Radiation Controlled Area (RCA)—and one with a large potential for contamination—directly to the out-of-doors. This door was used primarily for bringing into the building large pieces of experimental equipment. Examples of this apparatus included the rectangular concrete wall panels which had been cast outside, large diameter tanks such as the entire set of Annular Tanks, and various concrete and plaster cylinders which also had been cast outside. The procedure employed worked well. No contamination was ever detected outside the building due to apparatus moved into or out of the building through this doorway.

A physical inventory of fissile material on a periodic basis was imposed upon the CML as an additional means of safeguarding SNM. This author submits that this may have been reasonable for three of the four Material Balance Areas but *not for the fourth*. The actual inventory procedure varied markedly depending on the chemical form of the material; and that is why an inventory in one of these MBAs is considered a very ineffective safeguard.

The uranium metal hemispherical shells of MBA 0385-72 were visually examined and counted monthly to verify their existence. This procedure continued until the

TID was introduced. Then, a container with an in-tact TID was assumed to contain the proper holding. Shells were not weighed every month because they were coated with grease for a number of reasons. That grease changed with use; so weight changes could wrongly be taken for absent SNM. About the only nefarious way of circumventing this inventory as a practical safeguard would be to substitute an identical shape of another material for the pilfered uranium. This would be difficult to do because of color and density differences between uranium and any common metal.

Procedures for the inventory of the plutonium metal hemispherical shells of MBA 0385-73 during the very early years of the CML are not well recalled. Parts were returned to production well over a quarter century ago; so details seem moot. Procedures for the plutonium cylinders, later added to MBA 0385-73, are known. Each cylinder was quickly (to reduce radiation exposure) viewed to verify its existence. This inventory was done semi-annually as recalled. Again when TIDs were introduced, a container with an in-tact TID was assumed to contain its proper holding. Furthermore, a gamma ray radiation detector was used to verify that the unit in the storage container was, indeed, radioactive. The doubly canned cylinders were never weighed at Rocky Flats, at least until they were returned to production in January of 1983. About the only nefarious way of circumventing this inventory as a practical safeguard would be to substitute a different material in an identical outer can. This would be difficult to do because of density differences between plutonium and any common metal.

Cans of low-enriched uranium oxide in MBA 0385-74 were visually examined and counted quarterly to verify their existence. No TIDs were ever used because they

would be almost impossible to apply. Cubes were seldom weighed; and weighings were not done for inventory purposes. The inventory relied on the number of cans, the specific numbers engraved on their lids, and their general appearance. Possibly any decreased vigilance in the inventory of this material might be traced to its relative lack of value. The room (Room 102) housed so many other items of much greater interest that the oxide cans may have been viewed as a minimal risk material.

Inventorying these three MBAs as a means of SNM safeguards seemed to make sense. That was not the case in the fourth MBA—the uranyl nitrate solution.

Uranium solution is a much more difficult entity to inventory. Individual components are not tangible. They cannot be simply counted or weighed. Counting tangible items is a task with no error; an item is either missing or it is not. Weighing items has some error; but modern high-quality balances have a precision of a gram or two out of several kg. Other factors such as grease or another containment may complicate weighing; but it still is a very good first guess as to amount of material present. Uranium solution afforded neither option. Determining the weight inventory (grams of uranium contained in some 3000 liters of liquid) of the uranium solution was a complicated process taking months to complete and, even then, suffering from a significant uncertainty. That uncertainty was so large as to render any result of no consequence with respect to safeguards.

The enormous size of that uncertainty—as small as it really was—becomes apparent when one recognizes that each of the parameters on the right side of the following formula for  $U(g)$ , the uranium inventoried weight in grams, is a measured

property having an uncertainty of about a percent or so.

$$U(g) = \sum (C_j - C'_j)(V_j) + R_j$$

Here,  $C_j$  is the average measured concentration of nominal concentration  $j$ .  $C'_j$  is the bias correction for nominal concentration  $j$  as determined by a Measurement Control Program.  $V_j$  is the volume of solution of nominal concentration  $j$  measured in tanks. There were nine tanks in the farm; and each of these would have an uncertainty of about a percent or so in its measured contained volume. Finally,  $R_j$  is a small quantity of residual solution existing as holdup in certain impossible-to-access portions of pipe, as residue in sample vials, and other locations.

Combining all these uncertainties, each having an uncertainty—at one standard deviation—of between one-half and a couple percent, the net uncertainty in the calculation of the net uranium inventory weight might easily approach several percent. This useless information from a safeguards perspective is worsened since DOE required statements of inventory measurements be expressed at *two* standard deviations. Thus, the DOE-acceptable uncertainty to the above calculation,  $U(g)$ , could easily amount to 8% or more. The uranium weight within the solution holding was about 569 kg; and 8% of that is over 45 kg! A critical configuration can easily be constructed out of 2 kg of fissile solution given the right conditions. A sobering thought is to recognize that more than 20 critical masses could be missing from the uranyl nitrate solution holding and not be detected based on these statistics. No, a solution inventory should never be used as a safeguards measure.

In reality, however, the actual uranium content from one inventory to the next was surprisingly good. Most measurements agreed with the previous one within several hundred grams out of the 569 kg total. Two comparisons differed by up to six thousand grams; one was an apparent loss, the other, a gain. In summary, this author submits that the uranium solution in Building 886 was very well controlled, well managed, and generated state-of-the-art inventory procedures. It was not, however, a suitable parameter to lend confidence in safeguards considerations.

In spite of all this, the government (DOE) expressed concern over such a long time (three years) between inventory measurements. They wanted some interim corroboration that solution was not being mis-handled. Toward that end, an even more useless inventory (this author's opinion) was instituted. Called the Quarterly Inventory, the volume of solution in each of the nine tanks was measured and summed. This was effectively a *volume* inventory and had nothing to do with uranium mass. That total volume was then multiplied by the "average book value concentration" of the solution presently on hand. Mathematically,

$$U(g) = \langle C \rangle \sum V_j$$

where  $\langle C \rangle$  is that average concentration (with unknown uncertainty) and  $V_j$  is the solution volume measured in the  $j^{\text{th}}$  tank. CML staff were not asked to circulate the solution but, rather, to just read solution heights in site glasses. Even valves connecting the site glass to the body of the tank were not to be opened. One consequence of this is that the solution height inside the tank sometimes differed from that observed by several millimeters. The worst case ever actually noted was 140 mm! These differences were due to a

number of reasons including density differentials in the two regions, evaporation, air bubbles, etc. Compounding this uncertainty over nine tanks suggests the quarterly volume measurement would be totally irrelevant with respect to any hope of serving as a nuclear materials safeguard.

## Security

### *Badges*

Every employee in Building 886 had a "Q" security clearance. That was not the case for all buildings because some handled neither classified documents nor SNM; however Building 886 contained both. A security clearance required wearing a security badge; and those without clearance wore other badges. These badges signified the security clearance as being "Q-cleared" (access to secret data), "L" (some classified information), and un-cleared (no access to classified information). Q-cleared badges were green through sometime in the 1970s; and then were colored blue. L badges were yellow; and red signified "uncleared" for decades. Uncleared badges are now gray since the late 1990s; but wearers are still said to be "red-badged." Badges were to be worn at all times with the portrait photograph side facing outward. They had to be exposed on the upper front torso. Many wore them clipped to one lapel of a shirt, although others wore a necklace around their neck specifically to display their badge. The clip was sturdy enough to preclude the badge flowing off in a heavy wind; yet it did not damage garments. Workers required to wear radiation dosimeters, nominally the same size as the security badge except for thickness, often wore them clipped to the other lapel.

Badge color coding changed a little during the Clinton Administration. The president was concerned that color-coded badges may not be “politically correct.” It tended to lessen the status of persons with lower security clearances. He called for use of a single colored badge with small numbers in one corner to designate the clearance level. This served its purpose but made quick recognition much more difficult. The use of three colors has now returned.

Additional security measures of the 1980s led to the division of the plant into nine islands of different Material Access Areas (MAAs). The badge was then redesigned to show these areas by numbers one (#1) through nine (#9); and workers were allowed ready access through the appropriate Guard Post only for the MBA(s) assigned them. Building 886 was MAA #3. Criticality Engineers needed frequent access to more than MAA #3; so their badges were punched to admit them to other areas. This author visited other MAAs so seldom that his badge was only punched for MAA #3. Occasional access to another MAA was allowed and fairly easy to accomplish. The visitor merely needed to be “called into” the other MAA by a worker within the MAA. This required a telephone call to the appropriate Guard Post giving them the name of the visitor.

Other badges and special permits came into being during the 1990s. These, too, were to be displayed. Everyone needed the Gate Pass to access the gates at the boundary of the plant. Certain persons required a Camera Pass to permit having a camera or a Property Removal Permit to allow taking, for example, a lap-top computer home. Other workers involved with fissile material might wear their Respirator Qualification card and/or TLDs as required. The sight of men and women with a necklace

containing a number of badges flopping against their chest as they walk is both humorous and quite common.

Employees respected the significance of the security badge they wore. Many stored it at home in a relatively secure yet obvious location. These contrasting goals made the badge less susceptible to casual theft and yet difficult to forget as the worker left home for work in the morning. It was not abused, although at one time the plant issued everyone ice scrapers as the winter approached as a deterrent to those few who might use the security badge for removing frost from windshields.

Some workers tended to forget their security badge at home. This never happened to this author in over three decades at the plant. Still, a procedure was in place where a replacement badge, called a “Forgotten” badge could be issued for the day. Supervisor’s first advice was to go home and get your badge. The rare employee with the “F-Badge” was often teased by co-workers.

## ***Fences***

The security status of Building 886 meant that the building had to be encircled with a tall chain link fence. In later years, that fence was topped with a meter-diameter spiral of razor ribbon wire. Most regions on plantsite containing one such building had many similar buildings close at hand; so these “islands” would be surrounded by a common security fence. The fence around Building 886, however, surrounded only it and its support buildings.

Access through this security fence was only through a single Guard Post located just northwest of the building. Both personnel and vehicles were controlled by this Guard Post. Persons entering or leaving had to pass through a narrow walkway

fitted with a tall, well-enclosed, turnstile as they handed their badge to a Security Officer. Their belongings such as lunch containers and briefcases were opened and visually inspected upon entry and subject to search when exiting. Presence in the building was indicated by a simple toggle switch board. The handle of the switch merely leaned toward the building when present and away when gone from the building. This has been discussed previously in this chapter. The toggle switch board replaced an earlier version wherein a colorful magnet would be slid one way or the other depending on occupancy.

A second access gate had been built into the perimeter fence in 1964. It was located along the east fence and was not in view of any Guard Post. The plan was to supply Guards if and when this gate might ever be needed. The gate was used just once. The original shipment of weapons-grade plutonium metal in the form of nesting hemispherical shells was introduced to the building through this procedure. The transfer proceeded smoothly with no trace of any security or safeguards question in spite of the inadequacy of such a procedure even a few years later. The gate was removed in about 1970 and replaced by fence.

### ***Classified Documents***

Building 886 contained a very large amount of classified information. Criticality Engineers needed drawings of the latest weapons designs and other related data. They needed details of the sometimes secret processes involved in production. The CML had a lesser need; but masses of the nesting plutonium shells were classified Confidential. Subsequent masses of the plutonium metal canned cylinders were not classified. Only three experimental programs performed over a quarter century

were classified. Other than that, most work in the CML was purposefully kept unclassified. This made much of the accrued data suitable for publication in the open literature.

Still, storage of classified information for either group required proper repositories for this sensitive information. These containers were called “safes.” Four four-drawer safes were located in the Main Office just adjacent to C. L. Schuske’s private office. This office was inhabited all day long on working days making human supervision over them particularly easy. The Secretary was the principle custodian because she was there almost all the time. Whenever she did leave the room, she called someone else in to “baby sit” the open safes and their classified information until her return. Even the building’s Manager in the next room was not deemed adequate coverage. Some Q-cleared person from the building was always in constant vigilance in the room as long as the safes were open.

Safes were routinely opened at the start of a work day. Each safe had a single combination lock on one drawer, the top one, and a button inside that drawer which could unlock the other three. Normally, safes would remain open all day long but be fully attended by someone. A nightly ritual was to close and lock these same safes. The Secretary did this; but teams of two Q-cleared persons would also each assure themselves that each drawer of each safe was locked and would not come open. They also made sure that the combination was left on some random number. These teams served in that capacity for a week at a time. Both safe checkers signed a nightly check sheet to document their having checked the safes. No safe in Building 886 was ever left inappropriately open in over three decades.

The team of two Q-cleared checkers had a number of other duties to perform as well each evening. They were responsible to check that the Hot Area was properly locked and all log forms properly filled out. The pair walked throughout the entire building checking each individual office for compliance with the building's "Clean Desk" policy. This encouraged workers to leave their desks neat and tidy and devoid of any of the day's work—classified or not. The policy also called for an erased blackboard. This policy was not enforced as rigidly as it might have been. Desks had to be free of anything classified; but some workers had a habit of not being very neat or tidy. Blackboards, too, were seldom fully erased. The team construed their goal to be that no classified information was in either place. The whole day's end procedure took about 15 minutes.

Early on, one additional two-drawer safe was kept in another office; but that questionable practice ceased about 1970. That safe was under the supervision of H. W. King and B. B. Ernst. It, too, was subject to the nightly security check by the team of two. Curiously, that safe was mounted on a rectangular steel frame equipped with casters. It was quite portable. In spite of that, no security infraction ever resulted from that situation.

Classified documents could be taken to a worker's individual office; but they had to be logged out before they left the Main Office. A special form was constructed to record this removal and, later in the day, the document's return. That all documents removed during the day had been properly returned was another task of the team of two Q-cleared day's end checkers. Workers were very careful to maintain control over documents in their possession, especially when they had been removed to another

office. Some Q-cleared person was always responsible for the protection of classified information. Office doors were even fitted with small pegs and a painted sign. One side was green and announced the contents of the room as "Unclassified." The other side was painted red and read "Classified Information in this office." As classified documents were brought into a room, the sign would be turned to expose the red face to others entering the room. Use of the signs was optional; but most workers saw the advantage of a reminder.

If an uncleared visitor were to visit Building 886, an announcement to that effect would be made throughout the building's public address system before the person entered the building. Workers having classified documents in their room were not required to return them to the Main Office; but they were cautioned to take extra precautions. Usually, this meant that the door to the office was closed and the papers positioned such that someone in the hallway would not be able to see them through the glass in the door.

In summary, security and document protection were both quite good in Building 886. Very few security infractions were imposed upon anyone in the building; and the few that were were not of a serious nature.

### ***Miscellaneous***

An endless list of other security measures have been imposed at different times during the life of Building 886. Some of these dealt with documents and others were directed at materials safeguards. This author is unable to recall all of them; but the majority of facets associated with security have been described above.

## Appendix

### CRITICAL MASS LABORATORY

#### EXPERIMENTERS EMERGENCY EXAM

DECEMBER, 1985

Specify your response, in detail, to each of the following situations, from discovery or notification until the condition is considered secure or under control. Use any resource (textbook, procedure, etc.) you wish; however, discussion with others is not permitted.

1. During the assorted fuel geometries handstacking, the array collapses and one of the containers is leaking liquid.
2. During a critical approach, you are notified that the PA system is not functioning.
3. Liquid is observed on the floor of the pit in Room 103 after a heavy rain.
4. You observe a "bulging" waste drum as you enter the Assembly Room.
5. During a handstacking operation, the l/M curve is level but the instruments show a rapid increase in reactivity when an addition of fissile material is made.
6. The pump is activated from the control console during an experimental run, but the sight gage on the experimental tank does not indicate a rise in solution.
7. You are working in the radiation-controlled area and a neutron criticality alarm occurs during an earthquake.
8. During a poison tube tank or nested annular tank measurement, the solution will not drain from the tank when the scram is activated.
9. During the assorted fuel geometries program, the horizontal split table is separated, the table will not open or close, and the instruments indicate a slightly subcritical condition.
10. The CAM is activated in the Assembly Room during a critical run.

Approved By: J. D. McCarthy Date: 12-6-85  
 J. D. McCarthy, Manager  
 Nuclear and Facilities Safety

Date Administered: December 12, 1985 Passing Grade: 80%

85-6-6

CRITICAL MASS LABORATORY

EXPERIMENTERS ORAL EXAM

DECEMBER 1985

1. a. Discuss the procedure for transferring equipment from the radiation-controlled area to another building.
- b. Discuss the personnel monitoring procedure for leaving the building security area after working in the radiation-controlled area.
2. a. If OSA's exist for CML operations, specify the ones in effect. Include the hazards highlighted.

OR

- b. If no OSA's exist, explain the rationale for this situation since the HS&E Manual requires OSA's for RFP operations.
3. Discuss the experimental phases involved in preparing for and performing critical mass measurements.
4. Discuss one of the SNM inventories you are familiar with. Include frequency, documentation, etc.
5. Discuss the following:
  - a. The relative effectiveness of Al, H<sub>2</sub>O, and concrete as reflectors of a fissile metal assembly.
  - b. Optimum moderation.
  - c. Delayed critical.
  - d. Prompt critical.

Approved By: \_\_\_\_\_

  
J. D. McCarthy, Manager  
Nuclear and Facilities Safety

Date: \_\_\_\_\_

12-6-85

Date Administered: December 18, 1985

Passing Grade: 80%

85-6-6



CRITICAL MASS LABORATORY

EXPERIMENTERS EXAM

JANUARY 1986

The answers to these questions are to be based on existing documents, not proposed revisions. Use any resource (textbook, procedure, etc.) you wish; however, discussion with others is not permitted.

1. Specify the leak testing procedure for the Assembly Room. Include:
  - [1] a. The method used for the test.
  - [2] b. The parameters to be measured and the corresponding instruments used.
  - [1] c. Allowable leak rates.
  - [1] d. HS&E procedures and/or considerations to be done prior to the test.
2. Discuss the type of radiation measured, the units of measurement, and the use of each of the following.
  - [1] a. Ludlum
  - [1] b. Victoreen 440
  - [1] c. Bonner Ball
3. Discuss the following as applicable to a Work Permit.
  - [1] a. Types of operations requiring a permit.
  - [1] b. Required approvals.
  - [1] c. Length of time the permit is valid.
4. Discuss the various systems that would detect a nuclear criticality accident in the following situation.
  - [1] a. During an experiment.
  - [1] b. During hand stacking.
  - [1] c. During routine material handling.

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[2]

5. Discuss the hand stacking procedures for the assorted fuel geometries program. Include:
  - [2] a. The number and type of personnel that must be present.
  - [2] b. The number and type of instruments that must be used.
  - [1] c. The type of data collected.
  - [1] d. The limitations on addition of reactivity.
6. Discuss the following.
  - [1] a. Negative temperature coefficient of reactivity.
  - [1] b. Positive temperature coefficient of reactivity.
  - [1] c. The one that is permitted for experiments in RFP's Critical Mass Laboratory.
  - [1] d. Rationale for answer to 6.c above.
7.
  - [2] a. Describe the two independent scram mechanisms for the horizontal split table.
  - [2] b. Specify the load limit (total and per each half) of the horizontal split table.
8. Discuss the procedure for handling the neutron source in the CML. [4]
9. For each of the documents needed for reactor operations, discuss the purpose (intent), the contents, and the required approvals.
  - [2] a. Safety Analysis Report
  - [2] b. Technical Specifications
  - [2] c. Experimental Plan
  - [2] d. Nuclear Materials Safety Manual
10. Discuss the location (and corresponding rationale for that selection) of the neutron detectors in the assorted fuel geometries program. [2]

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[3]

11. Specify the location and use of each of the following.
  - [2] a. CAM
  - [2] b. Alpha Mets
  - [2] c. Combos
12. Discuss each of the following as pertaining to a solution excursion in the Assembly Room during an experiment.
  - [1] a. Expected number of fissions.
  - [1] b. Effect on equipment.
  - [1] c. Consequences to the worker, public, and environment at plant perimeter fence.
13. Discuss the criteria used for establishing the volume of the overflow dump tank used in the poison tube tank and the proposed nested annular tank programs.
14. For each of the following, discuss the corresponding security procedure.
  - [1] a. At beginning of shift - opening radiation-controlled area.
  - [1] b. End of shift - closing radiation-controlled area.
  - [1] c. Opening Vault 102.
  - [1] d. Closing Vault 102.
15. Discuss each of the following.
  - [1] a. The criticality effect of a void in the center of a core as opposed to the edge of the core.
  - [2] b. The effect of the thickness of a reflector on criticality and also the spacing from the core.
  - [2] c. The reactivity effect on the mass of a fissile-material-plus-water mixture from a concentration of dilute to solid metal.
  - [2] d. The effect of an effective moderator between the units of an array of fissile metal from a moderator thickness of 0" to 12" (assume fixed spacing).

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16. Discuss each of the following as applicable to the assorted fuel geometries program.
  - [1] a. The parameters measured.
  - [1] b. The instruments used to measure the addition of reactivity.
  - [1] c. The limitations on the increments of reactivity addition.
- [2] 17. a. Specify the minimum number and corresponding types of radiation channels that must be functional in order to perform critical measurements.
  - [2] b. Specify the required minimum number, type, and pre-set trip limits of the radiation channels that must have scram activating capabilities.
- [4] 18. For the assorted fuel geometries program, discuss the pre-run check - specify four items checked and give rationale for each.
- [2] 19. Describe several ways the experimental period can be evaluated by readings taken from instruments on the control console.
20. Discuss the following in relation to addition of reactivity in the poison tube tank and proposed nested annular tank programs - from start to finish of experiment. Include limitations and how each is monitored.
  - [2] a. Pump rates.
  - [2] b. Addition increments.
21. For the Log N meter in the control console:
  - [1] a. Discuss the type of information obtained.
  - [1] b. Discuss the use of this information.
22. For the neutron population during an experiment:
  - [1] a. Specify the maximum time it is allowed to increase by a factor of  $e$ .
  - [1] b. Discuss the rationale for 22.a above.
- [4] 23. Specify (a) the location and (b) the rationale for that location of the four solution detectors that will initiate a scram.

- 24. Describe the proper procedure for handling the following waste in the CML for transfer from the building. Include packaging requirements, forms, etc.
  - [1] a. Plutonium contaminated solid waste.
  - [1] b. Uranium (low enriched) solid waste.
  - [1] c. Uranium (high enriched) solid waste.
  - [1] d. Uranium (high enriched) contaminated liquid waste.
- 25. For the crane in the Assembly Room, discuss the following.
  - [1] a. The general use.
  - [1] b. The load limit.
  - [1] c. The load limit on the hook or attachment mechanism.
  - [2] d. The preventative maintenance program - frequency and how to determine if completed.
- 26. For each of the following, specify an indicator of malfunction.
  - [1] a. Picoammeter
  - [1] b. Log N meter
  - [1] c. 1/M meter
- [2] 27. For the assorted fuel geometries program, discuss the parameter that will be measured and plot the expected shape of a typical 1/M curve.
- 28. Discuss the radiation and also the criticality effects of neutron shielding in relation to:
  - [1] a. Composition of the material.
  - [1] b. Thickness of the material.

Approved By: J. D. McCarthy  
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Date: 1/2/86

Date Administered: January 10, 1986

Passing Grade: 80%

86-1-1



## ***A Chronology Of Experimental Programs***

A very informal summary of experimental programs performed to date at the Rocky Flats CML was written by this author in 1972. This unpublished collection of pages had no intended audience. It was his attempt to organize the CML's work in his own mind. The purpose was to collect a succinct statement of who conducted what experimental program, when the study was performed, and what information was published where. This simple discussion gave no scientific information whatsoever but only a terse description of each program. It did list where the experimental data may be found by citing Control Console Log Books, the bound formal record books religiously maintained for each program. Even this was known to be incomplete. In addition to the Console Log Books, each program had any number of loose leaf notebooks associated with it. Usually, these were collected in one or more loose-leaf binders. Dates of each program were given; and any published papers resulting from the work were also identified. The informal summary also told the number of experiments performed. Surprisingly, this document proved to be so useful, at least internally, that it was updated in 1977, 1990, and, again, in 1993.

The last update was written a few years after the last critical experiment had been performed. Its scope was expanded to include a little history of criticality safety at Rocky Flats prior to the CML as well as a then up-to-date discussion of post-experiment activities. Another purpose of the last revision was to highlight those experimental programs for which no

publications had resulted. For some indefensible reason, the urge to perform ever more experiments precluded the sensible completion of an experimental study that comes from publishing results. The folly of that policy is clearly seen now. Realization of that error, in turn, led to seven papers (Refs. 1–7) written by this author under a contract with the United States government and administered by the Idaho National Engineering and Environment Laboratories (INEEL). These papers reported never-before published data on a variety of experimental systems: plutonium and enriched uranium fuels, solution and solid studies, as well as both single unit and array geometries. The developing character of this expanded 1993 paper formed the impetus for the present history paper about the Rocky Flats CML. The hope is to preserve this history for posterity.

### **CML Overview**

Rocky Flats began operations in 1952 as discussed in another section. The Dow Chemical Company was the Prime Contractor to the Atomic Energy Commission (AEC) at that time. Early criticality safety was provided using the meager experimental data generated by only a couple of laboratories throughout the United States and a few theoretical approaches which have become known as “hand calculational methods.” Subcritical experiments—but ones which approached much closer to criticality than one would like to see in the plant—were carefully performed.

These were called *In Situ* experiments; and even the year of the first one is not known. In addition to C. L. Schuske, pioneers of the Nuclear Safety group at Rocky Flats were: Jerry Arthur, Donald F. Smith, Arthur N. Nickel, Aurel Goodwin, Jr., and George H. Bidinger. Arthur left Rocky Flats about 1959. The others contributed until between about 1959 and 1962.

This team performed several early experimental programs involving both enriched uranium and plutonium in solid, powder, and solution forms. Their fine work exemplifies simple elegance in a fledgling field not explored by many. A few of their publications, all internal Rocky Flats reports, were:

- RFP- 178 *Plutonium Plexiglas Assemblies*
- RFP- 190 *Plutonium Plexiglas Assemblies, Part II*
- RFP- 201 *Nuclear Safety Experiments on Plutonium and Enriched Uranium Hydrogen Moderated Assemblies Containing Boron*
- RFP- 246 *Nuclear Safety Measurements on Systems Containing Boron and Enriched Uranium*
- RFP- 265 *The Use of Nuclear Poisons for Criticality Control in Chemical Processing*

Others probably existed but may have been lost to posterity. Fortunately, most of these documents still existed in the files of the Criticality Engineering group at RFETS as of 2000. Hopefully, they will be donated to the Archives maintained at LANL during the next decade.

Rocky Flats was not the only CML in the United States. In fact, it was the last new laboratory built specifically for that purpose. The historic first facility was built in the 1940s amidst a cloak of

secrecy. The second was not far behind. Others laboratories pre-dating Rocky Flats were:

- Los Alamos Scientific Laboratory  
near Santa Fe, NM
- Oak Ridge National Laboratory  
Oak Ridge, TN
- Brookhaven National Laboratory  
Long Island, NY
- Lawrence Radiation Laboratory  
Livermore, CA
- Battelle Pacific Northwest Laboratories  
Hanford, WA

Los Alamos was instrumental in developing the first atomic bombs for the United States. Over decades, the laboratory has earned the reputation for quality physics research as well as training in reactor physics. The name was later changed to Los Alamos *National* Laboratory (LANL). Los Alamos now has three different experimental areas, originally called “Kivas,” now called “CASAs.” Hugh Paxton and Dave Smith are two pioneers whose names will always be associated with this laboratory. Oak Ridge was a close second to LANL. It, too, was pivotal in the war effort; it became the source of enriched uranium. In later years, it focused much of its efforts on uranium experiments. That CML had three testing areas similar to the Assembly Room at RFETS; but they were all in one building. It was closed in the 1970s. An icon of the industry, Dixon Callihan, served as its director throughout its entire life. He was also the editor of one of the country’s leading journals in the nuclear field. Both Los Alamos and Oak Ridge have conducted prompt critical experiments. These are studies where prompt criticality—with its attendant burst of energy and radiation—is *intentionally* created. The laboratory at Brookhaven focused more on pure physics experiments.



One test facility, called “Low Mass,” was a tall tower built in the woods on Long Island. No building even encased the apparatus. The intent was to minimize neutron reflection. Brookhaven’s CML closed in the 1960s. Herb Kouts is a name integral to that facility. The laboratory at Livermore was later known as the Lawrence *Livermore* Laboratory. Its history is often associated with the United State’s weapons programs. They performed a valuable series of experiments on a split table machine in the 1960s. Those experiments employed 375 kg of plutonium metal in the form of 125 cylinders weighing 3 kg each. Oscar Clint Kohler directed the studies, although Al Kirschbaum started research there.

Finally, the CML at Hanford, Washington, predated Rocky Flats by only a couple of years. In fact, Schuske closely copied Hanford’s physical design. Notable exceptions were that his Assembly Room was 50% taller; and Hanford had a better “blast door” design to the outside world. Another major difference between the two was that the Hanford facility specialized in plutonium experiments whereas Schuske’s dream would handle both fissile materials handled at its plant (plutonium and enriched uranium). E. Dwayne Clayton was one on the nation’s pioneers in the nuclear criticality safety industry; and his name is synonymous with that laboratory.

The first critical experiment at the brand new Rocky Flats CML was performed September 10, 1965. Since then, about 1,700 measurements were performed on systems composed of enriched uranium metal, enriched uranium solution at a number of concentrations, plutonium metal, and low-enriched uranium oxide. Most of these attained delayed criticality; but many did not for one reason or another.

All but a few were directly associated with plant operations at Rocky Flats. An exception to this generality occurred when the Nuclear Regulatory Commission (NRC) sponsored an extensive series of experimental studies in the 1970s and early 1980s. These involved low-enriched uranium oxide at increasing hydrogen-to-uranium atomic ratios. In addition, five short programs were carried out for special applications. These, too, were not associated with Rocky Flats plant operations. Almost all programs were unclassified and, thereby, easily accessible. Only a few short programs were classified. The last experiment occurred in October of 1987.

### — *Chronology* —

The discussion below briefly highlights every experimental program ever conducted at Rocky Flats. It is in approximate chronological order, although, on several occasions, one program overlapped or was contained within another. Interested persons seeking a specific program or class of studies may find reading this lengthy section arduous. To aid that reader, a descriptive phrase is displayed in bold face font at the start of each new program. Information supplied thereafter includes a very brief description of the program. Detailed information will require further research into published papers and/or archived data maintained at LANL. Some association with plant questions is often given. Factual data such as the coded identification number (A-BB-xxx), the Senior Experimenter in charge, the beginning and ending dates of the experiments, the number of measurements made, and the Control Console Log Book number(s) containing the original raw data (now housed in the LANL Archives) are tersely provided.

Finally, some discussion as to publications resulting from the study is attempted. This list is not necessarily complete, although an effort is made to cite both journal publications as well as internal report numbers whenever possible. Journal articles, of course, may be obtained from any well-stocked scientific library's collection. Internal reports may not so easily be found. A few of these less-well-distributed documents will be retained *in perpetuity* in this author's personal collection, although copies may be made by any interested person. One good source of criticality safety documents is a personal collection once belonging to Mr. Howard Dyer, now retired from the Oak Ridge National Laboratory. Dyer donated his collection to ORNL at that time; and it is maintained by them. This collection is known as the Howard Dyer Criticality Safety Library.

Most of these Control Console Log Books are presently already preserved at the LANL Archives; but a very few remain in this author's possession. These will be donated to the Archives within the next couple of years after every conceivably important aspect of the Rocky Flats CML has been documented. However, Log Books, alone, are never sufficient to reconstruct a given program completely. Loose leaf notebooks containing safety review documents, purchase order forms, analytical reports of elemental compositions, field measurements of apparatus dimensions, reciprocal multiplication curves, pre-run check sheets, and an endless variety of other equally important information are also housed there. They are more difficult to associate with a particular program as the Archives stand now. An uninformed investigator would have difficulty collecting all information associated with one given Control Console Log Book.

This author hopes to rectify this problem as soon as this paper is completed. He hopes to construct a document to be maintained at the LANL Archives. This would "cross correlate" all information within this entire collection. It would specifically and uniquely associate each box and folder (and, sometimes, sub portions of a folder) with each experimental program ever performed at Rocky Flats. Completion of this effort could occur by the end of 2005.

The list of publications is admittedly not complete; others almost certainly exist. Overlooked documents are not listed here simply because they are not recalled by this author. This History does not pretend to offer a complete bibliography of Rocky Flats' publications. This has already been done and will not be repeated here. Brian Koponen compiled useful bibliographies of previously published documents related to nuclear criticality safety. These references include Rocky Flats publications as well as a host of others. One is called the "Critical Experiment Bibliography" (UCRL-52769) and was published in 1979. Second, the "ANS-Transaction Compilation" (UCRL-53369) was published in 1982. Koponen is about to publish an updated bibliography with the descriptive title "Nuclear Criticality Safety Experiments, Calculations, and Analyses-1958-1999: Compilation of Papers from the Transactions of the American Nuclear Society" (April, 2000). These bibliographies are referenced in popular textbooks on the subject and in most reports issued by the Nuclear Criticality Information System (NCIS). They, together with the list of papers written since 1993 by this author under contract with the United States government and administered by INEEL, form a very complete bibliography of papers generated at or about Rocky Flats.

Experiments were coded for quick and easy reference among workers at the CML. This code consisted of a trio of numbers such as: A—BB—xxx. The first block referred to the principal fissile material used. Specifically, A = 1 pertains to enriched uranium metal, A = 2 corresponds to enriched uranium solution, A = 3 means plutonium metal, and A = 4 refers to low-enriched uranium oxide. The second block referred to the numerical sequence of whole *programs* using that fissile material. For example, the first program studied with uranyl nitrate solution carried the designation 2-1-xxx while the next was 2-2-xxx. Usually, program sequence numbers are chronological; but occasionally a smaller one became embedded within another, larger study. The final code block, xxx, identifies the actual chronological sequence of the individual critical or critical approach experiment within that series. The term “critical approach experiment” is used because not all individual experiments actually achieved criticality.

### ***Uranium Spherical Assemblies***

G. Tuck lead the first ever experimental program. Grover reflected enriched uranium metal spherical and hemispherical assemblies with oil. These were single units, not arrays. Some were solid; others, thick-walled shells. The oil resembled water in hydrogen content but did not adversely affect the fissile metal. Both liquids are very similar in hydrogen content with many liquids with which fissile metal came in contact at the plant. In all, 235 measurements were made between September 10, 1965, and April 5, 1967. The series were identified by 1-1-xxx and 1-3-xxx, the difference being geometry (spherical = 1 and hemispherical = 3). Four

Control Console Log Books<sup>71</sup> were needed to contain them: Book I ran through experiment 1-1-8 and ended 9/16/65. Book II continued spherical studies through experiment #11, ending 10/22/65; and it also contained the first 27 hemispherical cases through 1/26/66. Book 3 ran through 1-1-99 (1/26/67) and finished hemispherical experiments with 1-3-77 (1/12/67). Book 4 finished the spherical studies with experiment 1-1-158 on 4/5/67. Five unclassified Rocky Flats publications (RFP reports) resulted from this program (Refs. 8a–e).

In addition to these internal reports, Tuck published a number of journal articles (Refs. 9a–b). Two other persons published a calculational study of Tuck’s work (Ref. 9c).

### ***Massive Subcritical Uranium Spheres***

This author made 61 critical approach measurements on enriched uranium metal assemblies similar to Tuck’s series except no hydrogenous reflector was used. They were subcritical measurements subject to the multiplication safety limit of ten; so they resembled *In Situ* experiments. In spite of that, they proved very useful because even long extrapolations accurately measured critical masses as large as 185 kg. Even though liquid reflectors were not used, some configurations contained regions of mild steel. These studies simulated Rocky Flats’ metallurgical pressing operations. No program identification number was assigned, probably because these experiments were not highly regarded at the time. These data were not recorded in any Log Book. Experiments were performed between August 19, 1966 and March 8, 1967. One internal paper was issued (Ref. 10) in 1967. A more-complete paper (Ref. 6) was written under the INEEL contract in 1997.

<sup>71</sup>Only the first two Control Console Log Books were numbered with Roman numerals.

### ***Weapons Study***

A single measurement of the multiplication under full oil reflection of the fissile component of one weapon unit of special interest was directed by C. L. Schuske. R. E. Rothe actually performed the experiment; but this was the only experiment ever directed by Schuske after the CML had been built. The study was considered urgent because weapons engineers elsewhere had determined that their design might accidentally achieve prompt criticality if dropped into water. Their calculations about their own design produced that surprising result. The experiment was intended to verify that unacceptable fact. The experiment proved this clearly was not the case. The experiment ended at the very same moment those engineers telephoned Schuske to say they had discovered an error in their calculations. Corrected calculations agreed with experiment completely. The measurement was made April 20, 1966. It is not documented in the bound, unclassified Log Books because the experiment was classified. It was not assigned an experiment number. One classified report (Ref. 11), was authored by C. L. Schuske and B. B. Ernst.

### ***Special Materials***

G. Tuck and E. C. Crume of Oak Ridge National Laboratory measured four critical masses for spherical assemblies similar to those of the first series, except for two features. Two regions of fissile metal were separated by one region that contained a special non-fissile material. The purpose of the study was to evaluate that special material. A Secret/Restricted Data report, (Ref. 12), was authored by them in 1966. Soon thereafter, R. E. Rothe and N. L. Pruvost of the Lawrence Livermore Laboratory at Livermore, California,

continued the program with nine more measurements involving a slightly different special non-fissile material. The two authored another classified report (Ref. 13). None of these 13 experiments are recorded in the unclassified Log Books. There were not assigned experiment identification numbers nor are the dates of these studies recalled.

### ***Poison Plate I***

The first solution experiments did not begin until May of 1967. R. E. Rothe studied the “poisoning” of 450 gU/l uranium solution by a set of up to 103 parallel, boron-loaded, stainless steel plates. The thin plates contained about 1% elemental boron alloyed into the metal. The metal plates stood vertically along chords of the right circular cylindrical tank. The number of plates present was varied; but whatever plates were used were about uniformly spaced from one another. The study was loosely associated with the plant’s need to store large volumes of fissile solution in tanks made critically safe by fixed neutron absorbers. This geometry might be viewed as an alternative to storing these solutions in Raschig ring filled tanks. The study naturally fell into two groups. First, plates were so far apart that criticality occurred between them and below their top. For the second, a greater number of uniformly spaced plates remained subcritical when solution reached their top plane. In these cases, criticality was then attained via an unpoisoned solution slab directly coupled to the highly poisoned region below it. Rothe made 38 measurements between May 9, 1967, and August 11, 1967. These were numbered 2-1-xxx. The work is recorded in Console Log Book 4. At this time in the CML’s history, successive programs might appear in one Log Book.

Later, the tendency was to start a new Control Console Log Book for each new program. The data was reported by Rothe as RFP-1195 in 1969 (Ref. 14a); and this became a journal article (Ref. 14b).

### ***Oil-Reflected Plutonium***

D. C. Hunt lead a long, extensive program of measurements involving oil reflection of plutonium metal. The study was similar to the enriched uranium nesting hemispherical shells program led by G. Tuck except the fissile metal shells were only half as thick. Other than that, most aspects of the two programs were identical. Even the same brand of oil was used. The purpose of this study was two-fold. First, the plant no longer dealt with large amounts of enriched uranium metal; plutonium had become it's principal focus. Secondly, comparisons between two very similar programs which differed only in the nature of the fissile fuel could provide useful guidance for criticality safety engineers as they might hope to apply data from one fuel type to the other. Hunt labeled these 167 experiments 3-1-xxx and 3-3-xxx; and the second numbers carried the same distinction as before. Experiments were performed between May 31, 1967, and September 12, 1969. Console Log Book 4 contains experiments through 3-1-3, ending September 8, 1967, and 3-3-18 ending August 22, 1967. Log Book 5 ends the program at 3-1-86 (September 12, 1969) and 3-3-81 (August 26, 1969). Hunt authored one internal report (Ref. 15) on this data in 1968. This was classified Confidential/Restricted Data at the time; but it was declassified in 1997. Hunt and M. R. Boss (Merlyn) later published two journal contributions (Refs. 16a–b).

### ***The “Christmas Tree”***

B. B. Ernst lead a program of 110 critical experiments between September 12, 1967 and January 24, 1968. His study involved intersecting cylinders, called “arms,” branching off a square central column—all filled with ~450 gU/l uranium nitrate solution. The central column was tall and thin. Alone, it would be well-subcritical when full. Variables included the number of arms off each face, the number of faces of the square column possessing arms, and the diameter and number of arms along each face. One final variable was the angle between arms and column: some were at right angles to the column; others, inclined at 45°. The initial intent of this study was to provide data to safety engineers evaluating the criticality potential of the many complex arrays of piping at Rocky Flats which carried fissile solutions. Bundles of lines of different diameters and various spacings sometimes ran at various angles to other similar bundles at many places throughout the plant. These experiments were identified as 2-2-xxx. Results appear in Log Book 4 (to 2-2-33) ending in Log Book 5. They were not completely published at the time, although Ernst and Schuske did published a partial analysis (Ref.17a) in 1968. This document did not receive wide distribution for some reason; so copies are hard to find. Only recently and with Ernst's permission, this author wrote a complete report (Ref. 7) of Ernst's experimental program. It also contains a complete copy of the former as an Appendix.

Even though the plan had been to study intersecting bundles of piping, Schuske recognized the possibility for developing the data into a clever solution storage tank model. He called it the “Christmas Tree” tank because many arms safely spaced

from one another branched off a central column at a number of azimuthal angles around the column. This model was never put into plant practice probably because so many welds were required. One significant fact related to criticality safety was recognized through this program. A great deal of reactivity develops at the junction of two or more large-diameter (but still subcritical) pipes. This realization caused the Tree Tank to be modified such that its arms were separated from its column by lengths of small-diameter pipe. This necessity greatly increased the number of welds. Schuske and D. Dickinson (Deanne) published RFP-1553 (Ref. 17b) in 1971 concerning this model. Ms. Dickinson authored RFP-1499 (Ref. 17c) in 1970, relating to the same subject.

### ***Slab/Cylinder***

G. Tuck conducted a program of 48 measurements on a uranium solution slab interacting with solution-filled cylinders. Cylinders stood vertically in a flat slab tank. The solution was, again, ~450 gU/l uranyl nitrate. The study approximated a plant accident where solution-filled vessels might leak into a slab-like geometry. The program extended from February 16, 1968 through October 15, 1968, and is labeled 2-3-xxx. Data is contained in Log Book 5. Tuck and H. E. Clark (Harold) authored three RFP reports (Ref. 18a–c), with the last two being model developments. Two journal articles (Refs. 19a–b) were published in addition.

### ***Partially-Reflected Solution Slab***

Only six experiments were needed for a series conducted by R. E. Rothe following a suggestion by C. L. Schuske. Here, the criticality of uranium solution slabs under

various conditions of plastic reflection was measured. This include both top and bottom reflection. To the degree that plastic might approximate concrete in hydrogen content, bottom-only reflected experiments simulated plant conditions where solution might leak onto a floor. One interesting physics aspect involves the case of one-sided reflection. The critical slab thickness closely equals half the fully *unreflected* slab thickness plus half the thickness of a slab fully reflected on both faces. A second useful observation came from comparing these results with those from experiments 2-1-xxx. The unpoisoned slab atop a sufficiently poisoned fissile solution region is more reactive than a plastic reflector. The usefulness is that a complex system composed of absorber and fissile materials may be conservatively approximated by a simple plastic reflector. The experimental series was identified as 2-3A-xxx and was performed between May 24, 1968 and June 20, 1968. Experiments appear in Log Book 5. Rothe, Schuske, and E. E. Hicks (“Tim”) authored RFP-1343 in December 1969; and this was made into a journal article (Ref. 20).

### ***Plutonium Calorimeter***

G. Tuck and H. W. King (Howard) performed nine measurements on plutonium oxides in containers reflected by oil. No details are recalled because this author was not at all involved in this short study. The plutonium oxides were brought into the building on a temporary basis; and they were only used for this study. This series related to a plant application directly—calorimetry. This was one method used in the plant to estimate amounts of plutonium oxide. Experiments addressed a criticality safety question currently under study. The series, 3-10-xxx (program sequence out of order), was performed between February 3

and February 7, 1968. Raw data is contained in Log Book 5. No report was ever written.

### ***Coupled Assembly***

D. C. Hunt studied the nuclear interaction of uranium metal and uranium solution for a variety of conditions. This was called the “coupled assembly” study because of neutronic interactions between these two physical forms of fuel. The metal was spherical in geometry. Tanks of three diameters and uranium solutions of three concentrations were studied; so a wide variety of combinations existed. One plant operation represented by this study was the dissolution of metal in an acid bath. Some plant recovery processes involved dissolving metal away from a returned weapons components. Between November 17, 1969, and April 16, 1970, a total of 202 measurements were made. Then, four more followed in October 1970. The program is symbolized 2-5-xxx and is recorded in Log Book 5 (to 2-5-38) and Log Book 6. Hunt and R. E. Rothe authored six internal reports (Ref. 21a–f) including preliminary and final data, model developments, and calculated comparisons. In addition, Rothe and Hunt authored another paper (Ref. 21g) wherein the data were analyzed from a different and unique perspective. Cross correlation of the data permitted an estimate of the *change* in critical mass as a metal sphere might move vertically away from center within a tank of fissile solution. This set of static cases simulated, for example, the dynamic event of a piece of fissile metal dropped into a vessel and falling through a fissile solution region. Two of these internal reports appeared as published journal articles (Refs. 22a–b). A final technical note (Ref. 23) concerned the off-center notion.

### ***Plutonium Ingots***

D. R. Ferguson did two sets of hand stacking experiments on plutonium metal. Neither appeared in any Log Book nor were identification numbers assigned to the somewhat informal study. The number of experiments in each set is not recalled. The plutonium metal was only temporarily diverted from the normal Rocky Flats production stream because a sizeable fraction of the world’s supply of plutonium at that time was involved in some of these experiments (1800 kg). Both programs were directly related to plant criticality safety questions concerned with storage of massive ingots of plutonium metal. Ingots ranged between 7 and 12 kg each; and a large number were used. One study was a true *In Situ* experiment in that it was performed in a plant building, not the CML. Ferguson arranged up to 136 commercial drums (55-gallon)—each containing one, flat, thin, ingot. These included one-, two-, and three-layered arrays of drums. This study took place in the late 1960s. He published this subcritical data (Ref. 24) in 1968; but it contained insufficient detail for modern computational needs. This author wrote a much more complete report covering both this experiment as well as the next (Ref. 6) in 1998. Ferguson gave his permission for this author to publish his data. Furthermore, he was available for occasional discussions about the studies during the writing.

The second study took place in the spring of 1969. It was performed in the CML, not the production areas. They were similar to *In Situ* experiments in that they were subcritical approaches built manually. Many plutonium ingots, similar to those described in the preceding paragraph, were again temporarily “borrowed” from the

production stream for this test. They were returned immediately thereafter. The metal was contained in the same commercial film cans used for storage and handling of ingots in those days. These thin-walled cans were about half a meter in diameter by 60 mm high. Ferguson placed arrays of ingots approximately centered in film cans in a vertical stack. Four patterns were studied: 1xN, 3xN in a triangular pitch, 2x2xN, and 3x3xN, the last two having a square pitch. Even all that fissile metal proved to be well subcritical because the film cans provided just enough vertical spacing. An incomplete report (Ref. 25) was issued at the time, although it was further documented (Ref. 6) in 1998 as mentioned above.

### ***Uncoupled Coupled Assembly***

G. Tuck continued the “coupled assembly” study, described above, by separating the metal and solution regions by “uncoupling” materials, such as steel. Except for this difference, both studies were almost identical. This variation on the earlier study was referred to as the “uncoupled coupled assembly” program. The program had some similarity to certain hydraulic pressing operations in use at the plant at the time. Tuck performed 52 measurements between February 19, 1971, and May 11 of the same year. Raw data for the series, identified as 2-6-xxx, is found in Log Book 7. Tuck, H. E. Clark, and D. L. Alvarez (Donald) published RFP-1939 in 1972 which was made into a journal article (Ref. 26) in 1973.

### ***An Aborted Program***

An interesting experimental program had been proposed in the 1970s but was never actually performed. Through it, the “temperature coefficient of reactivity” of

solid fissile metals would have been measured. This “temperature coefficient” for any fissile system may be understood as the *change* in critical parameters (e.g. critical mass) as the ambient temperature of the environment changes. This property was to have been determined by measuring the critical mass of a simple enriched uranium metal sphere at two vastly different temperatures. Specifically, the plan was to measure that parameter for the CML’s uranium metal shells when reflected by room temperature oil. Then, the oil would be heated to some much higher temperature and the critical mass, again, measured. The slow introduction of hot oil around the metal sphere would have ensured that the metal adiabatically attained the oil’s high temperature. Therefore, both oil and uranium metal would have been elevated to that high temperature. Comparing the two critical masses would measure the “temperature coefficient of reactivity.” That parameter would have been useful in predicting events during a nuclear criticality accident. Some figures of the Liquid Reflection Apparatus in other chapters show the electrical immersion heater and pipe insulation installed for this aborted experiment. Silver-colored insulation around the tank and oil lines can be seen and were to have prevented heat loss; an insulated lid would also cover the tank for the same reason.

Unfortunately, this useful experiment was never performed even though all the equipment had been installed. No reason for this disappointing omission is recalled. Nonetheless, that equipment was never removed for later experiments at room temperature because it was such low mass as to have negligible impact on neutrons. The experiment seemed clever to this author, worthwhile, and would have been useful in understanding the dynamics of nuclear criticality excursion accidents.



### — A Theoretical Dilemma —

Actually, this aborted study had also been proposed for a plutonium sphere as well. Afterthought, suggests that the study on plutonium metal may *not have worked* very well at all even if tried. This comment is pure conjecture and may be totally fallacious and open to professional debate. The problem would have been the intrinsic high temperature of plutonium metal already existent under ambient conditions. In room air, plutonium metal was too hot thermally to handle comfortably. This elevated temperature was caused by stopping 5 MeV alpha particles naturally generated within the metal by the metal's radioactive decay. Given that initial temperature, it may have been difficult to alter using heated oil. In fact, the metal quite possibly began the experiment hotter than that to which the oil could have been heated. Without temperature probes actually attached to and inside the metal, the exact temperature of the metal at criticality may never have been known reliably.

This revelation may call into question all experiments ever performed at Rocky Flats or elsewhere on plutonium metal immersed in a room-temperature liquid. Two questions naturally arise: "What was the actual temperature of the plutonium metal at the moment of criticality?" The answer to the second question may make the first question irrelevant: "Is the temperature coefficient of reactivity for plutonium metal very sensitive at all over a few dozen degrees?"

If the actual temperature of the metal is not known at the moment of criticality and if that is an important parameter, then all past published results may be of doubtful value. The argument had always been made that plutonium metal's high ambient temperature would be brought down to the ambient temperature of the hydrogenous fluid (oil or water) before criticality was attained. Whether or not this actually was the case is unknown.

This possibly weakness is not raised to discredit any work done previously at Rocky Flats or anywhere else but to alert criticality safety experts of a previously unrecognized—and possibly significant—uncertainty.

### *Poison Plate II*

The next program was a continuation of series 2-1-xxx and was also performed by R. E. Rothe. Here, the same boron-loaded stainless steel plates were flooded with low concentration uranium solution instead of the ~450 gU/l uranyl nitrate solution used previously. Only concentration differed; the present two were 141 gU/l and 52 gU/l. The purpose of this study was to expand the earlier work such that parametric concentration curves could be used to evaluate sensitivity to concentration for any appropriate system. The program was identified as 2-7-xxx. Twenty critical measurements are found in Log Book 8. The program extended from June 1 to July 14, 1972. RFP-2012 was published by Rothe, H. E. Clark, and D. L. Alvarez in 1975; and this was made into a journal article (Ref. 27).

## ***Plutonium Cylinders I***

D. C. Hunt directed a lengthy series of experiments involving Pu metal cylinders in a three-dimensional rectangular array. This was the first of several programs using these fissile metal units. The plutonium cylinders had previously been used in a number of critical experiments at Lawrence Radiation Laboratories and had been transferred to Rocky Flats early in the 1970s. Each cylinder weighed a little over 3 kg. A total of 375 kg of plutonium metal was contained in 125 canned units. Previous experiments in California had not exposed them to water; so they arrived at Rocky Flats contained in thin-walled aluminum cans with crimped mild steel lids. Rocky Flats, however, planned to immerse them in water. To safeguard against this corrosive (to plutonium) liquid, the canned units were placed inside a second sealed container to protect them from water vapor. The second container also protected the thin-walled aluminum cans from mechanical abuse and a possible rupture if dropped. This second container was a thick-walled stainless steel cylindrical can fabricated as two halves glued together over a broad lip.

These plutonium components were especially useful when considering Rocky Flats' criticality safety limits. They conveniently equaled the largest sized single units (3 kg) nominally allowed on plant site. Exceptions to this generalization existed for unique geometries of course (ingots are one example); but most operations throughout the plant were limited to 3 kg or less. Therefore, any plant operation, such as storage, transportation, machining, etc., was well represented by these units.

The intention was to study  $2 \times 2 \times N$ ,  $3 \times 3 \times N$ , and  $4 \times 4 \times N$  water-reflected arrays. Unfortunately, not all were completed.

A total of 76 experiments with four units per level were performed between late 1973 and February 17, 1976, although an 11-month-long shutdown in 1975 to complete certain facility maintenance projects interrupted the study. The series was identified as 3-4-xxx and is recorded in Log Book 9.

Hunt never published this valuable data for some unknown reason. Two possibilities come to mind. The program was to have been continued with 9 and 16 cylinders per layer after the  $2 \times 2 \times N$  studies; the thought may have been to wait for the completed study. A second possibility is that preliminary calculations on the results obtained for the  $2 \times 2 \times N$  arrays suggested the apparatus contained just too much aluminum support stock too close to the doubly canned plutonium, casting a cloud over any results with this apparatus. This author wrote a detailed report (Ref. 2) in 1996 describing both this and a later attempt to revisit three dimensional plutonium metal arrays. This effort was part of the INEEL contract.

### **— A Digression —**

Experiments had always been applied directly to plant operations in evaluating criticality safety. That had been the design goal from the onset of experiments in the 1950s (even before the CML) through the mid-1970s. Experiments outlined above fell into this category. These came to be called "prototype" experiments because the experimental configuration so closely resembled some plant operation—the prototype.

A few computer codes had been created by the late 1960s which attempted to calculate criticality. These mostly solved neutron diffusion equations or, later, neutron transport equations. They were limited to the simplest geometries of slabs cylinders and spheres. About 1970, "Monte Carlo" codes, KENO and O5R, were developed. These were statistical in nature; and this seemed promising. The code could represent a wide range of configurations found in a production plant. The need to validate this code in its many areas of applicability was quickly recognized. This introduced the concept of a "benchmark" experiment which would be one whose geometry and material parameters were so well-defined (and also consistent with geometry and material description limitations of the code) that little or no discrepancy between the experimental critical data and the calculated neutron reproduction factor ( $k$ -eff) could be laid to experimental uncertainties.

Even though benchmark experiments began to flourish nationwide, Rocky Flats continued to study hybrid systems. These were well-defined experimental configurations which still resembled specific plant operations. They became "benchmark" experiments on "prototype" systems. Rocky Flats' management perceived that the CML had to justify its existence by conducting experiments on systems that resembled Rocky Flats operations. Some CML staff

members suggested a contrary approach. They pointed out that valuable benchmark experiments could be done examining specific *aspects* of the code without regard to the overall *appearance*. For example, one program was proposed where the majority of fissions would occur for neutron energies somewhere between a fast spectrum and a thermal one. Metal systems corresponded to fast spectrums; and solution studies validated thermal ones. This suggestion would test the code's ability to treat parameters properly at those intermediate energies even though the apparatus did not look anything like any plant process. Unfortunately, this position was not adopted by Rocky Flats management.

### ***Uranium Solution Cylinder Benchmark***

R. E. Rothe lead the next program which was the first to be specifically designed as a "benchmark" experiment. It involved high enriched uranium solution in simple geometries. The solution concentration was also high. One simple cylindrical tank was suspended from the ceiling in the very center of the large Assembly Room. The goal was to have the *least possible* environmental neutron reflection. Next, the same simple tank was situated within thick-walled cubical reflector "rooms." That goal was to have well-defined environmental neutron reflection. These rooms were about 1.73 m on a side with a 1.22 m cubical cavity. One was plastic, the other, concrete.

Both materials were thoroughly analyzed to determine the best possible elemental composition.

This benchmark study continued with square arrays of right circular cylinders contained within these same two cubical reflectors. This study was not motivated by plant problems, although many aspects were valuable to Rocky Flats. The program was suggested and sponsored by the Nuclear Regulatory Commission (NRC). A total of 182 experiments, identified as 2-8-xxx, were performed between April 21, 1976 and May 26, 1977. Later, four additional experiments were performed in the same series as a demonstration to official plant visitors. These occurred in August, 1977. All these experiments are described in Control Console Log Books 10 and 11. R. E. Rothe and I. Oh (Inki) co-authored three papers. One (Ref. 31a) is a Topical Report to the NRC. The other two were published as back-to-back journal articles reporting these results (Ref. 28) and a calculational study (Ref. 29) of the experimental results.

### ***Uranium Oxide Contract***

G. Tuck was the initial lead person on the next program; but, later, R. E. Rothe took over that role. This was another program sponsored by an NRC contract. Rocky Flats was selected for this work because it had the necessary Horizontal Split Table apparatus, the required expertise, and the schedule flexibility to accommodate some outside contract work. Originally intended to last about one year, the NRC Program Manager kept adding more and more facets. As a result, NRC-funded work pretty much kept the CML busy during the middle-to-late 1970s. This very long experimental program involved low-enriched (<5% U235) uranium oxide.

The material had little application to Rocky Flats because operations at the plant did not involve reactor fuel. The program was designated 4-1-xxx and 4-2-xxx.

The oxide was packaged into small plastic bags; and these were “pelletized” into square briquets under high impact. A number (28) of briquets in a 2×2 by 7-layer-high array were packaged into thin-walled aluminum cans which were cubical and 152 mm on a side. Well over 100 cans were prepared in this way. The intrinsic water of hydration plus ambient water absorbed within the oxide plus the small amount of plastic used to fabricate the cans yielded an initial hydrogen-to-uranium, H/U, ratio of 0.77. Each can weighed an average of 15.026 kg.

Cans were assembled on both portions of the split table. Arrays as large as 5×5×2 on one table faced arrays up to 5×5×3 on the other. Table halves were brought together to form a single 5×5×5 array of cans. Arrays were contained in one of three frameworks. One was concrete; another, plastic. The third, made of thin steel, was intended to provide as little neutron reflection as possible while still containing the cans. Other parameters varied included interstitial materials between cans and the spacing within the three dimensional array. Later in the program, water was intentionally injected into each can uniformly to raise its H/U ratio. Two enhanced moisture contents were H/U = 1.25 and 2.03.

A total of 116 experiments were run between February 1978 and September 1981. They are described in Log Book 12 and the last few pages of Log Book 13. A total of 15 Quarterly Progress Reports (Ref. 30a–o) were published as NUREG/CR documents between 1976 and 1979. Five more papers (Ref. 31a–e) served as “final reports.” They were formally called “Topical Reports on Reference Critical Experiments.”

One interesting fact was discovered during a periodic weighing of the cans. A few were *gaining* weight. Several explanations were suggested, investigated and disproved. They were not, for example, absorbing moisture from the air over the years since packaging. Evidence did suggest that the oxide state was changing very slowly. Freshly calcined uranium oxide is  $U_3O_8$ ; but, with time, this seemed to “burn” into  $3UO_3$ . The effect was small. Only a few cans gained 1 or 2 grams.

Years later (mid-1990s), an internal document (Ref. 32) was written by this author to discuss the then-present status of the remaining uranium oxide cans. This was never formally published even as an RFP document.

### ***Annular Tank***

R. E. Rothe ran the next series of experiments, designated 2-9-1 through 38 (April 1980 through February 1981). These experiments involved a set of six nesting annular tanks in four diameters. This study was undertaken in search of a replacement method for the storage of large quantities of fissile solution was sought for plant use. Annular tanks, however, proved much less efficient than the Raschig ring filled vessels they might replace.

In the experiment, each annular tank, alone, was well subcritical; but nested sets readily attained criticality. When all four different tanks were nested, a great deal of criticality data was obtained—all four tanks attained criticality at a low height; but the inner and outer sets of three tanks also did so at somewhat greater heights. Pairs of the nested four were also studied.

In another portion of the study, two adjacent sets of three nested tanks as well as a line-array of three nested pairs of tanks were studied. These measurements are

detailed in Control Console Log Book 14. No report stemmed from this program at the time; and this decision was not argued seriously because considerable (and neutronically significant) gaps existed in the center of important solution regions. These gaps were the result of necessary manufacturing tolerances. Also, the nested set of four tanks had six stainless steel walls complicating any understanding of neutron movements within a critical assembly. Years later, however, these experiments were published (Ref. 1) as part of the INEEL contract series.

The same apparatus was used again for a different purpose about a year later. These now-familiar experiments, numbered 2-10-1 to 2-10-9, were performed during May of 1982 specifically to train Dr. John S. Pearson as a Certified Experimenter. R. E. Rothe was, again, the Senior Experimenter. Steven H. Manglos sat in on many of these as his initial training. The same apparatus was studied a third time in April 1983. These experiments were designated 2-11-1 to 2-11-4. This time, the specific purpose was to achieve intentionally high relative power levels on a well-known system. The intent was not to obtain new criticality data but to generate a high neutron flux for a criticality alarm detector study conducted by Dr. Robert E. Miles. R. E. Rothe was the Senior Experimenter, with R. E. Miles in to observe the data taken for him. No report was published for either 2-10-xxx or 2-11-xxx because no new criticality information was generated.

### ***Plutonium Metal Cylinders II***

R. E. Rothe led a program of plutonium metal studies begun in the summer of 1982. Designated 3-5-xxx, the configuration consisted of a 3×3×3 array of 3 kg canned

plutonium metal cylinders in a large, plastic, open-top, “tank” reflected and moderated by water. This continued the uncompleted 2×2×N array study of the same plutonium components begun by D. C. Hunt between 1974 and 1976. The same doubly-canned plutonium cylinders were used. Improvements included a larger tank with more reflection on all six sides, much less non-fissile metal in the array’s support apparatus, as well as the larger array size. Criticality safety experts will recognize that a compact 27-can array containing a little over 81 kg of plutonium metal is a lot of material in a small space—especially immersed in water. Typical plant operational limits only allowed 3 kg of plutonium metal when liquid flooding was possible.

The study was ill-fated, however. A slightly contaminated floor was discovered December 20, 1982, after the 22nd experiment. Water was drained to storage and the massive array remained dry while the floor was cleaned and the source of contamination sought. None was found until January 11, 1983 when an alarming discovery was made. One of the doubly-canned plutonium metal cylinders had ruptured. The floor of the plastic tank was visually contaminated by a large quantity of yellow-green powder. One can had been physically pushed apart by the pressure of the growing plutonium compound. That discovery abruptly ended the program. This incident is discussed in detail in another section.

All plutonium metal was removed from the building that same night and returned to the Rocky Flats production stream. This was a safety measure because the internal status of every other plutonium cylinder was not at all known. Some may have been about to leak. The cause of the incident was eventually traced to moisture which had penetrated seals on both

containers and contacted the bare plutonium. These 22 plutonium metal array experiments are detailed in Control Console Log Book 15. Experimental results were not published at the time; but they were finally documented (Ref. 2) in 1996 as part of this author’s INEEL contract (INEL-96/0250).

This problem with plutonium metal made everyone nervous. Even though uranium metal is much more stable against contact with liquids, the condition of these 80 nesting hemispherical shells was considered suspect. The shells had never exhibited any degradation over almost two decade’s use on many, many past experiments; and the shells were stored with a coating of grease to retard degradation. Nonetheless, the decision was made to remove these components from the building as well. Whether this was done at about the same time as the plutonium removal or many months later is not recalled. The fact remains that these 80 enriched uranium metal shells and 5 rods were shipped to another Rocky Flats building (Building 991) for long term storage. The plan at the time was that they could be easily returned to the CML whenever another program using them was planned. That never happened. Eventually, the set of shells were shipped to the CML at Los Alamos as discussed elsewhere.

Years later, others at other facilities analyzed these results as part of the International Criticality Safety Benchmark Evaluation Project (ICSBEP) through a pair of companion journal articles (Refs. 33a–b).

### ***Poisoned Tube Tank***

The next program was, again, a uranium solution study designed to help the plant solve its long-standing problem of

fissile solution storage. Raschig-ring-filled tanks were simply fraught with too many real or imagined problems. The new study was called the Poison Tube Tank experiment; and it consisted of 61 experiments designated 2-12-xxx. It took place between May, 1983, and September, 1984, with R. E. Rothe as Senior Experimenter. The Poison Tube Tank Study consisted of a uniform square matrix of hundreds of small-diameter vertical tubes into which were placed 8 different strong neutron absorbers. Half were rigid solid materials and half were powders. Spacing between stainless steel tubes was also varied. The space outside the tubes was filled with high-concentration uranyl nitrate solution until criticality was achieved. One of the solid absorbers was a borosilicate glass, which closely resembled Raschig rings, in the form of long rods instead of rings. The experimental program is described in Control Console Log Book 16.

Several publications stemmed from this study. An ANS-paper (Ref. 34) was presented by R. E. Rothe in June, 1984, at New Orleans (Volume 46); and he delivered a summary (Ref. 35) of several fissile solution storage methods at Jackson Hole, Wyoming, in September, 1985. Years later (1993), he published an internal Rocky Flats Technical Report (Ref. 36) containing considerable detail. Finally, an even more definitive article (Ref. 3) was written under this author's INEEL contract.

In the summer of 1999, some questions were raised specifically about those few experiments using polyvinylchloride (PVC) as the fixed neutron absorber. These discussions led to a re-evaluation of those points; and this author wrote a "reexamination" (Ref. 37) of the data. This document has never before been published in any form; and the only copy exists in the author's personal collection.

### ***Assorted Fuels Geometry***

The next program was actually designed and conducted by Richard E. Anderson, recently the director of the Critical Mass Laboratory at Los Alamos, New Mexico. At that time, he was not certified as a Senior Experimenter at Rocky Flats; so R. E. Rothe was officially the lead and fully involved. This study involved cylinders, slabs and other geometries of uranium solution. The Horizontal Split Table was used to increase reactivity. These experiments were thought to test the computer code's ability to calculate reactivity for combinations of these odd geometries. The program was labeled 2-13-xxx and had 32 critical approach experiments. R. David Sachs participated as an experimenter-in-training and R. E. Miles was a frequent observer. Results are contained in Control Console Log Book 17. The time span covers July 1985 through August 1986. No publication resulted probably because of the questionable value of the program. This is the only experimental study ever conducted at Rocky Flats for which no publication of any kind exists at all.

### ***Shielded Annular Tank***

Another attempt to resolve the plant's long-standing problem with fissile solution storage was addressed through this study. The program sequence number was wrongly numbered 2-13-xxx; it should have been 2-14-xxx. The error has never caused great concern probably because the Assorted Geometry program had such limited value. R. E. Rothe led the program with David R. Sachs as the second experimenter. Results are found in Control Console Log Book 18. This apparatus consisted of an annular tank with laminations of neutron absorbers and moderators

both inside and outside the tank. High concentration uranyl nitrate solution was pumped into this annular region. Interior materials reduced neutron interactions between one section of the tank and regions on the other side of the tank. Exterior materials similarly reduced this interaction between this and an adjacent tank.

Another improvement over the first annular tank study was its geometrical simplicity. The fissile solution region was not broken up by a number of stainless steel surfaces and interstitial air gaps. Stainless steel surfaces were machined, not merely rolled; so dimensional tolerances were much improved. The 19 measurements were made between the spring of 1986 and October 1987. Two factors interrupted this program. In August 1986, Rothe was badly injured in a mountain climbing accident and required several months to heal. He was the only Senior Experimenter; so no experiments could take place without him. Second, the need for a much more precisely machined tank was recognized. The physics behind that declaration is discussed elsewhere. This new tank took time to fabricate. By the time it was received in 1988, actions taken by Rocky Flats Maintenance personnel to remove certain components from within the first tank had resulted in a contamination incident in Room 101. This incident is discussed in detail in another section. Decontamination dragged on too long for a number of reasons. During that delay, the investigation into Rocky Flats' policies by the Federal Bureau of Investigation was in full force. The plant was so involved in responses to that situation that the experimental program never resumed. The 19<sup>th</sup> experiment proved to be the last critical experiment performed at the Rocky Flats CML. The only documentation of this study was through the INEEL contract in 1996.

## — End of Chronology —

There are no more experiments to discuss, apparatus to describe, relations to plant problems to explain, or Control Console Log Books to identify. About 1700 critical and critical approach experiments had been performed at the Rocky Flats CML in 22 productive years. These had included plutonium, high-enriched uranium, and low-enriched uranium fuels. Material forms included metal, powder, and solution. Single units as well as arrays had been studied. Some had been unreflected; others, reflected and/or moderated by a variety of materials. Most non-fissile materials had been commonplace; others, exotic. Over those decades, the laboratory never experienced an unplanned criticality excursion. Indeed, the life span of the Rocky Flats Critical Mass Laboratory had been a noble one.

Almost all publications pertaining to critical experiments have been acknowledged within the preceding several pages in one fashion or another. Several other papers from the combined creativity of CML staff have been published even though they may not have pertained directly to critical experiments. Schuske, Hunt and Deanne Dickinson, now Pecora, contributed articles to an entire volume (Refs. 38a–d) of *NUCLEAR TECHNOLOGY* which was devoted to criticality safety issues. This volume was published in 1976.

G. Tuck wrote a fascinating report (Ref. 39) about how stainless steel gloveboxes respond to various high explosives. He had increased the amount and kind of explosive, including black powder, dynamite, and C4 plastic, until the glovebox was totally destroyed. An interesting movie about this project is housed at the LANL Archives in Box 45, folder 1.



Tuck also wrote a journal article (Ref. 40) suggesting a simple model for anticipating the consequences of certain nuclear accidents. He also analyzed the French prompt critical studies of the 1970s called CRAC. Much of his analysis, if not the paper itself, can be found in the LANL Archives in Box 27, Folders 6 through 14, and Box 28, Folder 1.

This author recently wrote a lengthy treatise (Ref. 41) on the long-term stability of certain properties of borosilicate glass Raschig rings. Rings removed from CML storage tanks after more than 30 years of service were analyzed for mechanical strength and retention of boron oxide. This paper was finished in 1998 but has not yet been published. It was written under DOE contract.

Years earlier, he also authored a paper (Ref. 42) describing a unique method of volume-calibrating Raschig-ring-filled tanks (28, 1976). This method was used successfully at the CML for decades but has not been implemented elsewhere. Another technically useful history paper (Ref. 43) about his experiences maintaining the uranyl nitrate solution at the CML appeared in *NUCLEAR SAFETY*. Only one of the triennial inventory measurements was even written up as an internal report; that paper documented (Ref. 44) the 1969 physical inventory.

His one venture into pure mathematics (Ref. 45) concerns the calculation of the solid angle at any point in space subtended by a circular opening. D. C. Hunt published one paper wherein he showed how to calculate nuclear criticality by a "Collision Probability" procedure. This was published both as an internal report (Ref. 46a) and as a journal article (Ref. 46b).

This bibliography is admittedly incomplete. This author does not own a copy of every paper written by all those involved

with the CML nor recall even a fraction of their literary output. The talented staff produced a large number of other papers; and this author has a few of them, not already mentioned above, in his personal files. These fall nicely into categories and are referenced below merely to make this book as complete a document as possible at this time.

Internal reports (RFP's) easily divided into three topics. Three of them pertained to plutonium and its use at Rocky Flats (R. 47a-c) while the another was an empirical analysis (Ref. 47d). Three others clearly related to calculational capabilities (Refs. 48a-c). Three more publications were journal articles (Refs. 49a-c) not discussed above; and still three more described electronic hardware (Refs. 50a-c) invented at the CML. One never-published paper (Ref. 51) pertains to the already-mentioned controversy over pure-physics experiments vs. plant-oriented ones.

Various personnel within the CML have been active in writing American National Standard documents; and this author served as Secretary for one (Ref. 52) such Writing Group. One frequently-updated summary of CML experiments (Ref. 53) has been mentioned several times throughout this book. Finally, one well-known journal published back-to-back monthly issues in the fall of 2003 related to a variety of nuclear facility histories. The Rocky Flats CML was included (Ref. 54) in this collection. That paper was written by this author and is a very-much-abbreviated thumb-nail summary of this book.

Surely, other documents have been omitted from this vast bibliography. This is due to this author's ignorance and is in no way intended to slight any papers missed.

## Post-Experiment History

The CML never recovered from that last contamination incident in Room 101 related to the Shielded Annular Tank. That, coupled with plant-wide consequences of the FBI raid, became overwhelming obstacles. This section, like the experimental chronology, itself, contains a sufficient number of different issues that they are subdivided to facilitate scanning. Each important issue is highlighted in bold face font.

### *Ventilation*

Manpower was not available to decontaminate Room 101 in the late 1980s because Maintenance personnel had all been dedicated to solving the plant's larger problems. Before decontamination could begin, Operational Health Physics personnel deemed ventilation in Room 101 to be inadequate. This surprising revelation was claimed in spite of the long-standing history showing no previous ventilation problems over three decades of use. This questionable determination may have been an overreaction to the FBI's findings, an issue pushed by others to delay the pending decontamination, or a legitimate observation. The truth will never be known as explained below.

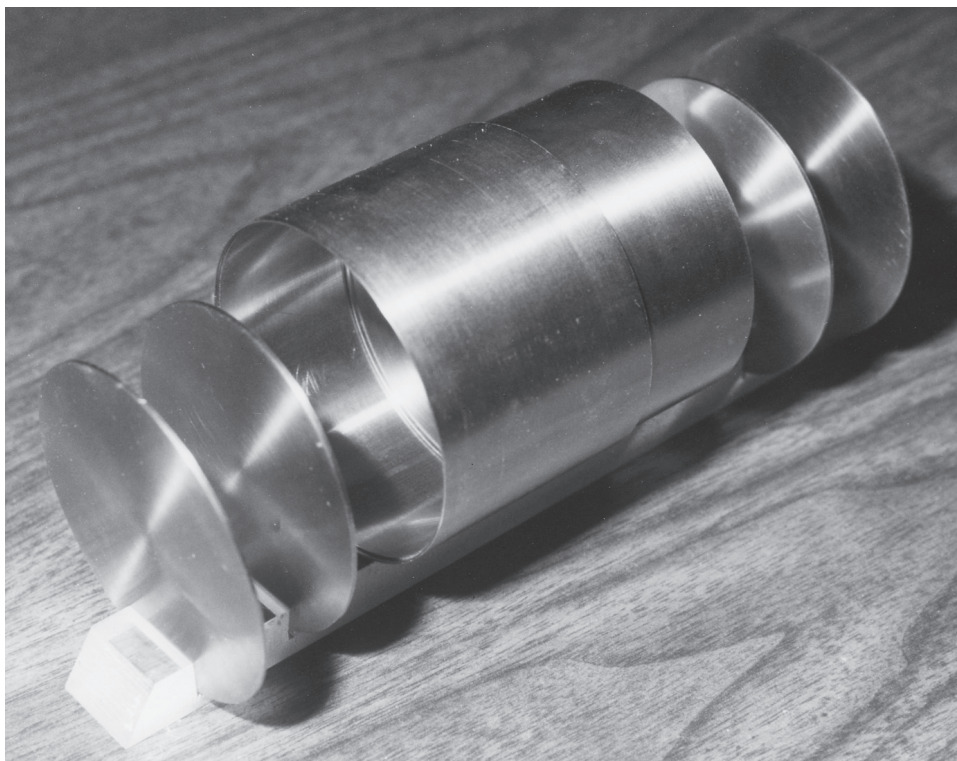
The engineered resolution took until 1989; and the newly designed ventilation system was installed shortly thereafter. Acceptance tests, however, were never performed because of the aforementioned FBI raid in June of 1989. As a consequence of that raid and its aftermath and a host of other reasons, the CML steadily spiraled down toward decreased activity—approaching inactivity. A hopeful few believed that the plant's crisis would pass in time and experimental operations would eventually resume at the CML. Toward that

end, a careful inventory of the uranium content within the uranyl nitrate solution was carried out starting in December, 1989, as had been done triennially for decades. Engineers knowledgeable in the metallurgy of plutonium designed a new container for a replacement set of 3-kg plutonium machined cylinders, again, in anticipation of future experiments. This new container, shown in Fig 102, consisted of two-thin-walled cans containing minimal stainless steel. Careful engineering was necessary to allow room for density changes without permitting a sloppy fit as the plutonium metal passed through several temperature-related phase changes. About 150 pair of nesting, precision-machined, containers were fabricated; but none of them were ever used. They have since been discarded except for one retained (by this author) for historic purposes.

These were not the signs of a facility about to slip into total disuse. Sadly, that proved to be the case however. Results from the high-precision uranium inventory ended up being used to help remove the solution from the CML a few years later instead of its intended purpose. Sometime during the early 1990s, the realization that the laboratory would ultimately be deactivated, decommissioned, decontaminated, and dismantled became unavoidably clear. Some accepted this fate earlier; this author was among the last to yield.

### *Documentation*

The plant as a whole had been faulted for weaknesses in documentation. Those contentions had some basis in fact; but this author believes that the story should not end there. Whether or not fully documented and approved, safety issues had always been important at Rocky Flats. Proposed work was always discussed and reviewed for safety. They may not always



*Fig. 102. The proposed “new” design for double containment for the planned new plutonium cylinders would contain much less stainless steel than the former design. One containment would just fit inside the other; and all lids would be electron-beam welded*

have been documented; but they were always addressed. Documentation weaknesses uncovered at the plant were, faithfully, mirrored at the CML. The laboratory lacked a consistent set of procedures; and its drawings were woefully out of date. Procedures were sometimes less than formal and may have lacked approval signatures later required in the 1990s. A systematic updating of facility drawings had been a budget requested goal of the laboratory for many years; but that task never received funding. The Safety Analysis written in 1964 would not meet the now-standard information requirements of modern-day Safety Analysis Reports (SARs). Therefore, that document, too, was inadequate both in content and

format. The Technical Specifications, long deemed to be the binding legal document between DOE and the Rocky Flats CML, had become woefully inadequate by then-current standards. That document was once thought to be a state-of-the-art identification of operational limitations.

### ***Reactor Decommissioning***

The decision was firm that the CML should become inactive. DOE required verification that the requirements of DOE Order 5480.6 concerning the “decommissioning of nuclear reactors” were fully met. That Order specifically refers to these machines as “reactors” although this author would prefer the somewhat less controversial term “critical assembly device.”

Nonetheless, four reactors were identified with the CML in this Order:

- The Horizontal Split Table
- The Vertical Split Table
- The Liquid Reflector Apparatus
- The Uranium Solution Base

Three of these were easy to argue that they were, indeed, completely “decommissioned.” The first listed was still intact but physically separate from its fuel, normally considered to be either uranium metal or oxide. DOE accepted this lack of fuel and a few padlocks as sufficient evidence that the Horizontal Split Table was decommissioned. The second listed had never even been fully assembled. Even its framework had sat idle for decades and would not function if called upon to do so. It was obviously decommissioned. The third had been disassembled a short time earlier in anticipation on an improved design modification. It currently sat in pieces. DOE accepted this as evidence of decommissioning.

The Uranium Solution Base, as DOE called this fourth “reactor,” was *not* recognized as being decommissioned because of two facts. (1) They argued that solution movement into a critically unsafe geometry tank in Room 101 was still possible. (2) The tank farm in Room 103 still contained a large inventory of uranium and was coupled by a single line to the unsafe tank. Many points were argued that the system, as it stood at the moment, could easily be rendered “decommissioned” in spite of the presence of this pipe. First, both SCRAM valves could be physically disabled in the “open” state. It would then be physically impossible to move solution anywhere in that state, much less into the tank. These two valves could be electrically disconnected to prevent closure and their mechanical mechanism clamped and

padlocked in the “open” position. Another argument was that the solution could not be moved into the questionable tank because electrically operated pumps needed to move the solution simply would not function in the SCRAM condition. The solution would not flow in that direction under gravity either because the bottom of the tank in question was well above the top plane of the storage tanks in Room 103. Furthermore, a number of both manually and electrically operated valves in this one line were “closed;” and any one of them would prevent unwanted solution movement. Manual valves could be padlocked; and electrical valves could be physically disabled.

All arguments fell upon deaf ears. Decommissioning an already inoperable “reactor” appeared much more difficult, at least procedurally, than initially thought. Toward that goal, a *Short Term Compliance Schedule* (STCS-51) was composed in 1991. The objective of this document was to finally decommission this fourth “reactor” in a satisfactory manner. DOE insisted upon a “physical separation” between the storage tank farm and the tank in Room 101. Ideally, DOE would have liked a length of pipe, called a “spool piece,” removed from this line and physically capped at both ends. Then, no solution somehow in the line could pass across the missing section and somehow enter the suspect tank. No such simple “spool piece” existed, however. DOE did accept one compromise discussed in STCS-51. Any flanged joint at any point along this line could have its gasket removed and replaced by a solid sheet of rubber—a “blind gasket.” Even if solution were somehow in this line and trying somehow to move toward the tank in Room 101, it could not pass through this impenetrable barrier. Four or five locations where this kind of

isolation could be achieved were identified. Each was discussed at considerable length. Finally, one was selected and the blind gasket inserted. The goal of STCS-51 had finally been achieved; but it took a team of almost 50 people almost four years to accomplish. Experience with similar maintenance chores suggest that a comparable task performed in the mid-1980s could have been done by three persons in half an hour.

### ***Boron Content of Raschig Rings***

The last uranium inventory of the uranyl nitrate solution was begun in December of 1989. This was mentioned above. This two-month-long procedure satisfied three goals at that particular time. First, a periodic inventory was required as a material safeguards measure; and that time was due. Second, inventory measurements always provided a fresh starting point for future experiments. New data (uranium concentration, density, normality, and impurity content) would simply refine knowledge about the solution; and that information would be helpful in designing the still-expected next experimental program. Finally, this inventory would officially document the uranium holding transferred from one company to the other as the plant changed contractors. On January 1, 1990, EG&G, Inc., replaced Rockwell International in that role. The new company was the third contractor in the history of the plant.

Inventory time had been always been selected to perform routine maintenance on each tank. Each would be empty at some time during the procedure; and this provided an excellent opportunity to sample the Raschig rings and perform many other useful measurements. These included:

(1) Sampling the glass Raschig rings from ports at the top and near the bottom of each tank. The relevant American National Standard (ANSI/ANS-8.5) called for several periodic tests on in-service rings to assure continued serviceability.

(2) Changing the clear plastic tubing used as sight gauge material. This tubing tended to yellow a little and become cloudy over the three years between inventories.

(3) Scanning the tank in search of fissile sludge buildup. Gamma radiation from possibly deposited solids was detected for this measurement.

(4) Calibrating the tank to generate a current height-vs-volume relationship. This information was used for the inventory itself; but it was also one means of measuring the amount of fissile liquid delivered to a critical experiment configuration.

Some of these were mandated by various documents such as the American National Standards (ANS-8.5) and plant policy documents; other tasks just made good sense.

Raschig ring sampling was usually quite routine. The glass was so stable and the solution so benign that the glass never showed any ill effects from continuous immersion. One test was intended to verify that the glass had not lost mechanical strength. A device called the "Tumble Tester" was used for this, although it has been seriously challenged by many at Rocky Flats as an invalid test. The Tumble Tester was simply too hard on samples; and, because of that, it was given a critically unsafe pass/fail criterion: one-quarter of the rings tested were allowed to break. Unfortunately, the Tumble Test was written into the National Standard, ANS-8.5.

A second test measured the boron oxide content of the *borosilicate* glass. Boron—more precisely  $^{10}\text{B}$ —is the only neutronically important material in this

glass; and a reasonable safety assurance would be to verify that  $^{10}\text{B}$  is not somehow slowly leaving the glass.

This measurement at Rocky Flats was made by measuring boron oxide content. Two reasonable assumptions allowed the *compound* to represent the isotope. (1) The ratio of elemental boron to boron oxide could always be derived from the stoichiometric formula for  $\text{B}_2\text{O}_3$ . No other oxide is at all stable. (2) The isotopic ratio,  $^{10}\text{B}/^{11}\text{B}$ , was natural. Depleted boron had not been used in producing the Raschig rings.

Production rings are made with a boron oxide content of about 12.6%, although some small variation (about  $\pm 0.3\%$ ), is allowed under specifications. The pass/fail criteria in ANS-8.5 was well below this: 11.8%. Historically, rings never failed this measurement.

The equipment used for this measurement at Rocky Flats was a home made device. The method was called *Neutron Transmission*. Simply described, a block of plastic had two neutron sources inserted into two holes drilled into edges. A third hole, in the center, was just large enough to accept freely one Raschig ring. A neutron detector in the shape of a short pencil resided in the very center of this hole. Without a glass ring, a certain number of source neutrons would be counted. When a ring was slipped over the detector, the neutron count rate decreased in proportion to the amount of boron present. The instrument was calibrated using a set of "secondary standard" borosilicate glass rings. Each standard had a different boron oxide content ranging from about 8% to 18%. These standards were hand made by Corning Glass, Inc., the manufacturer of Raschig rings in the United States. Dimensional control over radial dimensions was anticipated to be difficult; hand-made rings could vary a little from well-controlled production rings.

Therefore, the calibration took this into account; and the absorption of a Standard ring was normalized for the radial thickness of the Standard as well as its boron content. No adjustment for the length of the secondary standard was ever considered necessary because the length was such an easy parameter to make the same as mass-produced rings.

This *Neutron Transmission* procedure, unique to Rocky Flats and notably at odds with the requirements of ANSI/ANS-8.5, worked quite well for almost two decades. After all, the difference between the nominal concentration (12.6%) and the minimum allowed (11.8%) was so great that a high-precision method of measurement was not even necessary. Almost any laboratory method could easily distinguish between those two widely separated values.

In spite of this plant-wide history of success, Raschig rings from the CML's December, 1989, inventory did, in fact, fail this test; and that apparent failure was clearly evident. Eighteen sets (top and bottom samples from nine tanks) of four rings (required by the Standard) had been tested; and ten sets failed the 11.8% lower limit. This caused seven of the nine tanks to become disqualified because either or both sets failed the test. Both failed for Tanks 444, 451, and 452. This problem was discussed in detail in the chapter on Anomalous Events; and all 18 results appear in a Table in that chapter. Boron oxide contents as low as 11.36% were reported.<sup>72</sup> Even most of those that still

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<sup>72</sup>Two failures, however, perhaps should not have been regarded as such. Their reported contents were 11.79% and 11.77% (tanks 442 and 452). While those numbers are strictly speaking below the cutoff 11.8%, the precision of the method is simply not good enough to report four-place accuracy. Both should have been rounded-off to 11.8%. Then, they would have passed. This discussion is mute, however, because so many other samples clearly failed the test.

passed, did so only marginally. Reported contents were surprisingly low for almost all measurements—so surprising as to be incredulous. Still, the Analytical Laboratory merely reported findings—without casting judgement—to the tank’s owner (CML) and to the appropriate safety discipline (Criticality Safety Engineering). For some reason, the Analytical Laboratory never even questioned the sudden shift in boron content measurements on glass.

The clearly understood consequence of this failure—if one should ever happen—was that the affected tank would be summarily taken out of service. This was a plant-wide policy. This harsh consequence had never been a problem because rings rarely failed for that reason. Plant policy, anticipating the possibility of a failure, did allow a second set of rings be tested. If they passed the retest, the tank, itself, “passed.” Evidently, the first failure would be overlooked (a questionable policy in itself). In other buildings, this “second sample” policy, if ever needed, could have been easily implemented. Solution could be drained to any other empty tank to obtain another sample from the suspect tank. This was not possible at the CML because no empty tanks existed. There, fissile solution had been reintroduced to each tank after the glass samples had been drawn; so every tank contained some solution. The impossible dilemma was:

*Some tanks were out-of-service because the rings were no longer certified; but those rings could not be re-certified because the tanks were out-of-service.*

This was a perplexing situation that ended up taking years to resolve. If measurements were to be believed, Raschig rings in all but two tanks had to be

changed; but physical limitations on the 1960s design of the storage system at the CML would not allow this. Rings could not possibly be changed following standard plant practices.

One possible resolution of this problem was to change the plant procedures. They could be modified to permit this operation in this one specific situation. Two modifications would be required: where to house the solution and how to rinse rings. A temporary storage site for the uranium solution presently housed in the out-of-service tank would need to be found. Unfortunately, no spare tanks existed in the CML storage farm; and no means existed for transporting solution to another location. The contents of one tank could have been pumped into an experimental tank and allowed to reside there in the SCRAM condition for a few weeks; but this solution found very few supporters. Secondly, a means of rinsing the heavily contaminated rings would have to be found. The CML had no means of processing contaminated waste waters; and it was not connected to the plant-wide waste water processing stream. The suggestion was made to bypass rinsing in this one instance. This idea, too, was soundly and immediately rejected. The decade of the 1990s found the plant dedicated to verbatim compliance with existing procedures. The very thought of revising procedures for “convenience”—even if to do so could solve an impossible dilemma—was viewed unacceptable.

Another possibility for resolving this issue lay in the possibility that the laboratory measurements had been in error. That is, the Raschig rings really had not lost any boron. If a new-found laboratory bias were behind this sudden apparent decrease in boron oxide measurements, perhaps the rings would not have to be changed at all.

Possibly some routine error in some important calculation was being made repeatedly or some new procedural operation was introducing some sort of bias. If a bias in the method could be found, then, quite possibly, the bias-corrected findings would show the glass really did contain sufficient boron as always expected.

Investigating this possibility, this author was discussing their procedures with staff from the Analytical Laboratory. This discussion took place a couple of years after initial findings showed failures. That staff stated, in passing, that the “Neutron Transmission testing device, itself, should have been in excellent condition because a brand new set of secondary standards had just been obtained and used for the first time on this measurement.” The correlation of new Standards with the first failures raised an obvious question.

This author asked to examine the set of new Standards. Immediately upon viewing them, the entire long-standing problem was instantly solved. The new set of Standard rings were about 6% under length. They were shorter than rings being tested. This diminished length allowed neutrons to be detected which should have been absorbed by boron in the missing glass. The Neutron Transmission device interpreted this elevated count rate as a reduced boron content for a correct-length ring. Unfortunately, the original set of secondary standards was no longer available for some reason no longer recalled; so a simple return to an earlier status was not an option. This is the second of two safety issues to be discussed next.

Simply solving a problem and adequately documenting that resolution proved to be two distinctly different tasks. A new documentation procedure, called

*Compliance Schedule Agreements (CSAs)*, had been adopted by DOE. These documents discussed specific aspects of a safety issue as follows: (1) the requirement to be followed, (2) the problem or concern associated with that requirement, (3) a proposal for compensatory action aimed at resolving the issue on non-compliance, (4) alternatives to the proposal (if any), (5) exactly what systems or facilities are affected, (6) a consideration of increased risks or hazards, (7) arguments justifying why the CSA should be approved by DOE, (8) corrective actions already taken or to be taken, (9) an estimate of costs, manpower, and other impacts on resources, and, finally, (10) a requested priority seeking DOE approval. Buried within this formal structure would be a time-line schedule to bring the out-of-compliance issue into compliance with DOE Orders as well as consequences of taking no action.

The Rocky Flats CML had the dubious honor of writing the plant’s first *two* CSAs because a systematic documented approach addressing two issues seemed necessary. CSA-1 was written because of the non-compliance identified several paragraphs previously: The American National Standard, ANSI/ANS-8.5 (1986), clearly specified a particular method be used to measure the boron oxide content of borosilicate glass; and Rocky Flats was not using that method. The mandated method is called *Manitol Titration* and is detailed in another American National Standard: ANSI/ASTM C 169-80. Manitol Titration is a very precise wet-chemistry method; it is possibly the most precise method available. Unfortunately, it is slow, manpower intensive, and, therefore, expensive to perform. Only two or three rings per day can be analyzed. A plant like Rocky Flats



would quickly build up a backlog with its 107 Raschig-ring-filled tanks being tested periodically.<sup>73</sup>

The National Standard did allow an alternate method provided certain conditions were met. Section 4.1.2 states that “any method shown by comparison to have *equivalent* accuracy and precision” may be used. This condition was impossible to meet because, although several other methods would be *adequately* precise and accurate, none could *equal* Manitol Titration. The very *best* method is not required if many other *sufficient* methods are available.

The initial goal of CSA-1 was to implement Manitol Titration at Rocky Flats. The plant set out to meet that goal. Chemists traveled to other laboratories to learn the method. The CSA also contained a short-term goal. That was to determine the bias, if any, in the Rocky Flats method and apply that bias to future measurements. CSA-1 probably was never really fully resolved. Five revisions were composed between 1990 and 1993. The new direction of the plant, however, toward deactivation, decommissioning, and disassembly somehow seemed to leave the whole issue mute.

The second Compliance Schedule Agreement, CSA-2, was written to document the magnitude of this insidious bias that caused specific CML tanks to fail in 1989. The difference between CSA-2 and the short-term goal of CSA-1 is quite subtle.<sup>74</sup> The second emphasizes seven of nine specific tanks which failed a prescribed test whereas the first discusses a

laboratory bias in general. Once determined, the bias correction could easily be applied routinely to all failed 1989 measurements.

This appeared simple; but it was not. Completion of CSA-2 took about three years and four versions before it was finally accomplished. The reason for this was the mathematical complexity of the problem. The simple expedient of measuring a single set of samples by the two methods to determine the bias was not an option. Rocky Flats did not have the Manitol Titration method implemented; and, of course, no other facility had the Neutron Transmission technique. Rings analyzed at Rocky Flats would have to be sent to another laboratory to be analyzed by Manitol Titration. The statistically sound approach was taken to send rings tested at Rocky Flats to *two* independent laboratories, both of which had Manitol Titration capability. This, then, would compare Rocky Flats and its method against two independent laboratories using their method.

The problem was complicated further by the existence of *two* separate systems at Rocky Flats. One measured new or uncontaminated rings; the other, contaminated ones. Naturally, no rings once measured on the contaminated equipment could be sent anywhere to be analyzed by any method at any other laboratory.

The Rocky Flats Statistical Applications Group was called in to design the complicated statistical study. Their recommendation was that rings would be tested on the uncontaminated Neutron Transmission device; and a portion of these tested again on the contaminated one. This compared one Rocky Flats device against the other. The other still uncontaminated portion of rings would be divided between the two laboratories using their method.

<sup>73</sup>Eight rings were analyzed from each tank; and many tanks were analyzed twice yearly; so about 1200 rings per year required attention. One Manitol Titration apparatus could handle only about 500 rings per year.

<sup>74</sup>Both CSAs can be found in the LANL Archives in Box 37, Folders 3, 4, and 5.

A complicated combination of comparisons would be required to compare results in question against the Manitol Titration method at other laboratories.

Results of this lengthy study were clear. Rocky Flats measurements were clearly biased low—and by a considerable amount. All rings measured at both other laboratories fell well within the expected range. They ranged between 12.42% and 12.86% boron oxide while Neutron Transmission results fell as low as 10.8%. A quick scan of the data suggests an obvious and sizable bias exists. The average of all Manitol Titration measurements was 12.66%; the average Neutron Transmission result was 11.75%. The difference is +0.91—a huge bias.

Unfortunately, this is not mathematically rigorous given the convoluted propagation of errors resulting from all necessary cross correlation comparisons. The disappointing result of this statistical analysis yielded a quite low correction of only +0.6%. Still, even this low estimate of the bias easily brought all once-failed tanks from the December, 1989, inventory into compliance with the Standard. One more mathematical (statistical) obstacle remained however. Statistical uncertainties increases with the complexity of the statistical analysis and the number of cross correlations. The standard deviation of this bias correction grew to  $\pm 0.135\%$ . DOE desires high confidence (95%) in measurements of this nature; so the bias correction had to be reduced by *twice* the standard deviation. Combining these factors, the bias correction allowed from this study was only +0.33%. Still, this was sufficient to bring six tanks into compliance with the Standard; but one tank (#444) would remain out of service.

This author pointed out one adjustment to the error analysis which could legitimately be made. Safety can never be compromised by having too much boron in the glass. Therefore, the error analysis should take into account the one-sided nature of the bias determination. Details of this complicated statistical analysis are not even fully recalled by this author only a few years after the situation. That adjustment, incorporated by the Statistical Applications group, would increase slightly the absolute correction to be applied; but even this was inadequate to bring Tank #444 into satisfactory compliance.

In summary, the measurement bias introduced by too-short glass standard rings was the cause of the apparent “failures.” That is clearly understood. Results from the Neutron Transmission method should have been summarily discarded as invalid. That was not possible, however, because no alternatives existed. Moreover, mathematical error propagations combined with an always conservative approach to the problem consumed much of the true bias correction. This author submits that neither true science nor safety were being served in this situation.

### ***Solution “Stratification”***

Years passed while the CML staff worked to resolve the Raschig ring problems just discussed. The next scheduled inventory should have been in 1992, three years after the one in 1989; but the solution had been forced to remain dormant in no-longer-certified tanks that whole time. It could not be moved even to perform required inventory measurements. A safety question obviously supercedes a safeguards requirement. The solution sat idle for about six years before the next problem emerged.

One day in 1995, a visual audit of the uranium solution in the CML tank farm was being conducted. Auditors observed a small but distinct separation between two liquids in the plastic tubing of the sight gauge of one tank. Both liquids were clear and yellow; but a definite meniscus surface existed between the two. The top layer was only a few millimeters thick and sat on top of a tall column of familiar-looking yellow liquid. In the past, this column had always indicated the height of uranium solution within the tank.

The plastic sight gauge tubing had yellowed with age. It had been in place more than twice as long as ever before. In spite of the yellowed condition of the tube, liquid in the lower column closely resembled the familiar sight of uranyl nitrate solution in a sight gauge. The thin top layer was a puzzling mystery. It could have been uranium solution, too; but the extra meniscus could not immediately be explained.

Further inspection quickly revealed other tanks—but not all—exhibiting the same problem. Sometimes the top layer was many millimeters thick; other tanks only had a quite thin layer. A few tanks showed no separation at all. All plastic tubes were cloudy, yellowed with age, a little less supple than expected, and slightly etched on the inside.

The finding was reported immediately; and, just as quickly, speculations became rampant as to the cause of this apparent “stratification,” as the problem came to be known. Concerns for safety were voiced with a sense of urgency. Was the same stratification happening within the tank? Was the uranyl nitrate solution precipitating for some unknown reason? If so, could the concentration exceed that for which Raschig rings could preclude criticality? Had a chemically basic material

somehow found its way into the tanks? What physical mechanism could cause such a long-term stable liquid to suddenly start stratifying?

Next, suggestions for immediate response actions flooded the scene. Shall the solution be moved; but, if so, where and how? Is criticality imminent? Should Building 886 be evacuated? How can a sample of these two apparently dissimilar liquids be obtained. What can be done? What should be done?

An investigation team was formed in response to this unexplained situation. That team of 15 to 20 persons, drawn from many safety disciplines, met often to consider the problem. This author was one of those members. All suggested scenarios were given due consideration; all proposed actions, evaluated.

The team finally decided to obtain a sample of the top layer of liquid. This would be accomplished by disconnecting the top connection where the plastic tubing clamped onto a tank fitting. The plastic hose would be separated from the fitting; and a long, thin, stainless steel hypodermic syringe needle would be pointed into the top layer. A sample would be siphoned off and analyzed. This operation would have to be done cautiously because the plastic tubing had lost some of its resiliency. It did not feel as pliable as new tubing to a gentle pinch.

Those samples solved the problem. The liquid on top was simply di-actal phthalate, the plasticiser additive built into plastic tubing. This chemical is added during manufacture to give tubing its flexibility. Evidently, the cause of the phenomenon was that long-term exposure to the very mild acid of the uranium solution was causing plasticizer to leach out of the plastic. This is what made the tube less resilient, gave it its yellow color, and

caused it to become somewhat cloudy. This is what formed the top layer of liquid.

Evidently, without knowing why, the triennial replacement of tubes along with routine maintenance during inventory periods had been a wise policy. This practice had prevented the problem which came to light only when other factors precluded any solution movement. The solution was in no way stratifying. Indeed, no problem really existed at all.

### ***Solution Removal***

Sometime during 1993, the decision was reached that the CML's solution should be removed from Rocky Flats. Some considered it scrap to be disposed of as easily as possible. They gave it no value. Others viewed it as a valuable national resource that simply had to be relocated elsewhere. One fact was clear: it had to be gone from Rocky Flats. Nonetheless, transporting uranyl nitrate solution around the country in the mid-1990s was not an easy chore. Considerable effort would be required to ship this hazardous substance safely wherever and however it was going.

Another committee was formed to determine what to do with this now-troublesome possession. The first issue to decide was what chemical form should the solution be put into. Left alone, liquids are hard to ship and have a greater potential for leaking. Leaks could lead to serious contamination incidents in public areas not designed to contain the occasional leak. Another choice would be to convert the solution to a powder form. Then, more shipping container options open up. Powder is a little safer to ship and less prone to leak. The compound could be uranyl nitrate hexahydrate or uranium oxide. Oxide is much less water-soluble than the nitrate form. A final form would

be metal. This would be best from the leak perspective; but many with a materials safeguard mindset worried about theft while in transit. Terrorists might relish intercepting a shipment of pure, high-grade, enriched uranium metal. Secret routes and shipping times were postulated but did not receive wide acceptance from safeguards personnel.

One other consideration entered into the decision. Rocky Flats had promised the public—through DOE—that it would not “resume operations” until a number of shortcomings at the plant had been satisfactorily resolved. That goal was still years away; so “resumption” was not considered an option. Whether or not the fear was accurate, many felt that any conversion of the solution into any other chemical form might be interpreted by the public as an unauthorized “resumption of operations” at Rocky Flats. This concern, alone, tended to tip the scales in favor of shipment as a solution.

Related to chemical form, the next question to be addressed was which specific shipping container should be used. Dry forms (powder or metal) allowed many options. The perceived need to retain the liquid form presented limited options. One shipping container, the FL-10, had long been approved for shipping 10 liters of liquid at a time. It looked very promising except that its government-issued certificate allowing use was about to expire. The committee feared that extending the certificate or re-certifying the container would be costly and time-consuming. Expiration of the original certificate would surely happen before this could be arranged.

This panel of about twenty experts worked more than a year. Every proposal was given due consideration. Advantages were weighed against disadvantages in light of many safety and security

constraints. The dedicated group of talented professionals finally reached a decision that all could subscribe to. The material was to be shipped as an unaltered liquid using the FL-10 shipping container. Multiple round trips would be necessary because of the maximum number of containers (28) allowed per truck. Necessary steps would be taken to extend the certificate allowing use the appropriate length of time. A sufficient number of FL-10 containers had been found. This appeared to be the best all-around option. Their work was all but finished.

Suddenly, plant management summarily canceled the project and disbanded the committee. Another avenue was to be sought; and a new group of people would find it. No reason was given.

Two more years were spent by this second committee devising that new procedure. Their proposal would clearly render the solution a useless waste liquid. Their plan was to ship *into* Rocky Flats a large inventory of *additional* uranyl nitrate solution; but this would not be enriched uranium. It was slated to be either depleted or normal uranium solution. The plan was to blend the two uranyl nitrate solutions to create a new solution having about 9% enrichment and containing about 18 g of uranium per liter of solution. This mixture would be subcritical but not by a substantial margin; and that fact caused considerable concern for those not on the committee. The blending procedure was new and had never been tested. Homogeneity would have to be perfect. (A region of imperfectly blended solution at too high an enrichment or too high a concentration could lead to criticality in the blending vessel.) The new solution would be pumped into that blending vessel. Its movement would syphon small amounts of high-enriched solution into the stream via the Venturi effect.

The solution would continue to cycle until the developing solution grew in concentration and enrichment toward target values. Liquid flow controls would be set, monitored, and controlled to achieve the target enrichment and concentration in the blending vessel. Then, this subcritical solution would be pumped into the tanker truck. The committee's reason for adopting this route was that very large volumes could be shipped without fear of criticality (assuming homogeneity).

This plan was fraught with safety concerns. Truly, the technique had never been tried; it lacked a proven track record. Target parameters were just too close to criticality to be acceptable. Any inhomogeneity within blended solution could result in criticality. Flow control valves could fail to function perfectly allowing too much high-enriched solution to mix with too little new solution. Chemical bases could find their way into the truck causing precipitation enroute; and the attendant increase in concentration could produce criticality. The problem of shipping liquids still existed and was even exacerbated in two ways. First, a sizable volume of a new uranyl nitrate solution had to be brought *into* the plant; and this risk was not required by other methods. Second, a much greater volume—perhaps twice as much—would have to be shipped somewhere around the United States after the blending. Uranium solution of any enrichment is just as serious a contamination concern as would result from a leak in the original liquid.

This proposal was never popular with nuclear criticality safety experts. Several with a considerable amount of experience raised strong objections. Too many things could go wrong. Finally, their objections were heard and accepted. That plan was abandoned.

The uranyl nitrate solution was finally removed from the CML during the last half of 1996. Essentially, the first-proposed method was adopted. FL-10 shipping containers were used. The removal was slow because so many shipments were needed. The same shipping containers were used over and over again. In addition to the original volume of almost 3000 liters, additional shipments of heavily contaminated waste waters also had to be shipped. These were generated as residual uranium was rinsed from Raschig rings contained in the nine tanks. The solution removal was slow but uneventful. It was not inexpensive; but it was successful with no significant incidents reported. The solution was shipped to a company called Nuclear Fuel Services located at Irwin, Tennessee. It was stored there temporarily in long, horizontal, pencil tanks awaiting future use. This author understands that the solution has, by the year 2000, been converted into reactor fuel pellets. Even though enrichment has been blended down, the uranium will at least serve a useful purpose.

### ***Raschig Ring Removal***

The next task in decommissioning was the removal of the almost 100,000 still-heavily-contaminated borosilicate glass Raschig rings. The procedure was to remove enough rings at a time to fill a plastic bag about the size of a plastic grocery bag. They would be removed through the bottom 200-mm-diameter inspection port. A couple additional bags enclosed the first as a contamination control measure. These packages were then taped shut and placed into specially prepared, white-painted (standard for waste material), 55-gallon drums. Drum preparations included cardboard and

drum-sized plastic bag linings to prevent punctures and to control contamination, respectively. Each tank required several drums to contain its bundles of Raschig rings. Smaller tanks required fewer; Tank #445 needed the most. This ring removal operation took place during 1997.

These Raschig rings were regarded by most people as simply a waste product to be discarded in any way possible. Even worse, they were contaminated solid waste which complicated disposal. The initial plan was simply to withdraw them, package them, and ship them somewhere for disposal. No value of any kind was attributed to these rings.

That narrow vision was far from the truth. Raschig rings are a unique kind of glass with a specific application. Many industrial plants around the world rely on them for criticality safety. An American National Standard document even governs their physical parameters and other aspects of use.<sup>75</sup> Information about the stability of these physical parameters after decades of use could be very useful. Future versions of the Standard would benefit from this information. These well-used Raschig rings in the CML tank farm had a three-decade-long and well-documented history of service in

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<sup>75</sup>Raschig rings which meet or exceed the qualities defined in this American National Standard are called "certified." Truthfully, the CML's rings were not, strictly speaking, certified. They had been installed just before the Standard was written. However, the writing of the Standard itself was championed by Rocky Flats, perhaps the country's leading user of Raschig rings. The parameters written into the Standard were essentially *derived* from those Raschig rings installed at Rocky Flats during the 1960s. Other aspects of the Standard, such as ring packing fraction, were also based on Rocky Flats experience. Thus, while CML rings may not have been certified, they were, in truth, the prototype upon which certification was based.

a hostile environment. They could provide valuable evidence about the long-term stability of the glass in such applications. These rings had been installed in the 1960s; and none of them had ever been exchanged in favor of a fresh set. The Raschig ring's history was uniquely known; and this history was quite detailed. True, small sets of rings had been tested periodically; but replacement rings were specially marked to avoid confusion with first-installed rings. They could never be confused with the initial loading. These periodic tests measured important parameters such as mechanical strength and boron content; and that data had been collected and preserved for each tank over three decades.

A rare opportunity was recognized. These "waste" Raschig rings could be measured to provide valuable evidence about the long-term stability of this glass in hostile environments. Physical properties, easily measured on brand new Raschig rings, could be measured for well-used rings having a carefully documented history spanning more than three decades and which had been exposed to high-concentration, slightly acidic fissile solution the whole time. Toward that goal, portions of the waste glass filling dozens of drums for eventual discard could be set aside for one final detailed analysis. One drum representing each of the nine tanks was set aside for this purpose.

The good fortune behind that rare opportunity continued. The fissile solution was equally well known and historically documented as the Raschig rings. The uranyl nitrate solution had been introduced into the tank farm in 1965 and had remained there until its removal just discussed above. Solution parameters had been measured often and accurately for a variety of reasons. Parameters measured

included uranium concentration, solution density, acidity, impurity levels, and isotopic enrichment. All characteristics of the solution housed in these tanks were fully documented over the full three decades. Even changes in parameters with time were well known. This included the reduction of the highest concentration (450 gU/l) to a slightly lower one that fell within the domain of the National Standard (400 gU/l), changes in acid levels, and any slow growth of impurities through use. All these are discussed in another section of this document.

Quite probably, this unique situation did not exist anywhere else throughout the United States. The idea of testing these rings for the reasons outlined was suggested to DOE; and they wisely seized the opportunity. One drum full of rings from each tank was sent to the Los Alamos National Laboratory for analysis rather than directly to a repository for contaminated waste. In January 1998, nine drums of Raschig rings were shipped. The drums were opened in LANL's sample-receiving facilities on January 12, 1998, and ten rings were removed from each drum. Each was examined for contamination; and they were wiped with a clean, dry, cloth. No further effort was taken to wash, clean, or decontaminate these rings. The glass looked brand new; no cloudiness or etching was found. After sampling, an appropriate number of rings were submitted to LANL laboratories for chemical and mechanical testing.

Due to internal requirements for new projects at LANL, analysis was delayed for approximately two months. The boron chemical analysis and isotope ratio measurements were completed in early April, 1998. All mechanical testing were completed during the first week of May the same year. All findings were consistent with

the glass having been completely unaffected by its three-decade-long service at the Rocky Flats CML.

Chemical analyzes were performed by the now-popular (and quite precise) method known as Inductively Coupled Plasma (ICP). Atomic Emission Spectroscopy (ICP/AES) was used to measure boron contents; and Mass Spectroscopy (ICP/MS) measured isotopic ratios. The average boron oxide concentration, measured over the nine sets of CML samples, was  $12.27 \pm 0.15\%$ . That result greatly exceeds the finding from the flawed Rocky Flats Neutron Transmission study using the second set of Standards for calibration. This reconfirms that those December, 1989, results were wrong.

Still, even the LANL findings appear to be surprisingly lower than might have been expected for production Raschig rings. The measured range ( $12.27 \pm 0.15\%$ ) certainly overlaps the expected range ( $12.6 \pm 0.3\%$ ) for production rings but only by a little. Fortunately, the same apparatus had been used to measure a piece of National Bureau of Standards, NBS-SRM 93A, borosilicate glass. This standard glass is certified to contain 12.5% boron oxide (3.88% elemental boron). When tested at LANL using ICP/AES, that standard measured only 12.19% boron oxide indicating that even the LANL apparatus had a small bias. Based on this one comparison, the bias would add 0.31% to each unknown sample result. This bias correction changes the average for the nine 30-year-old samples to 12.58% in excellent agreement with the expected content for production rings.

The chemical tests also measured the isotopic ratio of the two isotopes of boron. No substantial change in this ratio was noted between an average over the nine 30-year-old samples, the new ring, and the NBS Standard. The measured average was

$0.2350 \pm 0.0018$ , although the one new ring and the NBS Standard glass measured higher than one standard deviation. These results are presented in a Table in the chapter on the Physical Properties of Raschig Rings.

LANL also performed mechanical tests too. Two types were performed. One was a simple static loading; the other examined what might be termed “dynamic strength.” Both tests closely followed the format begun by this author in an earlier study (mid-1990s). That was a similar effort to understand the mechanical strength of brand new or, at least, never used Raschig rings.

Static tests consisted of two or three rings subjected to a slowly increasing load until breakage occurred. This represented glass rings randomly distributed within a tank and subjected only to the weight of the column of rings above it. The laboratory tests are conservative relative to actual circumstances. Liquid in a real tank buoys up submerged rings reducing the weight of rings above the bottom one. Furthermore, the interconnectedness of these cylindrical shells do distribute some of the weight of a column of rings as an outward pressure against the tank shell. These laboratory tests did not take credit for either reduction in loading. Rings were allowed to touch each other in a number of different relative orientation because the weakest one was not at all obvious. These orientations included rings touching end to end, cylindrical parallel elements pressing against one another, and many others. One style even had the corner of one ring trying to split apart the cylindrical shell of the other.

The dynamic tests also consisted of two or three rings in contact with one another and subjected to a sudden impulsive loading. This impulse was increased until one or more rings broke. This test simulates the



plant situation where air or hot liquid is forced through a ring-loaded tank, often done during cleaning operations. This can cause adjacent rings to “click” against one another. The worst clicking normally encountered is about the same as one could impose striking two rings together passed over thumb and index finger. Bringing the two together produces a “tapping” similar to that in a tank being cleaned. Again, many relative orientations, or “styles” were studied because the weakest was not obvious. The results of the LANL tests generally agree with this author’s earlier findings except that one style proved slightly stronger in the LANL tests.

The earlier report found the weakest ring broke under the static test under a mechanical pressure found in a Raschig ring filled tank over two hundred stories tall. This result would be greater if buoyancy or lateral pressure on tank walls were considered. The weakest ring in the earlier study broke under a dynamic impulse loading equivalent to dropping a bowling ball about one-third of a meter onto rings in their most vulnerable orientation. Both tests confirm that commercial borosilicate glass Raschig rings are much stronger than previously thought.

Detailed results of both static and dynamic mechanical tests obtained for both this author’s earlier efforts and the LANL study in 1998 were completely documented in a lengthy treatise written under contract with the USDOE. This was completed and sent to them in 1999; but they lacked the funds to publish the book. Fortunately, this author retains essentially the complete text at his home on his personal computer.

## ***Removal of Low-Enriched Uranium***

The cubical cans of compacted uranium oxide left Building 886 over a very long time. Sometime in the 1980s, a portion of the total holding was sent to Building 991 at Rocky Flats. This is the building through which all fissile shipments off plant site normally occurred. Two or three shipments of oxide were then made from that building to a plant in Ohio (Fernald) which had agreed to take the material. These shipments took months because the same shipping containers were used over and over again. Years later, more oxide had been shipped from the CML to Building 991 when that company in Ohio announced it could no longer receive any more of this material. For several years, then, a number of cans of oxide resided in Building 991 awaiting a decision as to who might take it and a good portion of the initial holding still remained in Room 102 of Building 886. Building 886 continued to house 34 cans well into the 1990s. Sometime during the last half of the 1990s, a recipient was found; and all of the oxide was removed from both the CML and Building 991. This author does not recall who finally took the material nor more precisely what year the final shipments were made.

## ***Removal of the Uranium Metal Shells***

These 80 nesting hemispherical shells as well as five small cylindrical rods designed to pass through their pole holes had been removed from the CML and Building 886 sometime in the 1980s. This may have been done in conjunction with the 1983 removal of the plutonium metal after the incident in January; or it may have

been done sometime after that. At any rate, the uranium metal resided not in Building 886 for a number of years even though it was recognized as belonging to the CML. The clearly marked decision to shut down the CML meant no further need for the metal parts would exist. They were offered to the Los Alamos Critical Experiments Facility at Los Alamos and quickly accepted. They have received the parts. Whether or not LANL has put them to good use is not known at this time.

### **Demolition in the New Millenium**

Experimentation has been dormant for well over a decade. All the fissile material is gone. That includes the enriched uranium metal as well as the solution, the low-enriched uranium oxide, and the plutonium metal. Raschig rings have been removed and disposed of. No need existed any longer for continued high security and materials safeguards; so the fence around the facility and its corresponding guard post were dismantled.

Even the tanks themselves are gone from the building, although they remained at Rocky Flats as solid waste for some time. All the “clutter” collected during three decades of scientific research has been stripped out, packaged, and removed from the building. For a while, the impressive banks of instruments and electronic gear that once formed the Control Console in the Control Room had given way to bare floor space. Offices and hallways appeared ghostly. The tile had been removed from the floors; and test patches were found on walls in search of hidden asbestos.

Only a few items remained as the new millennium dawned through its first year. One of them was the walk-in hood in Room 101. Another was the elevated platform in the southeast corner of the

Assembly Room. The heavily contaminated annular tank, the last experimental study at this once proud laboratory, still stood on that platform. A few other vestiges of more-active years remained; but, for the most part, the laboratory had become a hollow—almost haunted—shell. The office area no longer teemed with criticality safety specialists nor experimental nuclear physicists.

The chronology of this laboratory was *almost* over. The waning years of the 20<sup>th</sup> century were filled with decontamination of equipment and rooms, deactivation of “reactors” and fuel handling equipment, final removal of all fissile material, and, finally, decommissioning of the entire facility. The building shell that remained, however, still contained some hidden snares waiting to surprise the unwary. That is why caution was never relaxed. That is one reason why this document was written. Many times those in charge of its demise obtained relevant information from draft chapters of this book. Many times private communication existed between this author and those cleaning up the facility.

April, 2002, saw a definitive end to that chronology. The building was explosively fractured one day and pushed in upon itself the next. The rubble was hauled away over the next weeks. Building 886 no longer stands these few years into the new millennium—not even as an eerie ghost of its once-proud self. Silence replaces echos of the hum of solenoids holding the SCRAM valves closed or the ‘whrrrr’ of the hydraulic drive closing the Horizontal Split Table. Tinkering sounds of creative craftsmen constructing any number of critical experiment assemblies only linger in the mind of this author—who recognizes (and apologizes to the reader) that the closing sentences of this chapter venture into sweet nostalgia.

## ***Normal Experimental Procedures***

The typical day at the Rocky Flats CML was a day of considerable progress toward the laboratory's objective unencumbered by problems. This chapter describes that normal day-to-day routine at the laboratory. It focuses on the CML only and does not address operations of the larger faction of building personnel (Criticality Safety Engineers) assigned to ensuring plant-wide criticality safety. The next chapter in this book presents considerable detail about unplanned events. These include accidents, near accidents, off-normal events, errors in judgement leading to abnormal conditions, and even unpreventable acts of nature creating problematic circumstances. Such events occurred in the vast minority.

This chapter presents the epitome of that "normal" day—the best norm as it were. Operations had not always begun that way; they evolved. Some recognition of earlier—and less useful—procedures is acknowledged but only when the contrast proves instructive. Sometimes, quite specific examples are offered to illustrate a point even though the point, itself, might apply more broadly.

### ***Program Selection***

Experimental programs were selected in a variety of ways. Some programs predate the laboratory and had been used to justify the initial construction of the CML in the 1960s. An example of this mode is the first uranium solution study: uranium solution "poisoned" with boron-loaded stainless steel plates in a cellular pattern.

This led to a later spin-off program derived from it: additional poison plate studies at two lower solution concentrations. Another way involved brand new studies associated with new operations introduced at the plant; the annular tanks studies yields one example. Occasionally, some manager or staff person from some other fissile material handling group on site might propose an experimental study aimed at one of their operations. An example of this method is the poisoned tube tank study. Some studies were suggested by a Criticality Safety Engineer experiencing an especially difficult problem; and this led to experiments with plutonium ingots in standard waste drums. One short program was urgently imposed by a governmental agency to ensure safe handling of finished weapons; and this was one of the very few classified assembly programs. A ten-year-long program was totally unrelated to Rocky Flats work but was done under contract to the Nuclear Regulatory Commission (NRC). This was, of course, low-enriched uranium oxide study.

### ***Program Implementation***

Once proposed, programs actually to be carried out were further refined and defined through an evolutionary and iterative discussion process. Typically, this would be discussed openly at CML staff meetings seeking pros and cons for the study as well as considering its applicability to plant problems. The suitability of fissile fuels on hand as well as the design of the four reactivity addition devices

certified for use was weighed. The work load currently committed to was considered. The expertise and experience of Senior Experimenters was factored in, although new experiences would facilitate growth in the responsible scientist. One program given serious consideration but eventually dropped for a number of reasons was the performance of some prompt critical studies, similar to the French series called CRAC. These would show, first hand, the consequences of such a criticality accident if one were to happen on plantsite.

This ideal of open discussion leading to the consensual adoption of a new study did not, unfortunately, always happen. Infrequently, management stubbornly directed the course of study for the CML ignoring advice from staff. This resulted in ill-advised programs that probably need not have been done, the omission of worthwhile studies that should have been performed, and even the performance on one program with physically unrealistic parameters. This last case will be discussed extensively below.

#### *Unwise Program*

Strong comments such as these demand illustrative examples. One program that probably need not have been undertaken was the so-called “Assorted Fuels/Geometry” study performed in the mid-1980s. Here, cylinders and rectangular boxes of uranium solution were planned to be co-mingled with uranium metal spherical and hemispherical assemblies; and all these were surrounded by a neutron reflector. (Actual experiments never got as far as the uranium metal geometries.) The reasons these experiments were superfluous were that the several Monte Carlo codes in common use at the time had already proven time and again their ability to handle these

different geometries and the different fuels. This study, therefore, had limited value.

#### *Overlooked Valuable Program*

An example of an overlooked study concerns a proposal by two Experimenters from the CML staff. That proposal would design a set of experiments specifically intended to emphasize fissions occurring in the epi-thermal range of neutron energies. Considerable data from many laboratories already existed in the range of fast neutron fissions (all-metal systems) and for thermal neutron energies (solution experiments); but the computer codes needed to be tested for their ability to handle properly intermediate energy neutrons. This proposal was summarily rejected because the importance of the project—basic physics research—was not recognized. The study appeared, to management, to have no direct application to Rocky Flats.

#### *Program with Impossible Goals*

The example of an experimental program with unachievable physical parameters was the second Annular Tank study. Management’s directive was to design a large-diameter and prototypically tall annular tank such that criticality would occur very close to the top of this tall tank using the high concentration uranyl nitrate solution then on hand. Physically, this is a nearly impossible order to fill. The circumference of this production-sized tank was about four meters; and the annular thickness was to be chosen such that criticality would occur as the solution rose to about two meters. Both dimensions are very close to “infinite” in this very thin right circular cylindrical shell. In such a study, essentially all reactivity sensitivity is associated with the radial thickness,  $T$ , for this geometry. This argument might be better

understood when this tall, thin, right-circular cylinder is viewed as a tall, wide thin slab of solution simply curved into a circle. In effectively infinite slabs of fissile solution, essentially no reactivity is associated with even large increases in either large dimension. Instead, the potential criticality of that slab is solely dependent on the critical slab thickness,  $T$ .

Practical aspects of the problem were even worse. Even if a critical thickness,  $T$ , could somehow be learned through calculations prior to the experiment, the very best machining capabilities would not be able to manufacture a tank of this precise radial thickness. The manufacturer asked for a tolerance in that dimension of  $\pm 3$  mm. This author argued that such a tolerance was a thousand times too large! The manufacturer agreed to devote considerable effort to maintaining much tighter tolerances; but even their very best effort would prove too “sloppy.” One final complication was recognized even before the tank was built. Even if the very best  $T$  could be chosen *and* the tolerance could be minimized too, then any reasonably large region of the cylindrical shell with an ever-so-slightly thicker radial thickness would dictate the reactivity of the overall annular tank while any large region with an ever-so-slightly thinner thickness would be inconsequential in setting reactivity of the entire annulus.

A much better design for this experiment would have been a fixed-radius outer shell and an inner shell that somehow slid over itself to vary the circumference—and, therefore, the radius—of the inner shell. The effective radius of the inner shell could then have been made adjustable from a subcritical full tank to a super critical tank at less than full height. Management rejected this proposal as being unfaithful to the design of a typical production tank.

So, tough constraints were mandated. A single tall tank of large diameter would have to be used. The best estimate of  $T$ , the critical thickness of a large-diameter very tall annulus would have to be made. Recognizing the probability for success in correctly obtaining these many and competing parameters was very small, this author elected to embellish the experimental design with three “reactivity shims.” These were stainless steel sheets of differing—but still very thin—thicknesses. The plan was to select  $T$  intentionally too large such that the radial thickness could be reduced by wrapping the inner shell of the tank with one or more of these very thin shims. The total thickness of all three shims was little more than 1 mm.

Even this clever ruse was flawed. True, a shim of thickness,  $t$ , reduced the radial thickness to  $T-t$ ; but this author failed to anticipate that the added stainless steel would increase the effective wall thickness, and therefore reflector, of the inner shell by the same thickness! These walls were several millimeters thick to begin with; and they were so closely coupled to the solution region as to be very effective neutron reflectors. Increasing this thickness added to the reflection of the system. This mistake was quickly realized when the installation of all three shims at the same time produced no where near the expected change in critical height. In summary, about one-half the reactivity subtracted from the annular tank by reducing the radial thickness was added back due to increased neutron reflection of the thicker inner wall.

This failure to account for all ramifications of an important component of an overall system might well have been included in the chapter on Anomalous Events. It was an error that led to considerable complications further down

the line. Eventually, two more very-much-thicker stainless steel shims were added to the inside of the T-t annulus. The consequence of all this “hardware” within the solution annulus made the interpretation of any experimental results considerably more difficult. Furthermore, the eventual removal of one of these shims did lead to a serious contamination incident which is discussed in the Anomalous Events chapter.

Late in the 1980s, a second annular tank was constructed and delivered to the CML. This tank had been made out of much thicker stainless steel on both inner and outer shells; and then the entire surfaces which would later contact solution were carefully machined to a better-estimated thickness, T, based on the failure of the first program. Not only was the T much closer to the necessary thickness; but machining, rather than simply rolling, produced greatly improved manufacturing tolerances. The tank was so well made that the finished product was delivered over routes and during seasons which would not subject the well-padded set of tanks to any extreme temperature variations. Sadly, the CML was shut down before this very precisely built and very expensive tank could ever be installed. It was subsequently discarded like so much scrap stainless steel.

### ***Program Values***

Most programs selected for the CML were basically good studies of value to the Rocky Flats Plant as a whole as well as to the entire nuclear industry. The boron/stainless steel plate experiments dividing solution regions into cells was an excellent approximation to Raschig-ring-filled tanks. The Poison Tube Tank study was a practical solution to a long-standing plant problem. All of the plutonium studies were

certainly applicable to Rocky Flats. Only a few programs emerged which seemed, to some, to be unwarranted.

Still, management seemed to have an unrealistic fetish for adopting only programs with strong ties to actual physical configurations encountered in the production areas at Rocky Flats. The fear was too often expressed that DOE would cut the CML's budget substantially if too many experiments were performed that did not possess obvious, direct, and immediate bearing on specific Rocky Flats production operations. This difference of opinion precipitated the early departure of promising young scientists on more than one occasion from the CML to other facilities more amenable to pure research.

Petty differences between managers from different areas of safety at Rocky Flats have also been known to squelch the very positive results of even a well-conceived experimental study at the CML. The so-called Poison Tube Tank program is a prime example of this. The study showed that a poisoned tube tank in production use could house at least as much fissile solution in a given sized tank as a Raschig-ring-filled tank. Theoretically, this limit could even be pushed to 90% efficiency—far exceeding the nominal 65% of a Raschig-ring-filled tank—in the use of tank capacity. That is, as little as 10% of a tank could be devoted to periodically distributed strong neutron absorbers and the tank would remain safely subcritical.

Conflict arose over the method of terminating the tubes containing the absorber. The Radiation Control Manager insisted that the tubes be seal-welded at the bottom and merely rest on the bottom of an otherwise flat (and unbroken) tank bottom. This design would prevent plutonium contamination reaching the floor if and when one of these welds should fail.

The manager of Criticality Safety Engineering, however, was equally insistent that the tubes containing the absorber should pass *through* the bottom plate. This design would ensure that the absorber rods, themselves, should never become contaminated upon a weld failure. The impasse was insurmountable. Neither would budge. Both managers had valid points; but neither scenario would be difficult to overcome. One Poison Tube Tank was built at Rocky Flats for production use. It had the pass through bottom design. It was never installed. Years later, the tank was donated to another nuclear facility. This inability to reach workable compromise is truly lamentable.

### ***Program Assignment***

Only three people were eligible to be assigned direction and control of one of the CML experimental programs. These three were called “Senior Experimenters.” In the 1960s, this was less “official”; but early the next decade, clear designations were made. The three included Douglas C. Hunt, Grover Tuck, and this author. Only one person other than those three have ever been in charge of a program. This was Bruce B. Ernst; and the program was the so-called “Christmas Tree” study in the late 1960s.

The first criterion upon which assignments were made was the fissile fuel involved. Hunt was in charge of the plutonium metal; and he would naturally be given those studies unless other reasons dictated otherwise. After January 1983, all plutonium was gone; so Hunt was forced to lead other studies. Likewise, Tuck managed the enriched uranium metal and conducted the majority of those programs. Only after Tuck retired and Senior Experimenters had had a lot of experience with all three fuels did this priority break down.

This author was in charge of the uranyl nitrate solution and would, therefore, be first choice for any experiment using that fuel. More programs involved this solution than any other fuel; so he could not manage all of them anyway. After the plutonium metal left the facility and the low-enriched uranium oxide studies for the NRC had run their course, the only fuels available for use were the enriched uranium metal nesting shells and the three concentrations of uranyl nitrate solution.

Hope for the eventual return of plutonium metal to the CML did not fade easily. Even as late as the late 1980s, serious plans were devoted to planning a new series of experiments using a fresh batch of plutonium metal machined cylinders. They would be very similar to the cylinders lost in 1983. They would still weigh about 3 kg each; and 125 cylinders were proposed. Differences were that “fresh” meant very low levels of  $^{241}\text{Am}$ ; and containment would be much more secure.<sup>76</sup> About 130 container sets were made for these still-hoped-for fissile units. Those hopes were never realized.

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<sup>76</sup>The new containers contained much less stainless steel; both inner and outer containers were only 1 mm thick. There were precisely machined such that the inner can slip-fit very closely within the outer. Upper and lower lids to both cans would be electron-beam-welded to ensure contamination would not leak out. The inner can would be completely freed of any residual contamination before being welded inside the outer can. Considerable calculational effort was devoted into determining the best clearance for the plutonium metal, itself, within the inner can. Too little clearance did not permit the plutonium to undergo its natural phase changes of the metal with their different densities. Too much clearance meant the metal would rattle around within the can reducing knowledge of where the metal truly was. These newly-designed and never used containers were a technological masterpiece of engineering and careful fabrication. The entire lot was discarded as so much scrap stainless steel during the 1990s. This author has the sole remaining can of this novel design in his possession.

Reasons for assigning a program to a Senior Experimenter other than the one associated with the fuel used were related to the work load before the CML at the time. Occasionally, several programs would emerge about the same time with all of them involving, say, enriched uranium solution. This author would be assigned the most complicated. Hunt and Tuck would be responsible for two others. The three always worked well together with each Senior Experimenter discussing all facets of his program with the other two. This ensured that no program would end up with undesirable modifications to the different fissile fuels which might adversely affect subsequent programs.

### ***Program Phases:***

#### *Experimental Design*

The first step was to design the experiment. Several options for this design might be considered, discussed, evaluated, and discarded before “the best” one emerged. Whether or not further discussion might have led to additional improvements is pure conjecture. The procedure used always created a quite workable design. Hindsight—many years later—often reveals ways designs might have been tweaked to improve the overall program; but that hindsight was never obvious during the planning stage. Usually the selection of which of the four DOE-approved reactivity addition devices was to be used was the first decision. This was almost always obvious. The next decision was how reactivity should be added remotely for the safe attainment of criticality. This usually amounted to determining how the nuclear fuel and other materials should be distributed initially. These materials had to be positioned according to well-subcritical safety limits and, yet, allow later

additions of reactivity reach criticality. Solution experiments often retained the nuclear fuel in the storage tanks in the Mixing Room. Plutonium metal cylinders, on the other hand, might need to be fixed in place for later introduction of water. The water would add reactivity through increased moderation and reflection. Design of neutron reflectors and any intentional neutron moderators and absorbers would have to be considered. This design stage was often iterative in that proposed plans would be discussed and modified as improved designs became apparent.

Quite often, especially in the 1970s and 1980s, preliminary calculations were used to guide experimental design. Designs under consideration would be calculated to determine final apparatus dimensions, rates of reactivity additions to be expected, and numerous other aspects of the upcoming program. Computational methods at the time were only good near criticality; so they had to be used quite carefully for systems well away from that situation. Before computer calculations became available, simple reactor engineering hand calculational methods were often used for the same purpose.

One of the most important considerations, from a safety point of view, was exactly how reactivity would be added to the configuration under study without physically disturbing pre-assembled apparatus. One example illustrates this all-important point. The Annular Tank was to consist of two cylindrical “cans” with a smaller one inside the larger leaving the desired radial thickness between the two. Each “can” consisted of a cylindrical shell welded to a bottom circular disk. Under this design, the inner “can” would tend to float under the buoyant force of the solution added to the annular region. This would prove unacceptable and could easily



lead to a prompt critical accident. In this example, the weight of the inner tank itself would not be sufficient to prevent floating; so a sturdy clamp across both cans was installed to maintain rigidity.

### *Material Procurement*

Once the conceptual design was complete, materials to be used had to be selected. Fissile materials were obvious because the very program suggestion itself arose because of the nuclear materials on hand. The only exception to this generalization concerns the decade-long program involving low-enriched uranium oxide. This program was suggested from outside the plant (by the Nuclear Regulatory Commission) and involved materials not routinely encountered at Rocky Flats. The entire study would be outside contract work.

Each study required its own complement of non-fissile materials. Some of these were not readily available on plantsite and had to be ordered. When this was the case, dimensions of commercially available stock materials often “tweaked” the original design a little. The Poison Tube Tank study provides one example. Commercial stainless steel tubing comes in a few sizes suitable for consideration within the original conceptual design; but the final selection depended on the available diameter of commercially available paper tubing which would be used to hold powered absorber materials. The paper tubing had to be sized to slip-fit easily down the interior of the stainless steel tubing. The second plutonium cylinder study of the early 1980s provides a second example. Commercial perforated sheet metal had been selected to be rolled into “sleeves.” Each sleeve would hold three properly-spaced plutonium metal cylinders. The commercial spacing

between perforation holes dictated the vertical spacing increments for the vertical array of three fissile units because these holes would receive retaining pins upon which the heavy cylinders rested. Purchase Orders for these unique materials were written and sent out.

Materials purchased were varied and intriguing over the years. One requisition ordered many large sheets of very thick commercial plastic (polymethyl methacrylate). This stock was *one-tenth meter* thick. Twelve sheets would be needed to construct a clear plastic cubical box for a neutron reflector. Walls of this 1.7-m cube were 0.2 m thick (two sheets each). Decades ago, this “house” cost some \$40,000 in material costs alone. Another time, huge cylindrical shells of another kind of plastic were laminated by spiral-winding hot filaments of nearly molten plastic into 76-mm-thick cylindrical tubes that were over 2 m long and more than a meter in diameter. These were neutron moderating materials for the Shielded Annular Tank program. Other unique materials ordered were concrete and plaster containing specified amounts of boron. Neither U. S. Gypsum Corporation nor any local concrete suppliers had any experience in producing boron-loaded castings of earthen materials. Research as to how to incorporate this absorber into common construction materials was carried out at the CML. The U. S. Gypsum Corporation even sent a representative to Rocky Flats to help prepare these unique materials. Both plaster and concrete were cast into 2-m-tall columns—locally called “plugs”—using thick paper tubes commonly used when casting bridge pillars as the outer form. Sometimes commercial road-drainage pipe was used as an inner form. The first solution experiment contained 103 plates of stainless steel alloyed with 1.02% boron,

another uncommon material commercially. Stainless steel sheet and plate stock were ordered in many sizes and types for many purposes because it resists nitric acid. Stainless steel tubing was selected for one program over comparable-sized pipe because the dimensional tolerances were better on the former. In summary, aluminum, acrylic plastic, mild steel, glass, stainless steel, polyvinyl chloride plastic, wax-coated paper tubes, wood, boron impregnated rubber stock, and cadmium metal sheets were only a few among the many and varied solid non-fissile materials purchased and used on experiments at the CML.

Non-solid materials were needed too. Almost 230 kg of cadmium oxide<sup>77</sup> as a loose powder was ordered for one program. That same program used large quantities of boron oxide, other uncommon boron-laden minerals from the Mojave Desert, and gadolinium oxide. Other applications required considerable purchases of boron carbide because that material contains about 75% elemental boron.

### *Apparatus Fabrication*

These materials—as well as more-standard stock items readily available on plantsite—had to be fabricated into specific apparatus needed for the program under study. This construction work was performed by the skilled craftsmen of the Rocky Flats Maintenance Department. Considerable credit goes to those persons for their careful attention to detail in these constructions. The successful completion of every experimental study undertaken at

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<sup>77</sup>The material was handled in the open with no protective gear required before it was recognized to be a carcinogenic hazard. The fact that whatever happened to that material is not at all known, is discussed in another chapter.

the CML would not have been possible without their skills. These men spanned many crafts including pipe fitter, carpenter, machinist, sheet metal workers, electricians, and painters. Their care and undeniable talents are gratefully acknowledged.

These workers usually came from two locations on plantsite. One was Building 334 which housed the Central Shops for the whole plant. They performed the larger chores. The second was an offshoot of the first; and these men were assigned to Building 881. Workers from that building supported smaller projects in Building 886.

These in-house fabrication jobs were completed through formal work requests called “Plant Job Orders” (PJO). One PJO was written for each new piece of apparatus. Fortunately, this author kept every PJO he ever wrote. That information is extremely valuable in reconstructing specific experimental programs and even specific experiments within a program because the drawings and text submitted with the PJO often give dimensions and material descriptions not thought to be included in some final report on the overall study. The entire set of PJOs spanning three decades at the CML are maintained at the LANL Archives. They may be found under Accession Number: A-1996-051; and this is located in their A-Bay: 03-H, 03-J, 03-L, 09-05, 09-06, and 11-41. In particular, the PJOs are retained in chronological order within Box 38, Folders 5, 6, 7, and 8.

To use this auxiliary information in researching a specific experimental program, the date of the study must be found from other chapters of this book or publications of the data. Then, PJOs written about that same time may be perused in the Archives; and a good chance exists that important ancillary information can be obtained.

### *Assembly and Details of Apparatus*

The actual assembly of the apparatus was often a joint effort between members of the CML staff and the Rocky Flats Maintenance Department. Larger or more difficult construction was left to that department; but even then, this work was closely supervised by CML staff. Frequently, vital information, such as final dimensions, important to the eventual conduct of the experimental program would be obtained during this final assembly. Simpler assembly projects would be performed directly by CML staff alone. Craftsman and scientist worked well together with never a mention of perceived union contract violations.

The casting of concrete slabs and other shapes is one example. Slabs were usually cast to make concrete neutron reflecting panels. These represented walls typical of those found in a nuclear production facility. Both dimensions and composition of this concrete slab needed to be known precisely. The CML staff closely monitored these Maintenance projects paying special attention to the way forms were made and braced to preclude bulging. They also helped select where the pour was made to ensure wet concrete did not flow under gravity causing uneven thicknesses. Often the side closest to the “reactor” received the most smooth surface (that in contact with the sheet plywood form) while a less-perfect troweled finish would be accepted for the neutronically less-important other face.

These simulated “walls” needed to reflect neutrons as well or better than concrete walls found in the plant. Toward that end, the density was maximized using air-driven vibrators to compact the still-fluid concrete. Furthermore, limestone was often selected as the aggregate because it

contained carbonates of various elements; and carbon is a better neutron moderator than most elements found in other rock. Even the moisture content of the sand—as well as the actual amount of water added to the wet mix—was measured to permit the best knowledge possible of the hydrogen content of the finished concrete. Concrete loses water as it sets; so a separate test panel was frequently cast along with experimental components. The weight of the wet concrete just poured into this test piece was determined; and the weight of the same block was measured periodically in the days, weeks, and months after the concrete had set. The decrease in weight was assumed to be all water loss.

This attention to detail paid off well in an accurate knowledge of the hydrogen content of the concrete slabs used in an experiment. In one case, the hydrogen content of a concrete slab, determined by analytical measurements on representative samples *long after the concrete had set*, was compared with that calculated from initial ingredients and the measure of the concrete’s water loss over time. The two methods of determining hydrogen content yielded precisely identical results.

These slabs would then be assembled in the Assembly Room to create the desired neutron reflection and moderation environment sought for the study. After assembly, careful measurements of the relative location of these components with respect to all other apparatus were made. When finally assembled and ready for the first experiment, a detailed knowledge of both material compositions and apparatus dimensions had been carefully recorded in the log books associated with the experiments to be performed.

Another example of care in addressing details concerns a 1066-mm-diameter stainless steel tank used in several experi-

mental programs involving enriched uranium solution. Although nominally a right circular, open-topped, cylindrical shell, this tank was known to have a slightly warped bottom. The warp was caused by welding the bottom to the cylindrical side wall and by welding SCRAM components into the bottom. Warpage was evident because regions of residual fissile solution remained in the tank after returning the bulk of the solution following an experiment. A few vertical millimeters of solution remained in some of the deeper “valleys” while two “mountains” clearly rose above the nominal bottom of this tank. These valleys and mountains spanned only a few vertical millimeters; but this irregular bottom would compromise any declaration of the critical thickness of a solution slab or cylinder using this tank. The top surface might be known to a precision of a hundredth of a millimeter along some height scale; but an uneven bottom profile reduced the precision of the overall critical height quoted in the literature.

This problem was addressed in a creative fashion. First, the bottom of the tank was wiped clean of all fissile solution. Then, a Rocky Flats photographer was stationed above this tank and about two meters above the warped bottom. His camera was fixed in place and adjusted to view the entire bottom. Next, several very small increments (a few hundred grams each) of fissile solution were added to the tank with long pauses between increments. The photographer photographed the solution pattern after each increment, after the solution had settled into its lowest valleys. The yellow solution was easily distinguished from the stainless steel of the tank’s bottom. A total of 19 photographs were taken during which 7.8 kg of uranyl nitrate had been added. That much solution was required to just cover the highest

“mountain.” Later, these solution patterns on the photographs were traced over with a draftsman’s device called a “planimeter” to determine the fraction of the surface area covered after each incremental solution addition. A graph of this data as a function of solution mass yielded a precise understanding of the irregular profile of this particular tank bottom.

Mass increments were determined from timed increments from a solution pump designed to introduce about *one liter per hour of steady pumping*. Mass and volume increments are, of course, related through the solution’s density ( $1.611 \text{ mg/mm}^3$ ). Additions of only ten seconds (easily timed) added about five grams of solution. Safety was ensured for the photographer during this procedure by ensuring that the other two pumps were locked out and inoperable.

This information has not yet been fully utilized even to this day. Results from many past experiments at the Rocky Flats CML could be enhanced greatly by analyzing again the raw data still residing in the LANL Archives. For example, a critical slab thickness of 126.4 mm was reported in 1969 (Ref. 14b) for a 1066.2 mm diameter solution slab composed of 450.8 gU/liter uranyl nitrate solution. That slab could now be modeled much more precisely as a thin imperfect slab whose upper surface is perfectly flat but whose bottom surface undulates a little. The bottom surface might be modeled with several thin circular wafers of various diameters stacked on top of one another projecting up into the solution region (the “mountains”). Properly including all non-fissile materials in this calculation could result in a superb benchmark calculation for uranyl nitrate solution of this concentration. This detailed calculation has yet to be undertaken.

### *Experimental Plan*

Two formal documents governed all experimental operations at the Rocky Flats CML. One of these, “Technical Specifications for the Rocky Flats Critical Mass Laboratory” (usually called just the Technical Specifications or “Tech Specs”), applied uniformly to every experimental program at the laboratory. It was first composed in the 1970s<sup>78</sup> and then only reviewed and modified occasionally by government auditors working jointly with CML staff.

The other document identified final experimental details for each new program; and one was written for each new experimental program. These details were recorded in an “Experimental Plan” which was generated by the Senior Experimenter in charge of the study. Both documents addressed safety issues of the upcoming experiments from a myriad of viewpoints. Both were well-written and clearly identified conditions under which experiments were allowed.

The Experimental Plan described the apparatus to be used in considerable detail; but it also allowed some flexibility for possible changes. A better description would be to say that the document defined *envelopes* within which the apparatus could exist. An envelope was also written for the range of procedures to be allowed. In addition, the Experimental Plan always included an evaluation of the worst

possible nuclear accident which might stem from the specific operations under way. A uranium solution experiment, for example, would have an entirely different accident analysis than a program involving, say, plutonium metal. Still, identifying the “worst possible” accident was often difficult to do with any degree of confidence. Therefore, the accident analysis performed may not actually have been the worst possible; but the analysis requirement did at least force experimenters to consider consequences of making a mistake during the program.

The Plan also documented formally a large number of operational limits which were to be followed. These included the minimum instrumentation used to monitor an experiment, the number and kind of automatic SCRAM initiators required, the radiation levels at which these instruments would set off a SCRAM, how and where an external source of neutrons would be used to preclude undetected changes in reactivity from occurring, and many others among a large list of safety-related issues. These important limits were not to be exceeded. Any violation of these safety limits would have to be reported to DOE, evaluated, and consequences determined on a case-by-case basis.

The Neutron Reactor Period<sup>79</sup> is one example. The Technical Specifications identified a “Safety Limit” (SL) for this parameter. This limit was the period below which physical damage to the apparatus might be expected to occur. This Safety Limit was set—quite arbitrarily—at two seconds. Surely, no physical damage would ever occur to any equipment in response to that slow a period. It was probably

<sup>78</sup>Prior to that more-formal government-mandated document related to the safety of operations involving nuclear materials, critical experiments were performed much more informally. Experimental procedures to be employed were discussed internally and faithfully followed out of informed respect for the inherent dangers associated with this kind of research. Thus, earlier programs were not less safe; but the formal documentation ensured an orderly review of all applicable safety issues.

<sup>79</sup>This “period” is the length of time taken for the indicated neutron flux to increase by a factor of  $e$  (approximately 2.718).

conservative by at least a couple orders of magnitude. For example, some reactors (eg, the Trigga Reactor at the Denver Federal Center) routinely reach their operational power level at that short period. Nonetheless, that Safety Limit was readily agreed upon by CML staff and government auditors because routine operations at the laboratory would never come anywhere close to that short a period.

The Technical Specifications next defined an even longer period designed to protect the Safety Limit from ever being exceeded. It was called the “Limiting Safety System Setting” (LSSS) and consisted of a mechanical trip point built into one piece of electronic hardware. Exceeding that safety point—even instantaneously—would automatically initiate a SCRAM of the experiment. The LSSS in this example approved for the Rocky Flats CML was decreed to be 10 seconds—five times more conservative than the Safety Limit. In practice, the electronic instrument measuring that parameter had its trip point conservatively set at 15 seconds—even more conservative than required.

All those limits on the Neutron Reactor Period were contained in the “superior document.” The Experimental Plan, however, went on to define further Operational Limits which, in turn, protected the above-named safety limits. Generally, an Experimental Plan would specify a shortest Neutron Reactor Period of, say, 30 seconds. In some cases this limit was expressed as a “time-averaged” period of one minute. The hedge words, “time-averaged,” were intended to avoid technical violations of the one-minute limit. Reactor “noise” easily could generate instantaneous noise spikes of shorter duration than 60 seconds. Then, completely apart from any stipulated limit in either document, the CML staff,

would adopt an informal self-imposed goal of never generating a time-averaged period shorter than three minutes.

If the three minute period was ever violated, the CML personnel would merely chastise themselves. If the period specified in the Experimental Plan were ever exceeded, the violation would be reported to and evaluated by an internal committee of Rocky Flats personnel. If either the SL or the LSSS were violated, on the other hand, that would have to be reported to DOE. Such an incident might have had serious professional consequences. That never happened.

DOE Orders do not distinguish well between various classes of reactors with respect to power level. Category A reactors deal with those producing in excess of 20 megawatts! Category B reactors are those producing less power; but that category includes also “zero-power” reactors—that is, critical assemblies. Reactors of any substantial power level require some means of dealing with the heat generated. Critical assemblies generate almost no heat; and the concept of “power level” is difficult to apply. Another category should be introduced to cover very-low-power reactors.

A consequence of this discussion about reactor categories is that DOE orders required the Technical Specifications to define a maximum power level for Rocky Flats experiments when there existed no measurable power at all. This impasse was resolved by specifying—quite arbitrarily—a maximum neutron flux that could be seen by the radiation detectors. That upper limit was arbitrarily set at a decade or two greater than neutron flux levels routinely encountered in experiments at the CML. A fair criticism of any attempt to couch low power levels in terms of neutron fluxes is that the flux seen depends on the distance

of the detector from the assembly. The Experimental Plan carried over this notion by limiting the maximum counting rates seen by the several detectors.

### *Safety Review*

The Experimental Plan was reviewed by several experienced professionals well versed in a wide variety of safety disciplines—nuclear and otherwise. Their unanimous approval of the Plan was required before any experiment could be performed. These talented men and women contributed greatly to the safe and successful completion of every experimental program undertaken at Rocky Flats. Mechanical Engineers evaluated apparatus design from a strength perspective. Load capacity and seismic stability were always considered too. Chemists ensured chemical compatibility of the many materials which would come in contact with one another during an experiment. They also reviewed the sampling plans for the nuclear and non-nuclear materials involved. Radiation Protection personnel were concerned over contamination controls as well as protecting personnel from undue radiation doses. Others made certain the fissile materials would be handled properly and would remain secure throughout the program. They all took their job seriously and subjected the Plan to a high degree of scrutiny. An Experimental Plan approved by this Nuclear Safety Review team ensured that a lot of thought by a diverse assembly of qualified professionals had been devoted to the program about to begin. Members of this team were selected for their hands-on experience within a safety discipline; high-level managers were seldom chosen lest they be too distant from the practical work-a-day world.

### *Apparatus Testing & Preliminary Experiments*

Once all materials were in place, several dry runs were performed to ensure all systems functioned as expected. Proper functioning of SCRAM systems was tested more than once; they were that important. The static, dynamic, and seismic stability of apparatus was confirmed one final time. Instrument responses to movement of external neutron sources (needed for uranium experiments only) were tested. When possible, these preliminary test were performed in the absence of fissile material, although that was not always possible for experiments involving uranium solution.

Frequently, but not always, the first few experiments for a brand new program were used as a “shakedown cruise.” Did all aspects of the apparatus function as expected? Were radiation detector responses close to anticipated levels as reactivity increased? Often solution experiments produced some surprises in this respect because of the competing effects of neutron reflection, moderation, and absorption. Did the SCRAM action actually remove reactivity faster than the fastest possible reactivity addition mechanism could add it? A fundamental requirement of all critical-approach experiments was that the reactivity *removal rate* by any one of the required redundant SCRAM devices should exceed the fastest possible reactivity *addition rate* under normal operating conditions. These early runs served as an opportunity to check just-installed plumbing for leaks.

These preliminary runs turned up some interesting and unexpected situations. For one program, a tank had been installed in anticipation of a uranium solution study; but the connection to the SCRAM valves had not been clamped properly.

The first introduction of uranyl nitrate solution readily leaked onto the floor because of this oversight. In another instance, the hydrostatic pressure head caused by a great vertical distance between the experimental tank, itself, and the SCRAM valves caused solution to seep through the valves and into the SCRAM tank. This rendered the SCRAM tank incapable of receiving its full volume, if needed; and this would precipitate an equipment SCRAM during an experiment. Preliminary functioning of the completed apparatus—even with no attempt to collect any useful data—proved quite useful from a safety perspective.

*(A Typical Day in a Typical Program)  
(Preliminary Actions)*

The first activity of the day would be to obtain the necessary keys. Critical experiments are potentially hazardous and access to performing them must be controlled. Unauthorized persons must not be able to operate this equipment. At Rocky Flats, this safety was ensured by locking out the most important panel on the Control Console. One focal panel had two such keylocks. One was the key which enabled access to all SCRAM circuitry for all four Reactivity Addition Devices. Without that key, all SCRAM systems were locked in their safe condition. The second key was the one which further enabled ONLY the controls to the specific device being used: the uranium Solution Base, the Horizontal Split Table, or the Liquid Reflector Apparatus—colloquially called “Snafu.” The purpose behind this second key is to preclude the inadvertent activation of two different Reactivity Addition Devices because operation of one might influence the neutronics of the other. The Assembly Room and CML staff were both small enough that such cross-purposed activities

could hardly happen; but the slight increase in safety was easily accommodated. A few other keys were needed for specific programs but will not be discussed further here.

Whatever keys a given program required were stored in the classified document repository (safe) in the main office. The Senior Experimenter would obtain the needed keys, document his removals on a key checkout log, and have his holding of the keys for that day approved by the Nuclear Safety Facility Manager (C. L. Schuske or, later, J. D. McCarthy). Their approvals were admittedly a bit informal. Neither ever asked to see the keys selected nor inquire as to what experiment was to be performed. Building 886 was small enough and so tightly knit that everyone knew when and even what—experiments were being done.

*(Pre Run Check)*

One very important safety document was a single page containing a terse list of items to be checked each day an experiment was to be performed. This “Pre Run Check Sheet” had been prepared as part of the approved Experimental Plan; and copies of it were filled out each day an experiment was to be performed. Completion of each step was initialed by one Experimenter; and the completed page was signed by both performing the day’s experiment. A typical checklist selected at random from some experimental program is shown in Fig. 103. Sometimes, one Experimenter had to be in the Control Room observing responses to items on the Check Sheet while his partner was in one of the other rooms performing the required task. When separated this way, the two were in constant contact via a small radio system; and, frequently, the one in the Control Room could see the other on





closed circuit television. Instrument locations and their responses to radiation sources placed in a reproducible location were recorded and compared against expected fluxes from previous days. The ability of certain radiation detection channels to initiate a SCRAM was also proven each day. During any other time other than this Pre Run Check period, the initiation of a SCRAM automatically activated the building's criticality alarm siren. This did not occur during the Pre Run Check because an "Interlock Override" key was used. One of the last items on the Pre Run Check Sheet was that the Interlock Override key had been returned to the safe before the experiment could begin.

Other items checked during this period was a visual observation that the SCRAM system actually did function as expected with no "hitches" in its mechanical operation. For a uranium solution experiment, the actual functioning of the heavy solenoids attached to the SCRAM valves was witnessed. The movement of both portions of the Horizontal Split Table was observed when that was the Reactivity Addition Device in use. Many other items of general safety importance to all programs as well as those specific to the study under way were tested daily via this Pre Run Check Sheet.

About an hour was required to complete the tasks on the Pre Run Check Sheet and a number of ancillary tasks to be performed before the experiment could begin. For experiments other than those using uranium solution, this often meant procuring the solid fissile material. This, in turn, meant removing the fissile metal from its storage vault, moving it into the Assembly Room, and installing it in place in the experimental apparatus. For solution experiments, it meant aligning manual valves in two rooms, reading initial tank

volumes of the concentration to be used, and ensuring that a myriad of other small details were tended to.

The last action on the Pre Run Check Sheet was for all personnel to leave the hot area, seal doors against radiation leakage, and lock them for materials security. For radiation protection, all three Blast Doors were closed and sealed tightly against gaskets using an array of eccentric cams. The assumption was that the worst possible nuclear accident might occur that day; and the room had to be sufficiently leak tight to preclude escape of radioactive nuclei. The room's ventilation was also sealed as well toward the same goal. Doors to and in the Hallway (Room 108) were locked with simple padlocks to achieve the security goal; but the keys were always kept in the Experimenter's possession. Quick access might someday be required to the Assembly Room; and this key control system permitted that safety feature. At other (non-experimental) times, access to this area was much more difficult. It required a number of persons aside from those entering to perform work. The list included Radiation Control personnel, armed guards, and even a coded telephone message to a security site outside the building. The quick access key control was considered acceptable because the entire Hot Area was deemed under the control of the experimental team during experimental work even if the rooms were uninhabited. Several television monitors continually monitored these rooms; so that was a fair assumption.

*(The Critical Approach)*

The experiment was ready to begin. One oscillatory blue warning light inside the building and two more outside signaled everyone that a critical approach experiment was in progress. The door to the

Control Room was closed and a posted sign forbade unauthorized entrance. Demeanor in the Control Room was serious but calm, not tense. Workers were just focused on the day's work. A minimum of two Experimenters (one being a Senior Experimenter) were required at all times from this beginning until the experiment was finally safely shut down later on. A third Experimenter was only present under a few conditions. Three were present when one was in training to become certified. Periodically, a third announced his intention to conduct an unannounced audit of experimental operations. Such unannounced audits were required by procedures. Some programs required a third Experimenter at the very moment criticality was attained; but this will be described later. Visitors were occasionally allowed. They were asked, however, to remain silent and save questions until completion of the experiment. All these policies rendered due respect to the true nature of the experiment about to be performed. Potential hazards did exist and certain experiments might come very close to a serious accident.

The Control Console Log Book was opened to the next blank page. These were bound, yellow-green "Record" books. Prior to the mid-1970s, one program would follow another in the same Log Book. The next was started only when the first became full. Later, the policy was to devote a single Log Book to each experimental program. Only occasionally did practice differ from policy in that regard. These Log Books still contain a wealth of useful raw data and should be studied carefully by anyone needing further evidence on a given program. All eighteen Console Log Books can still be found in the LANL Archives.

The first entry of the day was the Experiment Number—a three sectioned number such as "Experiment 2-10-57."

The meaning of each segment is described in another chapter. The second line gave the date; and the third identified the experimental team performing the day's study. The next few lines described the experiment in terse-but-adequate detail. It was terse because comments were cryptic and full of acronyms. It was complete in that enough detail was given to describe all facets of the apparatus even though references elsewhere might be required to fill in important details of items mentioned tersely. Occasionally, this description ran to a few paragraphs; less often, a few pages. The goal was to provide an unambiguous description of the configuration. One example of this entry might have been something like:

"3×3×3 array with same x and y same as last time but z = 130.15 mm"

That the plutonium metal was the doubly canned cylinders was understood from the overall scope of the program. The location of the array in the center of the thick-walled plastic reflector, described elsewhere, had been specified in the beginning of the Log Book. Horizontal lattice spacings, x and y, had been set on some earlier experiment and were merely repeated this day; but the vertical spacing was different for this experiment (130.15 mm).

Experimenters next prepared their blank reciprocal multiplication (1/M) data graphs. These were the documents used to map a safe approach to criticality. All data to appear on one of these graphs was subcritical; but curves being developed were continually being extrapolated to predict where criticality would occur. The Experimenter's responsibility was to NOT carry the experiment dangerously far into delayed criticality. These graphs, too, have been saved at the LANL Archives for

almost every experimental program. Commercial graph paper was used with the y-axis labeled 0.0 to 1.0, often with no notation that the axis was actually “1/M.” That was understood. The x-axis was scaled into appropriate units of the physical variable adding reactivity to the experiment being done. Solution experiments would show the solution height in metric units, Horizontal Split Table closure would show some parameter associated with separation of the table’s halves, and so on. Manual assembly operations might be expressed either in terms of the mass of fissile metals or the number of components. These graphs bore the date, experiment number, initials of the Experimenter generating the curve, and whatever additional information was deemed relevant.

Typically two curves were maintained by each Experimenter; and these were derived from two independent proportional counter data channels. These graphs would later ensure criticality safety as follows. As reactivity increased, so did the neutron counting rate. At criticality, the counting rate would become essentially infinite. The reciprocal of that rate decreased; and extrapolating a curve to zero is more reliable than extrapolating to infinity. Reactivity increments allowed between graphed data points were spelled out in the Experimental Plan. That limit was that the neutron flux shall not increase by more than a factor of  $e$  (2.7818) before pausing to measure the next data point. In practice, the goal was adopted to not more than double the count rate between physical data points. During these counting pauses, several things would happen once the experiment began. The new neutron flux data would be taken, the reciprocal multiplication calculated, and these data points added to the graphs at the proper reactivity

increment (solution height, table separation, etc.). Next, each Experimenter would independently extrapolate both curves to predict where criticality would occur. Each mentally would propose the next increment and addition rate (solution pump speed, table closure rate, etc.) to be used. The two would compare their extrapolations and suggestions for the next increment before proceeding. This discussion between the two would ensure that neither had made a graphing error.

Both Experimenters sat close to the controls and within easy reach of the Manual SCRAM button. One *had* to sit right at the table contiguous to the Control Console itself because he had to operate controls which added reactivity to the configuration in the Assembly Room. Both men were continually alert both visually and audibly to the events unfolding before them. The need for visual awareness is obvious because of the need to watch instrument responses, television cameras, and whatever apparatus measured the physical property producing the reactivity increases. Auditory senses came into play because the Assembly Room was equipped with a microphone and any sounds of improperly operating equipment would alert workers that all was not flowing smoothly. Furthermore, any change in the steady scratch of recording pens on strip chart recorders could warn them of a sudden increase in one of the pens.

The actual beginning of reactivity additions came next—be that uranium solution additions, table closures, etc. These were recorded chronologically in the Log Book. The time of the first reactivity introduction was specified along with the initial addition rate and who made it. Again terse acronyms were used. For example:

“08:47 GT begin fill at F(20) with H=0”

meant that uranium solution (understood by the nature of the program itself) was being added by Grover Tuck using the fastest pump (the F) at an air-pressure loading of 20%.<sup>80</sup> The sight gauge used to read that height showed a height of zero millimeters. He started this addition at 8:47 AM.

The addition would be interrupted—as explained above—to measure and graph the new reciprocal multiplication before the next reactivity addition was begun. This process would be repeated over and over again with the reciprocal multiplication ever decreasing and increased confidence developing in the knowledge of where criticality would eventually actually occur.

This method is called the “Reciprocal Multiplication Technique” and allows a safe approach toward criticality. This technique can be continued quite close to criticality because reactivity additions are made remotely; people are not exposed to radiation. Most experiments continued this data collection routine up to multiplications in the hundreds or even several thousand. The only limitation to the system beyond that stems from “dead time” losses. Radiation detection channels cannot detect all incident neutrons. An important observation is to note that this is a *non-conservative* limitation. Reciprocal multiplications tend to be *under*predicted leading to wrongly high estimates of the extrapolated critical parameter.

Throughout the reciprocal multiplication procedure, each pause to measure data was not separately mentioned in the

<sup>80</sup>This air-loading gauge was very non-linear; and increasing the loading did not allow much more solution to be moved in a given length of time. F(20) was typically the fastest speed used and delivered about one liter of uranyl nitrate solution per second.

Log Book. As the configuration, however, came closer and closer to criticality, reactivity addition rates (pump speeds, table closure rates, etc.) would have to be decreased or changed to another mode; and these modifications would be noted. The Log Book might show a change to:

“09:17 Changed to M(100)”

and this would mean that the Fast pump with an air-loading of 20% had been replaced by the Medium-speed pump with its air loading set at 100% which was nearly its maximum flow rate. As new—and slower—pumps were introduced, some physical effort was made to disable the previously used (faster) addition mode. A mechanical shield would cover the control button or the instrument would be locked out in some other fashion. The reason behind this safety measure was to preclude accidental use of this faster method of adding reactivity when a slower rate was expected.

*(Final Approach to Criticality)*

When dead-time losses rendered reciprocal multiplication data questionable, the technique was abandoned altogether in favor of monitoring the instantaneous neutron flux using two neutron-sensitive ionization chambers. These devices generated an electric current proportional to the instantaneous neutron flux. Currents generated lay well below any threshold similar to a “dead-time”; so no concern existed in that regard. A combination of the two instruments (proportional counters and ionization chambers) were necessary because, at the start of an experiment, currents generated by ionization chambers were too feeble as to be trusted confidently. Ionization chambers began to generate believable currents long before the

proportional counters began to suffer dead-time losses. By the time the transition to ionization chambers was made, the entire configuration was so close to criticality that little question remained as to what the critical parameter would be. The only reason for continuing the experiment was to reduce that “little question” even further.

By this time in an experiment, so many neutrons were generated by the fission process that the external neutron source was no longer needed for safety. The neutronic balance could be sustained based on the production and loss of fission neutrons alone. The continued presence of the external source only complicated the precise identification of the critical parameter. This external neutron source was then removed<sup>81</sup> by remote control (described later in this chapter) in alternating incremental steps interspersed with minute additional reactivity additions. The goal of these alternate steps attempted to keep the neutron flux nominally constant within about an order of magnitude. This source removal procedure was always documented in the Log Book.

*(Criticality)*

Once the external source was far away from the experimental configuration, a final few very small reactivity increments (typically, a few milliliters!) were added until a slightly super critical condition was achieved. This condition caused the neutron flux to grow exponentially. The further into delayed criticality, the shorter the e-folding time for this “positive” reactor period would be. The typical goal was to attain a positive reactor period of

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<sup>81</sup>External sources were used only in experiments involving uranium. Plutonium generates so many neutrons intrinsically that an external source was never necessary.

several minutes. The remotely controlled physical parameters affecting criticality would then be recorded in the Log Book. A typical entry for a uranium solution experiment might read:

“09:47 Critical at  $T_p = +3.6$  minutes at  
 $H = 100.2$  cm”

This terse writing stated that a positive reactor period of 3.6 minutes had been established several minutes prior to 9:46 AM; and the critical uranium solution height indicated by the sight gauge measured 1002 mm. Often other data related to this super critical configuration were documented as well; but this is discussed later in this chapter.

This positive reactor period was allowed to grow for several minutes—long enough to establish confidently that a straight line<sup>82</sup> was being drawn on the instrument used to measure the natural logarithm of the instantaneous neutron flux, the “Log N” instrument. This trace was watched intently. These moments were ones of total concentration by both Experimenters. Ears were tuned to the scratching of many recording pens; and attentive eyes flitted between television monitors and several strip chart recorders. Generally, this positive reactor period was maintained for about ten minutes. Both Experimenters confirmed to one another that the system was critical with the measured reactor period.

Next, a small amount of reactivity would be removed. This was accomplished by reversing the physical parameter that had been increased to add reactivity. For examples, a small amount of uranium solution would be returned to storage in a solution experiment; or the Horizontal Split

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<sup>82</sup>The natural logarithm of an exponential growth is a straight line whose slope equals the reactor period.

Table would be opened a fraction of a millimeter when that was the apparatus used. This reactivity decrease produced a slightly subcritical configuration; and a negative reactor period was created. The neutronic disturbance of that removal took a moment or two to settle down; but, soon, a discernible straight line of the opposite slope as the positive period developed. That period, also, was allowed to develop over about ten minutes. The goal was to obtain a negative period roughly comparable in magnitude to the previous positive period, although that was seldom achieved perfectly. The Log Book would then read something like:

“10:03 Subcritical at  $\Delta = 1.6$  mm  
and  $T_p = -5.3$  min”

This meant that at 10:03 AM a negative reactor period of 5.3 minutes had been obtained upon the removal of only 1.6 mm of solution. Again, other notations about this now-subcritical configuration were documented in the Log Book; but these, too, are discussed later.

Most experiments on any of the three Reactivity Addition Devices remained above or just below delayed criticality for about half an hour. This time allowed the necessary data to be collected with confidence; and yet it did not irradiate the fissile materials unnecessarily. The longer a system remained at or near criticality, the more fission fragments would form within the material. Excessive fission fragments were unwanted because they restricted handling operations following the experiment.

*(Experimental Shutdown)*

After that, the experiment was considered ended. The experiment was ready to be shut down. Two methods were used to effect this termination. One, the parameter

previously used to add reactivity was reversed. At other times, the experiment was simply and quickly ended by activating the Manual SCRAM button. Either method quickly removed reactivity rendering the recently-critical assembly very much subcritical. The two methods were considered equivalent with no preference given one over the other. In fact, using the Manual SCRAM method was preferred in Split Table operations because that was the only way to separate halves rapidly. One contamination incident, however, was traced to the intentional activation of the Manual SCRAM; but this is discussed in another chapter.

The critical value of the physical parameter was often interpolated right away and before performing any of the post-experiment procedures. The interpolation came from the data just obtained during the positive and negative reactor periods. If the positive and negative reactor periods were precisely equal in magnitude, then the interpolation was easy. The critical parameter was half way between the super critical and subcritical cases. This never happened; so a linear interpolation between the *reciprocal* of the two reactor periods was obtained. This procedure has been shown by careful analysis to yield an accurate critical value (Ref. 14b).

The keys were removed from the Control Console and returned to the safe. Their return was noted on the key sign-out log. That no keys were outstanding was verified again at the end of the work day by two persons performing the building's end-of-day security check. Rooms in the Hot Area were accessed as necessary to leave the day's configuration in a safe mode for the night. With all fissile solution back in the storage tanks after a solution experiment, manual valves to the storage tanks used were closed and locked.

Sometimes, solid fissile materials would be returned from the Horizontal Split Table to storage in the Vault Room. Sometimes, however, they were intentionally left in the Assembly Room to be used the next day. This end-of-the-day status was usually the final comment in the Log Book for the day's work.

The safe and secure overnight storage of any fissile material left in Room 101 was ensured; and the door to Room 101 was locked and secured. The Log Book, the day's reciprocal multiplication graphs, and other papers related to the day. The final act of the day was to lock and secure all doors within and leading to the Hot Area. Then, this status was again confirmed by the two persons performing the building's end-of-day security check.

### ***Interpretation of Data***

The day-to-day entries in the Log Book coupled with myriads of loose-leaf pages of data were the basis for data interpretation. This happened continuously throughout the experimental program and even continued for weeks and months after completion. The data had to be understood. Trends were graphed; and these trends were sought to be explained by the physical principals involved. Loose-leaf pages included reports on material compositions from the Analytical Laboratory, pages of physical dimensions measured for the many components of apparatus, as well as operational details of the apparatus and reactivity addition device.

For many programs, the data was reduced and interpreted in a manner suitable for professional reporting. The goal of the CML staff at Rocky Flats was not to "wash" the data too much before publishing. Every attempt was made to present the data in its most fundamental mode leaving any bias corrections to be applied by the

reader. For example, solution heights (uranium solution or water) were given with a clear admission that the absolute "bottom" of the tank may not necessarily have been "zero."

One interesting observation about daily operation involved "strange" (at first) oscillations in the reciprocal multiplication curves. The 3×3×3 plutonium metal array study provides that example. Water added to the lower components of the array caused the curves to *decrease* (count rate decrease) before it would increase. Then the curve showed a second decrease as the middle layer of metal was covered. These unexpected aspects of the data had to be understood completely before the experiment could safely proceed. In this case, competing effects of neutron moderation around cylinders, shielding of one layer from the next, and reflection around the entire array were causing these anomalous "bumps" in a curve otherwise expected to be smooth.

In another program (the so-called "Coupled Assembly" study), graphing specific data points from seemingly unrelated experiments against certain dependent parameters allowed one to estimate the changes in critical properties as a sphere of fissile metal fell through a region of fissile solution. This result was never anticipated and grew out of a careful examination of the data collected throughout the whole program. This clever interpretation of the data was published (Ref. 23) in the literature.

### ***Calculational Comparisons***

Results from many experimental programs were subjected to detailed comparison with calculations after the experiments. These were often done in the weeks and months immediately following



completion of the experimental study. In one case, results published in one paper were followed by a calculational comparison in the next paper in the same journal (Ref. 28). In recent years (the 1990s), many of this author's experiments culled from three decades have been evaluated against computer calculations through the International Criticality Safety Benchmark Evaluation Project (ICSBEP). This is a DOE-funded project administered by J. Blair Briggs of Lockheed Martin Idaho Technologies Company of the Idaho National Engineering and Environment Laboratory (INEEL). These were for programs that were never reported or had been under reported when first published.

No case has ever been found where a substantial systematic difference between Rocky Flats critical experiments and computed comparisons exists. This is, of course, a subjective statement. How large a "substantial" difference may be is open to debate; and judging how closely a calculation approximates an experimental setting is the responsibility of two persons: the Experimenter who is charged with accurately specifying composition, dimensions, and relative locations of every physical object within a few dozen meters of the experiment and the Computer Expert who must input all this information accurately into the computer.

The goal of this book and the several papers written by this author under his INEEL contract is to uphold the Experimenter's responsibility as far as possible.

### ***Publish Results***

The best time to document results of an experimental study is within months immediately following experiments. Details are still fresh in the mind. Not all details can we written into Log Books and

other records. Sometimes, overlooked data was deemed not as important as later analysis showed it to be. Sometimes, important information was not even recognized in passing.

Early experimental programs, under the reign of C. L. Schuske, did follow this proper pattern: design, construction, performance, analysis, comparison with other information, and publication. Such a process might be expected to span one to two years depending on the complexity of the program under consideration.

The uranium oxide program, funded under contract by the NRC, was very well documented. A number of quarterly progress reports and five (larger) summary reports were written. The larger reports covered the high-concentration-solution phase (Ref. 31b) of the benchmark study (no low-enriched uranium oxide involved at all) as well as the low-enriched uranium oxide (Refs. 31c–e) at its three degrees of wetness: H:U = 0.77, 1.25, and 2.03. Funds and time for the preparation of these documents had been built into the schedule for the contract work.

Later experimental programs suffered from a decision some may consider unwise. The current Manager of the facility (J. D. McCarthy) felt the urgency to present an ever-busy experimental schedule throughout the 1980s. He argued that publication of experimental results was an unnecessary expenditure of time and money. He argued: "The data was in hand and could be applied to plant problems. Why spend time and money to publish?" He felt no compulsion to share the data with the rest of the industry partly because it applied so very directly to Rocky Flats situations specifically. This author disagrees with that philosophy and argues that unpublished data may as well never have

been collected in the first place. Even he who collected it and holds it will not be able to use it years later when important details are lost to memory. Nonetheless, this omission of the 1980s prompted this author's contract with INEEL and, indirectly, the preparation of this book.

Through the INEEL papers, this book, and published literature from the facility, the nuclear industry now has ownership of every detailed aspect of programs and operations performed at the Rocky Flats CML over three productive decades.

The preceding pages of this chapter have outlined a typical experimental program performed at Rocky Flats. Examples are given to illustrate points raised and to guide others who, even decades later, may delve into the records of the CML as maintained at the LANL Archives. The only remaining task under the banner of Normal Operations at the CML is to describe some of the common practices (or at least broad classes) which transcended all experimental programs.

## ***Equipment Details***

### *The Neutron Source*

An external source of neutrons was used only for experiments involving uranium. This applied to the high-enriched uranium in either solution or metal form as well as the low-enriched uranium oxide studies of the 1970s. An external source was never used with any plutonium experiments.

Uranium experiments benefitted from the source's presence in that every actual physical addition of reactivity would be manifested in the proper responses of radiation detection channels. Without the source, the possibility existed that a physical reactivity addition could have been made—even into prompt criticality; but, if no neutron was present to initiate the chain reaction, *nothing would happen*. Then, an errant neutron could initiate the chain and cause a prompt criticality accident—with all its negative consequences—within the

next instant. A benefit of being able to remove the external source at or near criticality was that the neutronic response of a precisely critical configuration (never really possible to attain) would be an absolutely constant neutron population within the assembly.

Plutonium contains an intrinsic source of neutrons. No external source was necessary to manifest reactivity additions. A defect of not being able to remove the embedded source of neutrons was that a precisely critical configuration would exhibit a linear, but positive, growth on its neutron population. That is so because the source neutrons are constantly being “pumped” into the critical system which, on its own, replaces neutrons one-for-one. This linear growth would be difficult to distinguish from the true growth expected for a slightly super critical system having some real positive reactor period. This problem is unavoidable. Fortunately, it is a small effect.

Early neutron sources were sealed pellets containing a mixture of polonium and beryllium. Natural radiation from the polonium “fissioned” the beryllium, releasing a neutron. Beryllium, after all, can be viewed as two alpha particles and a neutron loosely bound into something called a nucleus. These sources had a half-life of about 137 days and, so, were really quite impractical. About 1970, new technology allowed the preparation of Cf<sup>252</sup> neutron sources. They were prepared elsewhere by absorbing liquid Californium chloride onto porous aluminum metal. A tiny bit of the contaminated metal was cut off and doubly encapsulated in cold-welded enclosures. These source capsules were about the size of a little finger. Californium emits about 10<sup>12</sup> neutrons per second per gram; so quantities of only a few to a dozen micrograms would be adequate for applications at the CML. The isotope has a half-life of about 30 months; so less than half a dozen sources were needed over the lifetime of the CML.

The Electronics Technicians at the CML devised and then improved on a device for the remotely controlled removal and, if ever needed, insertion of the finger-sized neutron source capsule. The capsule was screwed to a long length (about one meter) of stainless steel welding wire. The wire enabled the user to keep the source well removed from his body, a radiation safety measure. For the experiment, the wire with the source at the far end was screwed, in turn, to a very long run of very flexible stainless steel aircraft cable. The source was always withdrawn vertically upward. Passing the aircraft cable over a pulley allowed the source removal motor to be mounted some distance away from the test setup. The contraption worked quite well even though the aircraft cable occasionally became entangled.

A later improvement allowed the source to be removed even further away from the experimental assembly; and it eliminated the entanglement problem. A remotely-controlled radio system was constructed that could allow operation of the overhead five-ton crane from the Control Room. Walls were too thick for radio signals to penetrate; but these creative Technicians devised an antenna system through which radio signals created in the Control room would be “broadcast” in the Assembly Room. In this application, then, the source-and-wire unit hung from a shorter length of aircraft cable suspended from the hook of the crane. The hook could be remotely raised, raising the source. Once clear of the experimental apparatus, the crane and its crossed bridge could be moved to the opposite corner of the Assembly Room. This improvement also worked very well.

The neutronics of source movements was interesting and will be explained. The source was to be removed from an experimental configuration that was just a very little less than critical. The neutron flux would remain constant only because of the presence of the source. The first movement upward always caused a sharp decrease in the indicated neutron flux. That movement may have been only a millimeter or two. One Experimenter would then add reactivity at the same slow rate (or slower) used just before the start of the source removal procedure. This was added until the flux lost was just about fully recovered. Then another movement was made with the same decrease observed. This time the movement would have been a little larger. A couple seconds of reactivity addition returned the flux to near its initial value. The iterative withdrawal process continued a few more times. Each time, the amount of the movement could be larger

and larger as the decrease in observed flux became smaller and smaller. In time, both Experimenters agreed that the source could be effectively removed to “infinitely far away.” A final tiny increment of reactivity would bring the configuration to its ultimate positive reactor period of a few minutes. The whole withdrawal-and-incremental-addition procedure was beset with transient neutronic effects; and this required considerable patience and a thorough understanding of the neutronics on the part of Experimenters. Typically, the whole procedure required almost half an hour of focused attention.

### *Radiation Detectors*

A minimum of seven neutron-sensitive radiation detection chambers were used with every experiment. These were commercial instruments manufactured by Reuter-Stokes Company. Four were boron-trifluoride proportional counters about 50 mm in diameter and about 350 mm long. Two others were ionization chambers which were the same length but larger in diameter (perhaps 90 mm). The last was also an ionization chamber of the same dimensions. The difference between the three was that two were designed to produce an electric current linearly related to the instantaneous neutron flux; they were called the “Linears.” The third’s output was linear in the *logarithm* of the neutron flux; and it also indicated the time-rate-of-change in the flux. This instrument was called the “Log N/Period” detector.

All seven chambers were physically placed one to two meters from the heart of the experimental apparatus. Electronic cables connected them to their counterpart readout instruments in the Control Room at the Control Console. Proportional counters were not capable of initiating an instrument

SCRAM of the experiment; but all three ionization chambers could. Both high-level and low-level trips existed. For example, the two linear ionization chambers were configured to initiate a trip of the SCRAM if even a transient noise signal should exceed 100% of whichever scale the device was set on. The higher-level trip was electronically set to operate at 140% of full scale. This trip not only caused a SCRAM; but it also caused the building-wide Building Alarm to function. Personnel within the building were well trained to evacuate the building immediately upon hearing that sound. SCRAM trips on the Log N/Period meter were typically set a couple decades greater than normally achieved and, as stated elsewhere, at a period of 15 seconds.

### *Reciprocal Multiplication Technique*

Approaches to criticality were monitored by the Reciprocal Multiplication method. This was done to ensure safety. Here, the fact is used that the instantaneous neutron flux at any and every point within a system increases as criticality is approached. This flux is proportional to a neutron count rate measured at some fixed distance from the assembly being built using one or more neutron detectors. At any point of a growing assembly,  $R$ , this count rate,  $C(R)$ , will be some factor greater than at the start of an experiment,  $C_0$ , for which  $R = 0$ . This ratio,  $C(R)/C_0$  is called the *Multiplication* of the system. At criticality,  $R_c$ ,  $C(R_c)$  would be essentially infinite relative to that initial count rate; and the multiplication would also become infinite. Infinity is a difficult point to plot on a sheet of graph paper. The inverse of the multiplication is, obviously, the reciprocal multiplication,  $C_0/C(R)$ . It obviously approaches zero as criticality is achieved. This produces an attractive

feature for graphing safe critical approaches because extrapolating graphs to zero is clearly defined.

All parameters of critical approach experiments should be fixed save one. This is a safety consideration because, otherwise, changes in the reciprocal multiplication curve could be attributed to *either* true increased multiplication *or* to changes in the manner other parameters respond to neutrons. This policy was adhered to faithfully throughout the life time of the CML.

The equipment used to measure the instantaneous neutron fluxes,  $C(R)$ , was the set of four proportional counters mentioned above. Typically, the source/counter geometry was such that the initial count rate,  $C_0$ , was a few to several thousand counts per minute. Dead time losses did not begin to affect counting until several million neutrons were counted per minute. Obviously, then, multiplications up to a few thousand were possible without fearing these losses.

The early days of experiments were tedious in this regard. Each  $C_0$  had to be entered into an electromechanical calculator by hand. Then, the just-observed rate  $C(R)$  would be entered and the “divide” button pushed. Dividing four digit numbers by six digit ones took about a minute to obtain the result. Furthermore, electrical noise generated by these machines threw unwanted “counts” into the neutron detection channels. Data could not be accrued during the electromechanical division process. This was discussed elsewhere. About 1970, Rocky Flats CML became the proud owner of one of the very first electronic desk-top calculators ever sold. It was a cumbersome package about half a meter square and half that in thickness. Quite limited in its arithmetic capabilities, it did not, at least, add spurious counts into the data channels.

These were replaced as soon as possible by the now-familiar pocket-sized calculators.

W. R. Sheets was a very clever man; and he invented a labor-saving device used from about 1970 on. Observing Experimenters enter the same neutron fluxes,  $(C_0)$ , over and over again, he devised an electronic instrument whose display meter could be set to unity via a potentiometer at that beginning. Then, this instrument would automatically divide each new counting rate into that pre-set rate; and the result of this analog division was a direct readout of the reciprocal multiplication. The display meter showed four decades from the preset unity down to a reciprocal multiplication of 0.0001. The device was so trustworthy that, in time, hand calculated quotients were abandoned altogether.

Only one other radiation detection channel needs to be mentioned. As criticality is approached, gamma radiation in and around the apparatus increases in direct proportion to the neutron growth. Gamma radiation is less affected by materials around it; so, in a sense, it is a more independent measure of the approach to criticality. One gamma-sensitive detector (also Reuter/Stokes) was mounted permanently on the north wall of the Assembly Room about three meters above the floor. This device displayed the logarithm of the gamma flux at that point. It, too, had a high-level and a low-level trip point with the same meaning as the neutron chambers.

Previous subsections of this chapter described methods and procedures common to all experiments regardless of which fissile fuel and which Radiation Addition Device was being used. The next few sections discuss common practices appropriate to certain fuels and/or machines.

### *Solution Height Determinations*

Uranium solution experiments were conducted within the confines of the walk-in hood in the Assembly Room in most programs. A few others took place on the Elevated Platform in the southeast corner of the room. These were the several Annual Tank studies. Interestingly, one short set of experiments took place in about the geometrical center of the room with the apparatus hanging from the hook of the traveling crane! This was a benchmark cylinder study intended to be as absolutely free from any environmental reflection as possible. It was part of the NRC study of the mid-1970s.

Solution heights within an experimental tank were often measured three independent ways especially in later years.

The three were: Site Gauge, Mass Flow Meters, and a delivered-volume measurement. The last two could only be used when the geometry of the apparatus under study had a constant cross sectional area.

The Site Gauge was a good means of measuring the solution height in an experiment. In fact, it was the parameter employed for the reciprocal multiplication graphs because it was the most basic. It worked best when the solution was not in motion. Unfortunately, the pipe connection branching off the fill/return line was not very well designed for dynamic measurements. Differing pumping impedances caused the gauge to read incorrectly during actual solution movement. The height in the Site Gauge sometimes exceeded the true height in the tank by almost a meter when the fastest pump was being used.

Better data was obtained when the Sight Gauge sampled solution height via a connection right to the bottom of the experimental tank itself rather than the line feeding that equipment. Since the

Site Gauge was the most fundamental measure of the solution height, no knowledge of density or cross sectional area was needed. It was simple and direct. Meniscus effects, optical problems caused by the clear plastic tube being a cylindrical lens, cloudiness in an older tube, tiny air bubbles, and other subtle factors slightly diminished the theoretical simplicity of the method. Nonetheless, all reciprocal multiplication safety curves were graphed against the solution height indicated by the Site Gauge. Additional improvements on reading the Site Gauge remotely are discussed several paragraphs later.

The Mass Flow Meters (MFM) provided the most accurate means of measuring solution heights. These were commercial items manufactured in Colorado. They were installed just outside the walk-in hood in a vertical line through which all solution passed as it entered the experiment. A larger unit measured the solution mass delivered via the fastest pump. A second (smaller) unit did the same for solution introduced by either of the other two pumps. Within a mass flow meter, a U-shaped tube was set in vibration; and the movement of a liquid through the tube caused a rotational twist due to the Coriolis effect. The physics of these devices is described elsewhere; but, in the end, the final redout was proportional to the mass in the tube. The clever contraption was very precise and accurate. In application, the mass delivered into an experimental tank equaled the density of the solution times the cross sectional area being filled times the height in question. That is:

$$\begin{aligned} \text{mass delivered} &= \text{density} \times \text{volume delivered} \\ &= \text{density} \times \text{cross sectional area} \times \\ &\quad \text{solution height.} \end{aligned}$$

This was so provided the cross sectional area of the apparatus remained constant over the height of the experiment. The only caution was that the liquid passing through must not contain trapped air. The larger MFM, used with the fastest pump, would record over 1000 kilograms delivered; and this mass was believed to within about ten grams. The smaller MFM recorded solution (either slower pump) to the nearest gram. Obviously, the sum of the two meters equaled the total mass delivered. The accuracy claimed for this was about 10 grams out of, say, 1000 kg!

In practice, both Mass Flow Meters would be reset to zero during a brief pause just before the first uranium solution was about to spurt into the experimental tank. Sometimes, this situation was determined watching the solution rise in the fill line on closed circuit television. Sometimes, another camera would observe solution in a short section of clear plastic tubing just below the apparatus being studied. When these MFM devices were used, their height determinations were given greater weight than either of the other two methods.

In the absence of solution movement, the very same MFM device served as a measure of density. In this case it was called a Densitometer. One Densitometer was installed into the solution piping in the Mixing Room in the late-1980s. One example of its remarkable precision has been discussed elsewhere.

A third method of measuring solution height in an experiment was often used. Just prior to the fissile solution entering the experimental tank, the experiment was interrupted long enough to record the starting volumes of the solution in the full storage tanks feeding the experiment. This would be the same pause during which the Mass Flow Meters would be reset to zero. Later, when criticality had been attained,

the remaining volumes in those same tanks was recorded. These occasions were mentioned earlier in this chapter as one situation where a third Experimenter would be called to the Control Room. (The Control Console could not be left under the control of one person at any time during an experiment.)

The difference between the starting volume and the volume when the configuration was just slightly super critical equaled the amount of solution transferred into the experimental tank. Mathematically,

$$\text{volume delivered} = \text{cross sectional area} \times \text{solution height}.$$

Again, this method only made sense when the cross sectional area of the experimental tank remained constant over the height of an experiment; but this was more often the case than not. This method was generally considered the least reliable of the three. Raschig ring filled tanks are never perfectly linear in their height-vs-volume calibrations; and some interpolation between raw calibration increments was necessary when reading both the initial and final volumes in the storage tanks. Nonetheless, the three methods almost always yielded very close to the same height.

A fourth method of measuring solution heights received a considerable amount of inventive attention; but, in the long run, it proved to be not very trustworthy. This was called the "Level Detector" (LD); it might also have been called a Liquid Surface Sampler. Operationally, a gold rod, ground to a point, moved cyclically downward until it just touched the solution's surface. It stopped there with the point precisely at the liquid's surface. The gold point remained there for a few seconds during which time the height (transmitted by a fixed displacement rod over a meter long

up to a visible scale above the tank) could be read in the Control Room by closed circuit television. After the pause, the point automatically withdrew about 50 mm above the surface, paused again, and returned to begin the next sampling cycle. This movement was driven by an electric motor turning a fine-pitch screw with electronic circuitry governing the rise and return as well as the duration of the pauses. The backside of the device can be seen near the far edge of an experimental tank in Fig. 104.

The cycle was fast enough to keep pace ahead of the fastest solution rise. Reading during solution additions were meaningless because of the wave action; but, once the addition stopped and the surface becalmed, the LD could resume its normal functioning. It would have followed the solution up to its new height. Sometimes the gold was fully out of the solution; sometimes, several millimeters into the solution. The gold rod was long enough, however, that the solution never wet the upper end of it.

This device showed great promise; but it never quite had all its “bugs” worked out. In theory, a residual drop of solution clinging to the gold point would indicate a premature halt to the cycle. The drop would touch the surface, not the point. Occasionally, the electronics became confused and quit working altogether. In summary, probably none to very little of the height data obtained from this instrument should be weighted heavily.

Weighting factors of one method relative to another are quite arbitrary and not at all scientific. This author’s estimate is that, on a scale of 10, the Mass Flow Meter would be that 10, Site Gauge results would be 8 or 9, and the delivered volume method might be a 5 to 7. Occasionally, this argument was used to ignore altogether a volume measurement that seemed greatly different from the other two.

Both the MFM data and the storage tank volume data were recorded in the Log Book for the super critical height. Again, cryptic notations were used. To continue the example from earlier in this chapter, an hypothetical Log Book entry might read:

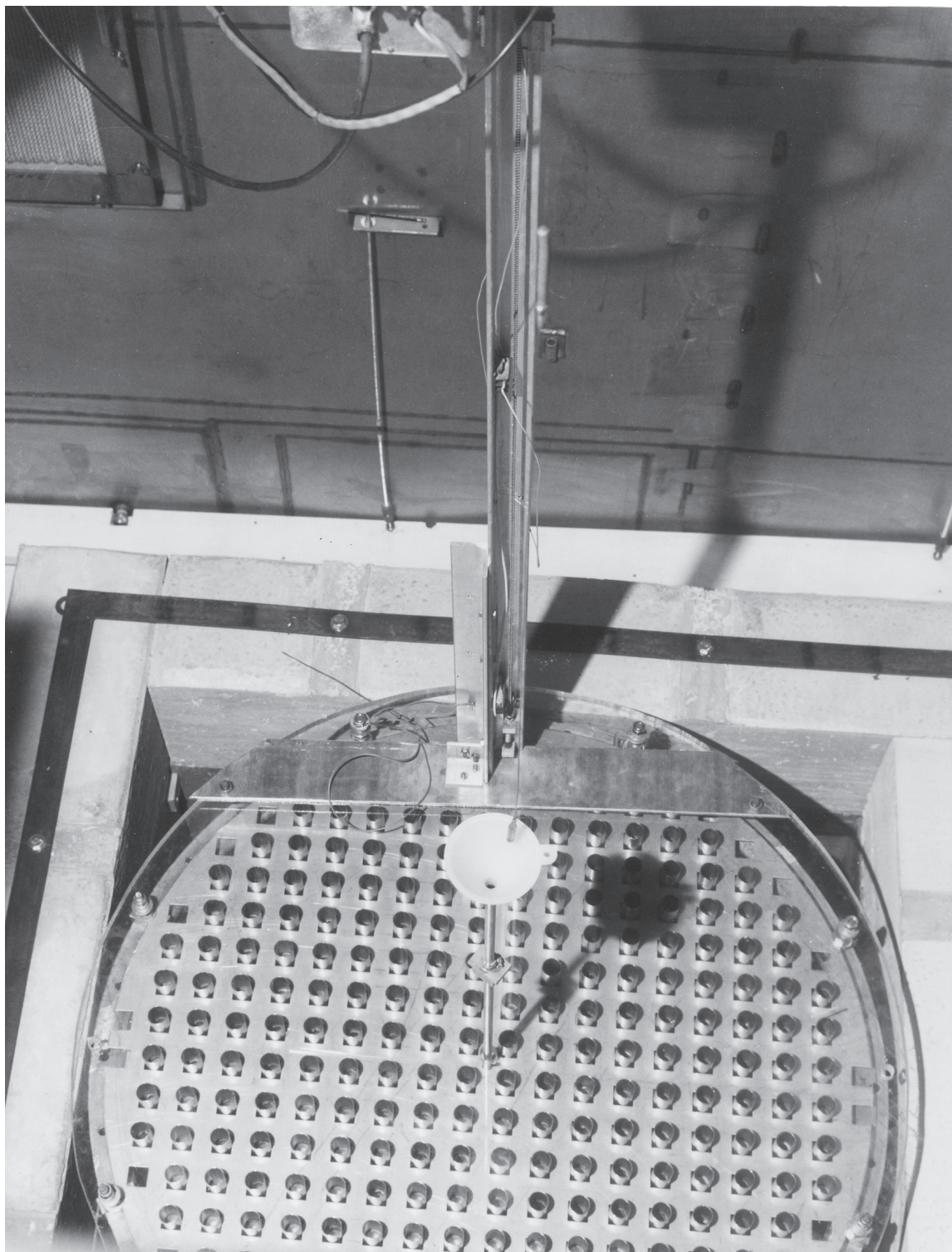
“09:47 Critical at  $T_p = +3.6$  minutes at  $H = 100.2$  cm  
MFM = 952.445 kg + 2,139 g  
tk vol delivered = 592.3 liters”

This (fictional) entry would mean that a slightly super critical condition with a reaction period of 3.6 minutes had been attained at 9:47 AM. The three solution height measures were: a direct reading of 1002 mm, a mass-based height calculated from 954,584 g delivered, and a total volume transferred from the storage tanks of 592.3 liters. An independent measure of solution density might have yielded, say,  $1.611 \text{ mg/mm}^3$ . The delivered volume times the density equaled 954.195 kg—a comparison with the measured mass.

One more point should be made concerning the Site Gauge method. During the early years, scientists put up with the optical confusion of reading heights in a vertical, clear, plastic tube against the backdrop of a television monitor. Nearly horizontal retrace lines caused by the flyback transformer optically interfered with reading the truly horizontal solution meniscus. Sometime in the mid-1970s, this author recognized that the television camera viewing the vertical tube could be rotated  $90^\circ$ . Doing so cleared up this interference pattern completely. The only penalty to this clever ruse was that solution would rise “up” the sight gauge by moving “right” on the television monitor.

Another improvement on the reading of solution heights via the Site Gauge concerned the mounting of the television camera used to view the clear tube and





*Fig. 104. The Level Detector, seen at the far edge of an experimental tank in this photograph, never really lived up to its expectations. The backside seen here shows some of the screw and chain mechanisms that ran the sampler through its cycle. The white funnel allowed the neutron source (shown within the funnel) to be readmitted remotely, if desired.*

its adjacent scale. Early experiments employed a television camera screwed to a fixed-height tripod. The camera's height about bisected the expected full height range in the site gage. The consequence of this design was that observed heights at the start of an experiment found the camera tipped downward to see the meniscus. As criticality was approached near the top, it had to be tipped upward to see the upper reaches of the scale. Both situations complicated an accurate interpretation of the true height of the liquid because of parallax in the viewing system. A better design would have the camera always viewing the rising liquid level perfectly horizontal. Later experiments solved that problem by using a television camera mounted on a vertical pole such that the camera, itself, could be raised or lowered to view the rising or falling meniscus; but the camera, itself, never had to change orientation.

The device worked well. Readability was also improved by adjusting the camera's height along the pole so the meniscus on the television monitor always appeared in the same part of the screen. Combining all these meniscus readability improvements, uranium solution heights observed in the Control Console are probably within about  $\pm 0.2$  mm anywhere along the tank and in any experiment. An important caveat is that this uncertainty is only a comment on the precision of readability. Whether or not the result is also accurate to that precision is another question. Air bubbles on either side of the Site Gauge or any differential in density from one side to the other could influence accuracy.

Nonetheless, uranium solution heights were well known and carefully measured throughout a great many experimental programs at the Rocky Flats CML.

### *Horizontal Split Table Closure Measurements*

A simple ratchet-and-gear mechanism permanently mounted on the inside of the Table recorded South Table closure toward the North from the start of the experiment (wide separation) down to about 50 mm separation. This was indicated on the Control Console on a multi-decade mechanical readout. Operationally, the moveable South Table contacted the Power Screw at 250 mm; and this limited Table closure to no faster than the Power Screw could be withdrawn into the fixed North Table. The Power Screw withdrew at two rates which differed by a factor of ten; but the actual withdrawal rates are not confidently recalled these decades after use. The final 50 mm of Table closure activated two widely spaced "differential transformers." These were electronic devices whose cylindrical rod-like plungers gave an electric signal proportional to the penetration of the plungers into their cores. The two were separated by about half a meter so that any tendency for the moveable Table to "cock" would show up as a difference in the readings on the two readout meters. The fear was that a slight cock might release itself with a lunge toward the opposing face. Close to criticality, this could have dire consequences.

In addition to the above Table closure readout devices which came with the table originally, the Instrument Technicians installed a commercial linear measuring device called an "X-Y-Z Indicator." Unfortunately, details about this device are not recalled.

One clever measure of Table separation at the closest approach should be mentioned. This was used with the uranium oxide study of the late-1970s. Two 1.3-m-square plastic faces approached one

another in these experiments. Experience had showed that these closest approaches would be less than 4 or 5 mm. Just before the experiment began (and after all fuels and other materials had been loaded), an array on nine pinched mounds of putty—similar to a child’s modeling clay—were placed on one face in a  $3 \times 3$  array. One mound in the middle was surrounded by eight close to the outer edges. Each mound resembled a small cone which adhered to the vertical surface simply by the stickiness of the putty. As the moveable Table Half closed—ever so carefully—close to the opposite face, it would flatten the points of the nine cones, changing their appearance to flattened disks. Moments later, after the experiment had ended and the room accessed, the remaining thickness of each putty mound was measured with a precision machinist’s tool. The pattern of nine final separations not only revealed the *average* Table separation at the slightly supercritical period; but it also showed any slight tendency for the two faces to be not perfectly parallel to one another.

#### *Liquid Reflector Height Determinations*

Liquid height measurements within the Liquid Reflector Apparatus were probably the least sophisticated of all three machines. A simple “U-tube” of clear plastic was connected to the bottom of the experimental tank at one end with the other end fixed to a vertical viewing board. The viewed part rose along this board immediately adjacent to an inexpensive, commercial, wooden, printed “meter stick” similar to those used by college freshman in physics class. Perhaps, later programs replaced the wooden sticks with a better-quality engraved satin-finish metal scale; but this is not recalled confidently. The height of the experimental tank was over a

meter; so two sticks were actually required in either case. Although carefully butted together end-to-end, no measurement was ever made to prove specifically that no bias, even a small one, existed across that joint. A small gap at this point would manifest itself as a bias in height readings from the upper scale. No such bias is believed to have existed; but this was never proven.

That liquid in the U-tube was a commercial oil when bare fissile metal (uranium or plutonium) was studied; but it was replaced for both programs using the doubly canned plutonium machined metal cylinders by water. This “Sight Gauge” was always viewed via closed circuit television observed in the Control Room on a television monitor. As stated just above, early experiments contained a significant readability problem due to parallax. The use of the vertical pole with a fixed-orientation camera solved that problem.

The few plutonium metal assemblies which Hunt flooded with oil in the early 1970s were contained in an additional (much smaller) cylindrical tank containing the same kind of oil. The smaller was contained within the larger tank. The small volume of oil was contaminated with plutonium on first use while the oil in the larger tank remained uncontaminated. A “Capacitance Probe” was used to indicate the height in that inner tank. This was a cylindrical tube-like device with a concentric rod. The capacitance between the two changed as oil was introduced (the dielectric) between the two conductors. The method is not very reliable. No more-sophisticated devices were ever used successfully for measuring liquid heights on this equipment. A few ideas may have been put forth; but they never received much attention.



## *Anomalous Events*

A number of unplanned events happened at the Rocky Flats Critical Mass Laboratory over its three-decade-long history. Some of these may be considered “accidents.” Some fit a category called “off normal” events. Others are only the consequence of erroneous measurements and were never truly a safety problem at all. Fortunately, none of these ever led to a nuclear criticality accident. No such accident ever occurred anywhere on the Rocky Flats plant site. In fact, no event even closely approached that condition. Rocky Flats personnel can feel justly proud of that record; not all nuclear facilities can boast the same. Sometimes, on first view, the following history *might* suggest that a nuclear criticality accident, sometimes called an “excursion,” *could* have occurred if one or more other factors had been different. The important point is that those circumstances did not exist. Usually, this can be attributed to good controls being in place. Possibly, in isolated cases, good fortune played a role.

Excursions carry dreadful consequences; and prevention warrants considerable time and expense. It is the *second* most dramatic event in all of nature from the standpoint of energy release. About 0.1% of the mass involved is converted into energy. That is extremely large compared to chemical reactions wherein only a few eV of energy may be released out of hundreds of thousands of MeV involved in the reaction in the form of mass. The most dramatic event in nature, in point of interest, is the particle/anti-particle annihilation reaction found in another branch of

physics. There, 100% of the mass is converted into energy.

Incidents at the Rocky Flats CML fall into the categories of spills, contamination releases, mis-direction of fissile materials, poor engineering practices, operator error, and a host of other “mistakes.” These incidents were usually less a hazard than an “inconvenience”; they disrupted routine experimentation. Cleanup and recovery were costly but not nearly so expensive as an excursion would have been.

These incidents are discussed here for three reasons. First, they complete the historical record of events and operations spanning three decades. That is the purpose of this document. This paper, coupled with the complete set of files housed at the LANL Archives, truly preserves a complete historical record of this entire facility for posterity. Specific reference to the archival location of individual events are given in this section within the description of each event. This is done either in text or enclosed in square brackets giving box and folder number. The second reason for documenting these happenings is that they illustrate some pitfalls into which a new facility and its young staff might fall. If this discussion can ward off similar mistakes, the personal embarrassment to this author is worth while. The final justification was the most important. Some incidents had left fissionable material in unsuspected places. Draft versions of this document warned the next generation of nuclear workers of those hidden problems by drawing attention to places within this small facility where unsuspected

contamination may have existed. All these problem areas have been freely discussed in the past by this author with anyone who may have a hand in the decontamination, decommissioning, and eventual destruction and removal of this building. For this reason alone, the repetition of this information more formally in a history document seems prudent.

Some of these incidents have been published elsewhere in even greater detail; and that discussion—including figures and tables—is repeated here almost verbatim. It has been edited only to fit current context. Reference to the original publication is, of course, provided. That repetition is made without apology. The importance of this information warrants that. A chronology of these events follows. To aid the reader, each new event is titled by a bold-faced heading in italics font. Furthermore, a summary list is presented on the following page in chronological order.

### ***The First Uranium Solution Spill***

The start of this author's career at Rocky Flats did not begin propitiously. Hindsight, three decades later after a successful career, makes that clear. The enriched uranium solution had been shipped into the brand new CML in June of 1965. That process has been chronicled elsewhere in this document. The first contamination incident occurred July 2<sup>nd</sup>, about two weeks after receipt. This author, assisted by another staff person, and a "Health Physics Monitor," set out to drain horizontal and vertical lines interconnecting the four tanks then housing the solution. Higher-elevation lines were opened to atmosphere to serve as a vent for lower lines; and a valve at the lowest point was opened to receive drained solution.

About four liters had been collected; but gravity drainage proved too slow for the impatient team. They hoped to accelerate movement by blowing into the pipes with compressed air. The Monitor connected a length of plastic hose between a compressed air port and the vent line. The other staff member, attending the collection of the liquid, called out that the compressed air was, indeed, helping the flow rate. Shortly thereafter, however, a small plastic bag (50 mm × 100 mm × 200 mm), which had been slipped over the connection for contamination control, was observed to fill with high-concentration (450 gU/ℓ) solution. The bag burst allowing the solution to splash onto the floor and nearby equipment. The report to building management (Schuske) was only 5 pages long; and it identified 22 square meters of contamination. Cleanup required 39 man-hours and cost about \$700. The report did not discuss the cause nor any corrective actions to be adopted in the future [LANL: box 28, folder 5]. The eventually-determined cause is, however, discussed a few paragraphs below.

### ***The Second Uranium Solution Spill That Month***

The next spill occurred two weeks later (July 14, 1965). The same goal of draining lines again precipitated the incident. Almost a liter had been drained from the lines and poured back into the tops of one of the tanks. For some indefensible reason, compressed air was again employed to speed up transfer. No hose clamp had been fastened to the hose where it connected to the vent line. Consequently, the compressed air quickly filled the line; and the back pressure exerted on the unclamped connection caused the hose to disconnect itself from the line with an audible "burp."

***Summary of Anomalous Events  
at the Rocky Flats CML Over Three Decades***

<b><u>Anomalous Event</u></b>	<b><u>When Happened</u></b>
First Uranium Solution Spill	July 2, 1965
Next Uranium Solution Spill	July 14, 1965
Final Uranium Spill That Month	July 22, 1965
Cracked Connecting Lines to Holding Pit	1966
Holding Pit Built in Underground River	Late 1960s
Bumble Bee Trapped in Solution During Experiment	Late 1960s
Errant Bird Trapped in Contaminated Area	Unrecalled
Uranium Solution Vent Line Overflow into Exhaust Duct	November 30, 1967
Experimental Component Falls During Experiment	January 22, 1968
Uranium Solution Leaks Into Cable Trenches	February 16, 1968
Workman Painter Causes Small Solution Leak	May 11, 1968
Large Discharge of Uranium Solution to Mixing Room Floor	May 9, 1969
Uranium Metal Handstacking Controversy	July 15, 1969
Uranium Metal Hemishell Falls to Floor and Bent	Early 1970s
Plutonium Metal Hemishell Decomposes Into Compound	1970s
Void Discovered in Raschig-Ring-Filled Waste Holding Tank	April, 1976
Uranium Oxide Can Falls to Floor and Destroyed	Late 1970s
Uranium Oxide Cans Gain Weight By Slow Oxidation	Late 1970s
Test Use of Boron Oxide for Casting Concrete Components	1980
Concrete Cylindrical Casting Fails During Wet Pour	May, 1980
Lifting Anchor Breaks Away From Concrete Wall	June, 1980
Bird Droppings Prevent Shield Door Operation	1980s
Improperly Assembled Valves Leak Uranium Solution	November 25, 1980
Aluminum Rod Sheared by Plutonium During Demonstration	Early 1980s
Moisture Destroys Plutonium Metal and Contamination Incident	January 12, 1983
Plutonium Metal Cylinder Ignites Spontaneously in Glovebox	January 19, 1983
Nuclear Reactor Period Exceeded During Experiment	February 16, 1984
Problems Surrounding Small Uranium Solution Leaks	July 7 to 20, 1984
Boron Oxide “Poison Tubes” Collapse Before Use	August, 1984
A Personnel Contamination Incident Involving Reactivity “Shim”	Early March, 1987
A Second Personnel Contamination Incident	March 23, 1987
Truck Backs Into Exterior of Storage Vault Room	March 23, 1988
Tar Leaks Into Building During Roofing Repair	June, 1988
Broken Cable Discovered on Criticality Alarm System	September, 1988
Outside Waste Water Leak at Holding Tank	September 26, 1989
Raschig Ring Failure Traced to Faulty Standards	Early 1990s
Uranium Solution Attacks Plastic Sight Gauges	Early 1995
Holding Pit Completely Floods with Water	Spring, 1995
Criticality Alarm Activations and Evacuations	All Three Decades

Seconds later, high-concentration fissile solution flushed backward through the vent connection just vacated by the absent hose. Solution squirted onto the floor and onto a portion of the Monitor's clothing. Fortunately, he was wearing the required company coveralls; but his face showed some dismay as he viewed fissile yellow liquid running down his pant's leg. Ten square meters were contaminated not including the Monitor; and the cost of recovery was 24 man-hours which translated into \$440.

This 5-page-long report to building management [LANL: box 28, folder 6] *did* discuss the cause of both spills. Vertical lines empty quickly in any such operation; but horizontal lines do not. Very small dips in a supposedly horizontal line will retain small puddles of solution along its bottom. Raised weld beads inside a horizontal line can also trap small volumes of solution. The compressed air quickly filled pipes above the trapped residual solution. If that air should suddenly be released, it will sweep over the top of these "rivers" of solution causing them to generate waves. The process is analogous to whitecaps forming on a lake during a violent wind storm. These waves grow larger until they block the full interior of the pipe. Then the remaining compressed air simply blows the solution out the open connection.

This report does end with the observation that both spills that month had occurred because of the same "unsafe action." It states further that "This practice will be discontinued... ." In light of modern-day procedures, that response seems remarkably terse and informal.

### ***The Final Uranium Solution Spill That Month***

The final spill that month occurred about a week later (July 22). Two *other* persons were attempting to homogenize fissile solution in one tank by pumping it out and back into itself. They properly checked and rechecked all of the valves which had to be opened in order to perform that operation. They also checked *most* other valves which had to be closed to prevent undesired movement of solution. The one valve they failed to check was the same drain valve which had played a role in the previous spills. It was located at the lowest point of the entire plumbing system and was hidden from view behind a large control console. It had inadvertently been left open following some previous drainage operation. When the pump was turned on to start the mixing action, a small amount of the liquid was diverted out this small valve onto the floor. Quick action limited contamination spread; but recovery and cleanup still cost \$145. The 3-page-long report includes an Appendix written by the two persons responsible for the leak [LANL: box 28, folder 7].

Clearly, a trend was emerging. Three spills had occurred during the solution's first month of residency. The trend suggested poor planning and unwise judgment by several persons including this author. Today, such a record would result in numerous remedial actions and, possibly, some professional consequences. That no further discussion followed these three events is not consistent with modern practices.



### ***Cracked Lines Connecting to the Holding Pit***

The next event would have resulted in environmental contamination except that the problem was discovered and corrected *before* fissile material ever became involved. The facility was built with an underground Holding Pit some distance to the west of the main structure. Its purpose was two-fold. One was to contain fissile solution during the long radiation decay process following a nuclear excursion if one ever were to occur. The solution would be drained into a tank within this pit where the earth around it would adequately attenuate the radiation from the fission fragments. Two Raschig-ring-filled tanks (one for uranium, the other, plutonium) would provide storage. The second purpose was to collect contaminated waste waters generated in the laboratory into still a third tank. These waters would come from the decontamination shower, an eye wash station, a laboratory sink, and a few other sources in the area of the laboratory where fissile materials were handled. This was a large Raschig-ring-filled tank (nearly 1000 liters) connected to the laboratory by a buried 75-mm-diameter pipe. That pipe was made of a material called Duroiron as specified on the approved construction drawings. Duroiron is a glass-like substance.

A mystery concerning this Holding Pit unfolded during May of 1966. A quantity of water was discovered in two of the three holding tanks. No water had been sent there; its presence was unexpected. The liquids tested slightly acidic (1.8 N nitric acid) but contained “essentially no uranium” (less than 0.01 ppm). Where this water came from was not known. Neither was it clear where any nitric acid came from. One conjecture was that this water

may have been runoff from heavy spring rains which, somehow, had found its way into the tanks. This would imply a break in the Duroiron lines buried half a meter under ground.

The perimeter of the Holding Pit was excavated; and this was, indeed, found to be the case. A number of breaks were discovered in this too-fragile glass-like material. Heavy trucks moving about the grounds during construction of the facility in 1964 had broken these lines. The presence of water in both tanks was thereby explained; but no explanation is clear, even to this day, as to the source of any nitric acid. All Duroiron lines were dug up and replaced by welded stainless steel pipe of comparable diameter. The new lines were packed in sand for better support and the area just outside that was back filled with gravel to aid drainage.

History later records that these tanks were not used long nor did they ever contain any significant amount of fissile material. The plutonium holding tank was removed and its line capped off within a year or two. Plutonium solution would never be used at the Rocky Flats CML. The uranium holding tank was never used for its intended purpose because no criticality accident ever occurred. Still, the tank remained in the pit until the 1990s. The waste liquid holding tank was occasionally used to collect very low-level rinse and waste waters until the mid-1970s when it, too, was abandoned. A more-suitable waste liquid handling system was introduced as explained elsewhere in this paper. No significant amount of uranium was ever passed into this tank.

A curious observation involves the naive notion, held in the 1960s, that highly radioactive solution could be housed in this underground pit following an unplanned nuclear criticality accident should one ever

occur. Irradiated solution would be drained there and held several months until it had radioactively decayed to a level safe enough to reuse as the CML resumed its experimental studies. Several aspects of this picture seem naive. Consequences of a criticality accident would not likely allow the laboratory to restart experiments using the same liquid no matter how long the waiting period may be. The safety of storing this irradiated liquid in an underground pit with a thin concrete cover is also questionable. Radiation would stream upward through the concrete, a hazard to anyone nearby. The cover, itself, did not fit tightly onto the pit's walls; one could see patches of sky standing atop the tanks within the pit.

### ***Holding Pit Exists in Underground River***

The Holding Pit had another design flaw. The building was built like many standard basements; concrete walls and floor rested on concrete footings. Unknown to anyone during construction, the area selected for this pit just happened to be in the middle of an intermittent underground river. This river only came into being during the spring's heavy runoff. As a result, this pit often contained water on its floor. That ranged from merely a damp floor to the pit filling to half-a-meter depth on one occasion. The problem was abrogated two ways. The entire perimeter was excavated to a considerable distance from the walls. The concrete was painted with a tar-like substance before backfilling with fist-sized rocks. These stones diverted water around the pit. Second, the interior of the pit was lined with a thin stainless steel shell. This included a floor welded to four walls about a meter high. This was intended to keep any small residual water

from finding a path through the concrete from collecting on the floor.

In summary, this Holding Pit was hardly ever used for any of its intended purposes. A few thousand liters of very slightly contaminated waste water did pass through the Waste Holding Tank; but the other two never saw any service at all. Waste water records show that only a few grams of uranium were discarded via this route over the facility's history.

### ***Bumble Bee Trapped in Uranium Solution***

The first event to happen during an actual critical experiment has a humorous overtone. During the first program involving uranyl nitrate solution, the series had evolved to an experiment with over a thousand liters of high concentration solution pumped into a large-diameter tank. An unpoisoned slab of solution was being formed immediately above a large volume of solution heavily poisoned by the presence of 103 spaced metal plates containing boron. Unpoisoned slabs quite near criticality have a very sensitive dependence of reactivity on solution height. That is,  $dp/dH$  is large.

At the moment in question, this author was standing before the television screen looking down upon a large portion of the surface of this nearly critical solution experiment. He was watching intently for any surface waves possibly introduced by the slow-speed pump used to add solution. This pump added about one liter of solution per hour. No ripple effects were seen. Suddenly, small surface ripples were noticed even though solution was not being added. The source of these ripples was unknown; and they appeared to be almost circular and growing in amplitude. They moved from right to left across the television screen and propagated in a

growing circular pattern seemingly consistent with some sort of surface disturbance<sup>83</sup> off to the right side of the television camera's view. Instinctively, this author glanced quickly at the instruments at the Control Console representing the neutron population; he was looking for any wild fluctuations coinciding with the ripples. None were seen because the experiment was still slightly subcritical. Still, the source of the ripples was unknown; and they appeared to be growing. This author started to move to SCRAM the experiment but stopped short just when the source of the ripples became humorously visible. A bumble bee had flown dangerously close to the solution's surface and had become entangled in its surface tension. The insect was madly fluttering its wings in an effort to escape as it swam over the surface of the uranyl nitrate solution. It swam into view of the camera. The nitric acid content of the solution soon ended its misery; and the surface disturbances vanished. The experiment was carried on to criticality with no further interruptions. Subsequent chemical analysis of the solution never found any measurable evidence of protein.

### ***Bird Trapped in Hot Area***

Nature's animal species provide one other light-hearted anecdote in a chapter of serious events. One summer's day, some large equipment was brought into the Assembly Room through the large pair of doors in the south wall leading to the out-of-doors. An errant bird had found its way inside the room and was trapped there when the doors were closed and sealed. Men from Plant Protection Forces were called upon to trap the bird and, hopefully, release it in an humanitarian act. This could

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<sup>83</sup>Surface disturbances of this kind are known to be described by Spherical Bessel Functions.

not be done, however, because the bird *might have come* in contact with contamination; the poor bird would have to be destroyed. The officer stalked the bird for several minutes waiting for it to light somewhere. In time, it did; and the officer aimed his shotgun carefully. The loud report frightened the bird before the shot arrived; but the four long fluorescent light bulbs of the bird's earlier perch could not escape. Shards of broken glass from the lighting fixture rained down upon the floor to the poorly hidden chuckles of onlookers. The bird did not escape the next attempt on its life.

### ***Uranium Solution Vent Line Overflow***

The first was discovered on November 30, 1967; and it, once again, involved the uranyl nitrate solution. The event became known as the "Vent Line Overflow." In summary, a discharge of uranyl nitrate solution had occurred over an unknown period of time prior to its discovery into an unanticipated location. This diversion had occurred in small increments on a number of occasions and had continued undetected for a long time. This fissile solution had been diverted out of a once-presumed "closed-loop" solution handling system. These discharges occurred toward the end of each of an unknown number of experiments. The diverted solution passed into a critically unsafe geometry; and this, alone, constitutes a significant concern. Fortunately, the problem was detected well before a sufficient quantity had accumulated to cause a criticality accident.

This analysis of the physical phenomenon at the root of this problem may prove useful in preventing future similar incidents. At first examination, the accident would be thought to be physically

impossible. Several respected physicists even rejected the explanation when it was finally hypothesized. In order for the solution to move from the experimental equipment into the critically unsafe area, the solution had to raise well above any height thought possible.

### *Discovery*

That November day, a surprising situation was discovered. During routine end-of-experiment shutdown procedures, a small pile of dried, yellow, uranium salt crystals was discovered on the floor of the stainless steel enclosure surrounding the experimental equipment. These crystals were in the form of dried droplets of solution; and they spanned an area about one to two meters in diameter. From the splatter pattern, the source of the contamination was easy to determine. It was a clear plastic vertical tube which had been installed as part of another study but never yet used. This line was still connected to the vent from the SCRAM tank associated with the present program. That vent line provided a path for escaping air from the SCRAM tank. The unused line leading in the opposite direction and having the open-ended plastic tube dangling from it was ignored because it was believed it would never see fissile solution. That horizontal ventilation line was near the top of the walk-in hood and well above (nearly a meter) the maximum height ever attained by fissile solution during any experiment to that date. No physical mechanism could be conceived which would propel the solution higher than that. A drawing of the situation to that point is shown in Fig. 105.

That very high horizontal vent line had a small air filter housing between the SCRAM tank vent line and the building's

contaminated air exhaust system. A paper filter was contained in that metal box which measured about 180 mm square and about 250 mm high. It had a removable cover plate on one face. The day after the initial discovery, that filter box was opened with the intention of just confirming that solution, which had obviously gone the opposite direction, had not also traveled so far as to contact this filter housing. Upon opening the box another surprising discovery was made. The entire housing was almost completely packed with damp uranyl nitrate salt! The salt was not so fluid as to run out the opened face of the box; but the yellow iridescence of the contents produced surprise and alarm to the eyes of this author!

### *Initial Recovery*

At this point, several projects were begun simultaneously; and each is elaborated in following paragraphs: (1) The damp salt in the filter housing was removed and as much recovered as possible. (2) The horizontal ventilation line near the top of the hood was removed and cut into short lengths to recover those salts also. (3) A large rectangular hole was cut into the vertical leg of the building's 250-mm-diameter ventilation line to view inside for possible contamination. These projects led to other tasks.

The cover plate had been returned only moments after discovering uranium within it. A few days later, the housing was disconnected from the line along the top of the hood, bagged, and moved to another room where it was placed inside an open-faced hood. Loose salts on either side of the filter medium were carefully collected for recovery. About 2 kg of yellow cake was collected and dissolved easily in about 3ℓ of dilute nitric acid. The heavily

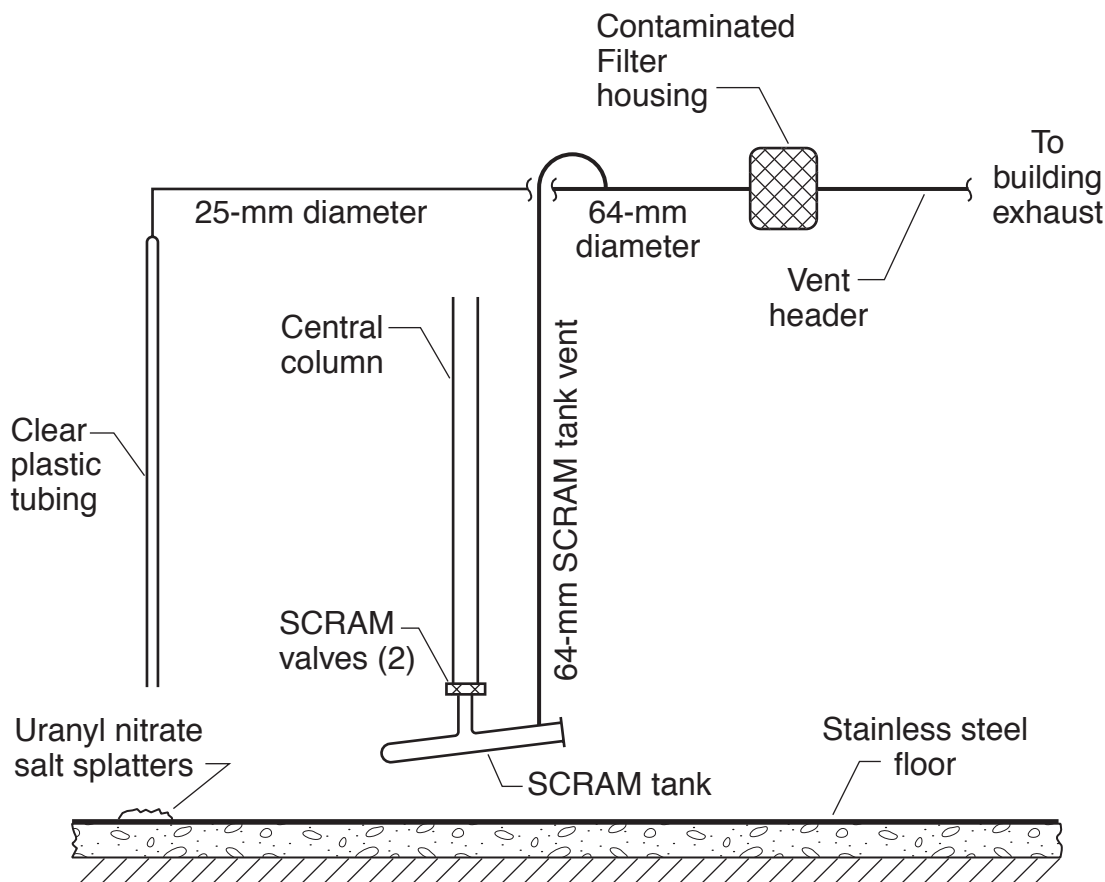


Fig. 105. Splatters of dried droplets of uranyl nitrate solution were found on the stainless steel floor as indicated at the lower left of this elevation drawing of a portion of the experimental apparatus. The discovery was made November 30, 1967. The liquid had obviously fallen from an unused length of clear plastic tubing attached to a very high horizontal line which served as a ventilation header leading, in turn, to the building's exhaust system for potentially contaminated air. This header stood well above the highest point to which solution could possibly rise. Diameters of important lines are shown.

uranium-laden paper filter medium was carefully removed from inside the housing and gently kneaded and shaken to loosen uranium salts. These salts were also collected for recovery. The filter paper medium was even washed in nitric acid to recover as much uranium as possible. A few kilograms of uranium were recovered in this operation and eventually returned to the solution tank storage farm. The short lengths of horizontal pipe on either side of the housing were also found to contain dried

salts. Not much uranium was recovered from these pipes.

#### *The Exhaust Duct*

Fissile solution had evidently passed through the paper filter because dried salts had been observed beyond the housing. To explore just how far uranium solution had traveled, a rectangular hole was cut into a vertical segment of that 250-mm-diameter building exhaust duct. The hole was large

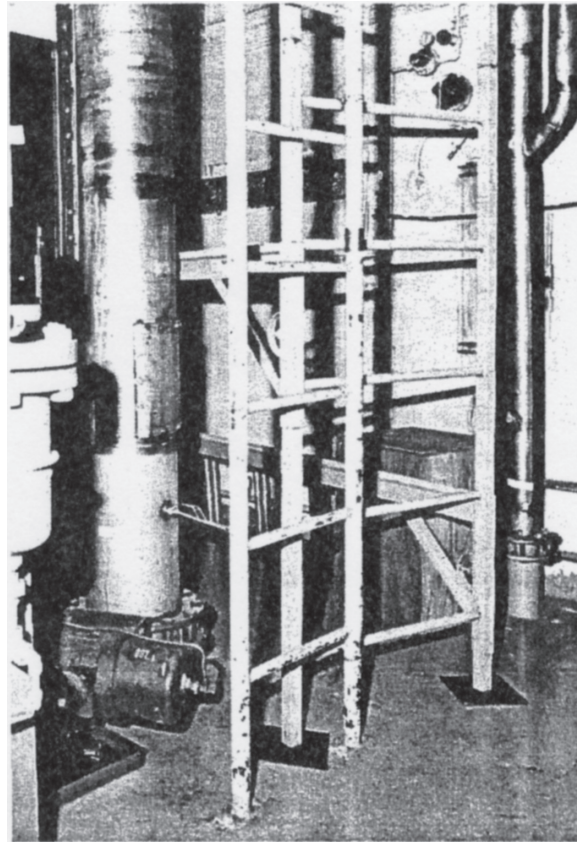
enough to permit easy viewing inside the pipe. The hole was about 4 m past the housing and a little over a meter above the floor. That vertical line was certainly never intended to contain solution. Its purpose was to carry contaminated air from the experimental area to a below-grade horizontal run of this 250-mm-diameter pipe. This buried line, in turn, led to a large, multi-stage filter plenum. Following this plenum, the once-contaminated air was considered pure enough to release up the stack to the atmosphere.

Once the rectangular hole had been cut, a depressing scene was revealed. Dried and brightly-colored yellow salts of uranyl nitrate spotted and streaked down 10% to 40% of the visible interior of this line. Although streaks were thin, they extended as far as could be seen. Thicker layers of dried salt were found all over internal surfaces of the Butterfly Valve—a distance below the opening and just above the floor of the Assembly Room. The actuator of the valve can be seen near the bottom of Fig. 106. The location of the rectangular hole is revealed by the patch seen bolted to the exhaust duct in the middle of the photograph.

To facilitate cleanup and recovery of these dried salts from this large-diameter exhaust line, a 1.5 m length was removed just above the Butterfly Valve. The weldment upon returning the length after cleanup can be seen to the left in Fig. 106 between the 4<sup>th</sup> and 5<sup>th</sup> rungs of the ladder. This removal permitted unobstructed views back up the vertical exhaust line as well as down into the buried portion of the line. A simple mirror was lowered into the buried pipe to permit viewing the buried line several meters underground. The bottom of this line was covered by a thick layer of uranyl nitrate salts as far as the hand-held light source could illumine

the interior of this 6.3-m-long underground duct. The path of dried salt was about 150 mm wide.

The full extent of this large-scale incident was finally recognized. Well over twenty liters of high-concentration uranyl nitrate solution had passed into a 250-mm-



*Fig. 106. The vertical leg of the 250-mm-diameter building exhaust line is shown to the left as it enters the floor of the Assembly Room. Just below grade the line curves and leads horizontally under the wall seen to the right background. The cover plate (seen on the right side of the duct in the middle of the photograph) was later installed over the hole cut into this line for the first viewing of the extent of this contamination incident. Close inspection above that patch shows the weld seam when the length of temporarily removed exhaust line was reinstalled after completing cleanout. The horizontal object at the bottom where the duct enters the floor is the butterfly valve discussed in the text.*

diameter horizontal pipe buried just below grade level. The long length of the pipe limited the collected solution to a well-subcritical depth. The more-extensive elevation schematic drawing of areas involved in this serious incident is presented in Fig. 107.

The Butterfly Valve was scraped clean of easily collected salts and washed. The partially cleaned valve was then bagged in plastic and stored until it could be returned to routine service. The long, underground, buried, exhaust duct proved a bigger

challenge. A hoe was built to facilitate recovery of the salts as far as the arm could reach extended by the hoe's handle. The profile of the hoe matched the circular cross section of the duct; and this worked well to recover salts within a meter or so of the opening.

Reaching deeper into the abyss proved much more challenging. A child's roller skate was employed for this purpose! Another scraper blade with the same profile as the bottom of the duct was fixed to the middle of the skate. A long string was attached to the front end; and a cloth

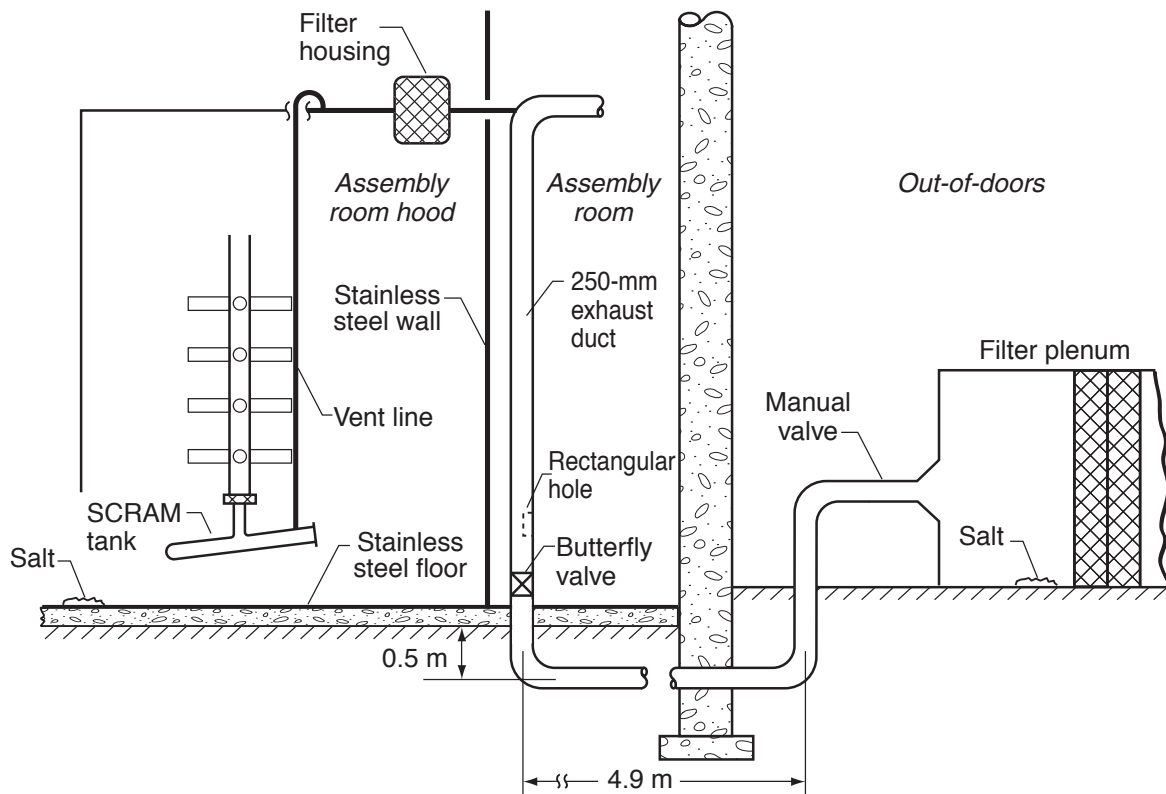


Fig 107. Regions of the ventilation header and the building's exhaust system heavily contaminated with uranium salts are labeled in this elevation drawing. One hypothetical tree-like experiment is shown to the left. The Assembly Room Hood is separated from the Assembly Room by a thin stainless steel wall. The dotted rectangle just above the automatic valve marks the opening cut into the Exhaust Duct when the incident was first discovered. Exhaust air passed through the east wall of the Assembly Room (concrete symbols) before rising above grade only to pass into the Filter Plenum. There, the air passed through filter banks (cross hatched) shown to the far right before being released to the atmosphere through a chimney off the drawing to the right. The drawing is not to scale. Bends into other planes have been ignored in this 2-dimensional schematic drawing.

parachute was fixed to the opposite end. The assembly was lowered into the duct and set on its wheels. Then, the exhaust ventilation was turned ON just slightly. The draft inflated the parachute and pulled the skate deep into the blind duct work. The ventilation was turned OFF; and the skate was slowly drawn back toward the opening by a long string. The blade scraped the salt from the bottom of the duct and plowed it back toward the opening. From there, it could be retrieved using the long-handled hoe. This procedure was repeated many times until not a great deal of salt was collected per operation.

### *The Outdoor Plenum*

A considerable amount of salt still remained. It could be seen stuck to the bottom of the duct such that the roller skate would have just ridden over the hard-to-remove yellow cake. A quantity of warm water was poured down into the horizontal duct. This water was intended to dissolve the stuck salt and put it into the form of a damp paste. The roller skate withdrawal procedure was repeated several times collecting additional uranium.

With a significant number of kilograms of uranium retrieved from this underground duct and an unknown remnant still contained there, the question naturally surfaced: "How much further did the dried salt propagate toward the exhaust stack?" The buried duct again rose above grade just outside the building and led into an open chamber in front of the first of two closely spaced banks of High Efficiency Particulate Air (HEPA) filters. The front face of the first filter bank was found to be somewhat contaminated; but this was expected. Thankfully, the back face of the second set of filters was found to be completely free of contamination. The furthest point of

the salt propagation had been finally determined; and, fortunately, no contaminated air had ever been released to the atmosphere via the tall stack.

The chamber in front of the first bank of HEPA filters did present one surprise during this investigation. When the door to this chamber was opened from the 1.22-m-wide airlock which, in turn, remained open to the out-of-doors, a layer of well-dried uranyl nitrate salts was observed lying on the stainless steel floor in front of the first bank. The size of this layer is difficult to recall for certain. It was approximately circular and probably between 200 and 400 mm in diameter.

### *Facial Contamination Incident*

At this point, the author made another error in judgement. Not wanting to disrupt the building's air flow, he made the decision to collect these salts off the floor without shutting down the exhaust fan. The task seemed simple enough even though the work was to be performed out-of-doors. The salt crystals were very dry and appeared to be quite stable on the floor. The plan was to slide a thin sheet of metal under the salt such that they might be transferred into a wide-mouth bottle to be carried back inside the building. The problem was that the air flow really did sweep low across the top of the salt collection. Even though not much air flow could be felt just above the layer, sufficient turbulence existed only millimeters above it such that the very first minimal disturbance of this collection caused a puff of yellow salt to become caught up in the air stream. This puff struck this author in the face causing considerable skin contamination. Fortunately, none was found in the eyes, nose, or mouth. Two facts contributed to a very red face that evening: embarrass-



ment and the chlorine-based bleach needed to decontaminate the author's skin.

### *Recovered Amounts*

The amount of enriched uranium recovered from each of the several areas discussed on the preceding pages is presented in Table IX. These are very coarse estimates of the uranium and are almost certainly *underestimates* of the amounts actually involved in the incident. A roller skate on the end of a long string run out into the dark abyss of an impossible-to-view hole is not likely to enable a complete recovery of yellow cake. The amount of solution actually recovered is not accurately known. Over 9 kg was recovered overall with between 4 kg and 5 kg from the duct alone; how much remains is unknown.

Dr. Paul D. Felsher, a Criticality Engineer at Rocky Flats read an advance copy of this chapter in November, 2000. This led him to probe deeply into available documents. Those documents revealed some additional data inadvertently overlooked on first writing. They found a graph of four gamma-sensitive surveys of the duct at different stages of cleanup. The data for these gamma surveys extends a surprising

six meters deep into the buried duct. The first (December 7, 1967) was before any cleanup; and the area under that curve might correspond to between 4 and 5 kg. The "initial cleanup," dated December 18<sup>th</sup>, showed a marked reduction. The next day, a slight improvement was observed "after scraping." The last gamma survey was dated December 20<sup>th</sup>, after a "hot water soak." The area under that last curve is but a percent or two of the first survey. Thus, this information suggests that this duct could contain, today, anywhere from a few grams to a couple of hundred grams of dried uranium salts. This physical data must be accepted in spite of intuitive feelings. That the cleanup of such a difficult-to-reach, underground, small-diameter duct was so thorough using a simple roller skate and a home-made scraper blade is truly remarkable.

Felsher also reports two other possibly useful facts. He has viewed a video tape of a televised visual survey, called a "characterization," of this duct made in October, 1995. Unfortunately, no one can locate a copy of this video recording some five years later. He states that his recollection of viewing this tape showed very little uranium salts, possibly only a band about 25 mm wide and near-zero depth. In addition, he states, "...little specks of dried (salts) could be observed randomly distributed throughout the duct." He noted further that: "No large deposits of dried (salts) were observed." This televised survey entered the vertical riser of the larger duct through a short section of small-diameter horizontal line well above the floor. It turned and traveled straight down through the larger duct until it encountered the 90 bend just below grade level. The camera then traveled some one to two meters along the underground horizontal run. This is where most of the salt resided. Felsher

**Table IX. Estimated Weights of Enriched Uranium Eventually Recovered from Various Locations Following the Vent Line Overflow Problem Discovered November 30, 1967.**

Area Described in Text	Uranium (g)
In-line filter housing close to experimental apparatus	3100
Horizontal lines just before and after filter housing	230
250-mm-diameter buried exhaust duct	4100
On floor in front of first bank	740
Front bank of HEPA filters	900
<b>Total</b>	<b>9070</b>

claims about one-fourth of the entire length of the larger duct (vertical plus horizontal) was surveyed. These observations are of uncertain value because the video recording has been lost. Felsher's veracity is not questioned; but the proof is not available.

Secondly, Felsher reports reading a statement in a high-level-management document concerning the problem that the duct was "washed clean of any yellow salt" as far as the arm could reach in this awkward position. In fairness, this comment came from a letter from the Rocky Flats Nuclear Materials Management manager to his counterpart at the Atomic Energy Commission (AEC). The author of that letter had no direct association with the incident. Some slight "minimization" of the problem at these levels of reporting might be understood.

This author has discussed the probability that residual uranyl nitrate salts still lie in that buried line with many people at Rocky Flats and elsewhere. It is also discussed in considerable detail in the INEEL report referenced earlier. This is not a situation that wants to be kept private. All persons responsible for the disassembly of that Rocky Flats facility during the coming years were warned to be cautious of this particular area.

### *Physics of the Incident*

The physical explanation of this unusual event was not at first recognized. It was not even believed by many very capable physicists when finally realized. When viewed as a simple U-shaped tube composed of the tall experimental apparatus and the vent line as vertical legs connected only by the SCRAM tank as the bottom of the U-tube, laws of physics argue that the height attained in the vent

line ought never exceed the initial height of solution in the experiment. This is so regardless of the elevation of the solution in the apparatus. That fact is also independent of differences in diameters. Therefore, even following a SCRAM of an experiment with the experimental apparatus brim full, physical arguments limit the height the solution could attain in the vent line. Frictional losses, in time, would eventually end up with solution filling the SCRAM tank and both legs of the "U" to the same heights as the solution finally came to rest.

Evidence, however, clearly shows that the fissile solution *did* rise much higher than that and did so on a number of occasions. Something was flawed in these physical arguments. After considerable discussion, an hypothesis was proposed which attempted to explain the obvious facts. That hypothesis revolved about the air contained within the SCRAM tank at the instant a SCRAM acation was initiated. Initially rejected, two different demonstrations verified the truth of the conjecture. These are described below.

The column of solution contained in the vertical experimental apparatus, called the "Central Column" in this study, rested about 0.75 m above the entrance to the SCRAM tank which was full of air just prior to opening the SCRAM valves. Upon opening these valves, solution plunged into the air-filled SCRAM tank. There, the uranyl nitrate solution mixed with the air because of the turbulence of the rapidly falling solution. Huge "gulps" of air would be trapped by solution as the splashing liquid sloshed about within the SCRAM system. Rather than expelling air up the vent line as anticipated, well ahead of the smoothly flowing solution, the liquid being pushed up the ventilation line was a random and varied mixture of uranyl nitrate solution and air pockets.

This air/solution mixture may be viewed in two ways; but both produce the same explanation. First, the contents within the vent line may be considered full-density solution merely displaced upward by sometimes large cushions of air. Under this interpretation, the laws of physics discussed earlier are correct except that this solution would be displaced upward by the sum of the height of all air cushions trapped within the solution. Second, the air/solution mixture may be considered a reduced density solution,  $\rho'$ , with that density being the mass of full-density solution in a volume occupied by solution *and* air. Under this interpretation, the physical laws of hydrostatics would apply:

$$\rho g H = \rho' g H',$$

where  $H$  is the initial height of the full density ( $\rho$ ) solution and  $H'$  is the greater height of the lower density ( $\rho'$ ) air/solution mixture; of course,  $g$  is the acceleration of gravity.

#### *Documentation of the Conjecture*

The first demonstration that validated this unexpected conjecture involved a glass model of the complex geometry involved. This was constructed with glass tubing of different sizes representing the various components. A single glass valve was fused into the model to represent the two SCRAM

valves. The “SCRAM” valve was closed and the “experimental apparatus” filled with dark colored water. When the glass valve was opened, the situation shown in the photograph of Fig. 108 clearly demonstrated precisely the phenomenon observed.

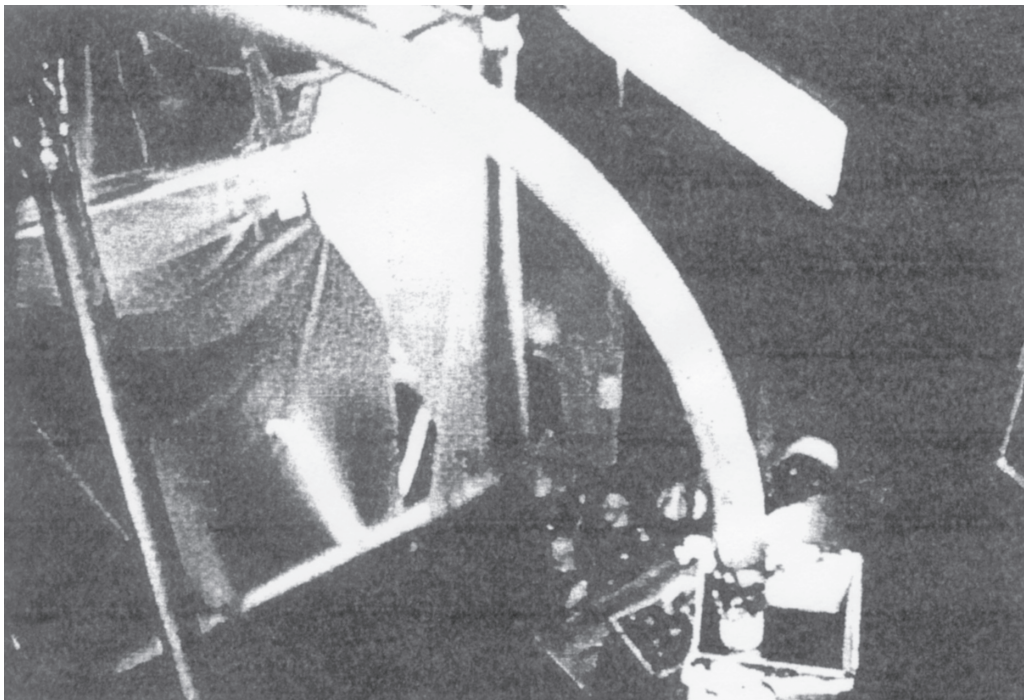


*Fig. 108. A glass model of the experimental apparatus clearly demonstrates the accident phenomenon. The large diameter tube represents the central column sitting on top of a single simulated SCRAM valve. The vent to the SCRAM Tank, at the bottom of the photograph, is represented by the smaller diameter vertical tube. Colored water in this demonstration clearly shows the liquid being broken up by large air bubbles.*

The second demonstration was even more dramatic; and an 8-mm motion picture was made of it. This movie can be found in the LANL Archives in Box 47, folder 1. The vertical ventilation line leading from the SCRAM tank was re-routed back into the top of the tall column via a length of 64-mm-diameter clear plastic tubing. The photograph of Fig. 109 shows this curved length of large-diameter tubing. This would indeed make a closed-loop system out of the experimental apparatus because the entire system would exhaust into itself. This configuration is shown schematically in Fig. 110.

The experimental apparatus was filled with uranyl nitrate solution as had been done many times before during

experiments. It came to within a few millimeters of the top. When the SCRAM valves were opened, the solution quickly dropped from view as it plummeted into the SCRAM tank. All remained quiet for a second or two. Then, suddenly, *dozens of liters* of yellow, foamy, frothy, liquid spewed through the clear tubing and gushed back into the Central Column. The tube does not appear clear in the photograph because it was, indeed, full of foamy high concentration uranyl nitrate solution! The realization that the fluid was concentrated uranyl nitrate solution added gravity to the scene. The photograph is a copy of one frame from that 2-minute-long, silent, 8-mm movie film made on January 26, 1968.



*Fig. 109. This photograph is excerpted from a 2-minute-long motion picture made of the ventilation line overflow problem. The accident phenomenon was demonstrated most graphically by reenacting the scene with the actual equipment and uranyl nitrate solution. The curved once-clear plastic tube connects the vertical ventilation line (left) to the opened top of the square central column (lower right). The tube does not appear clear because it was full of gushing uranyl nitrate solution during this frame of the movie.*

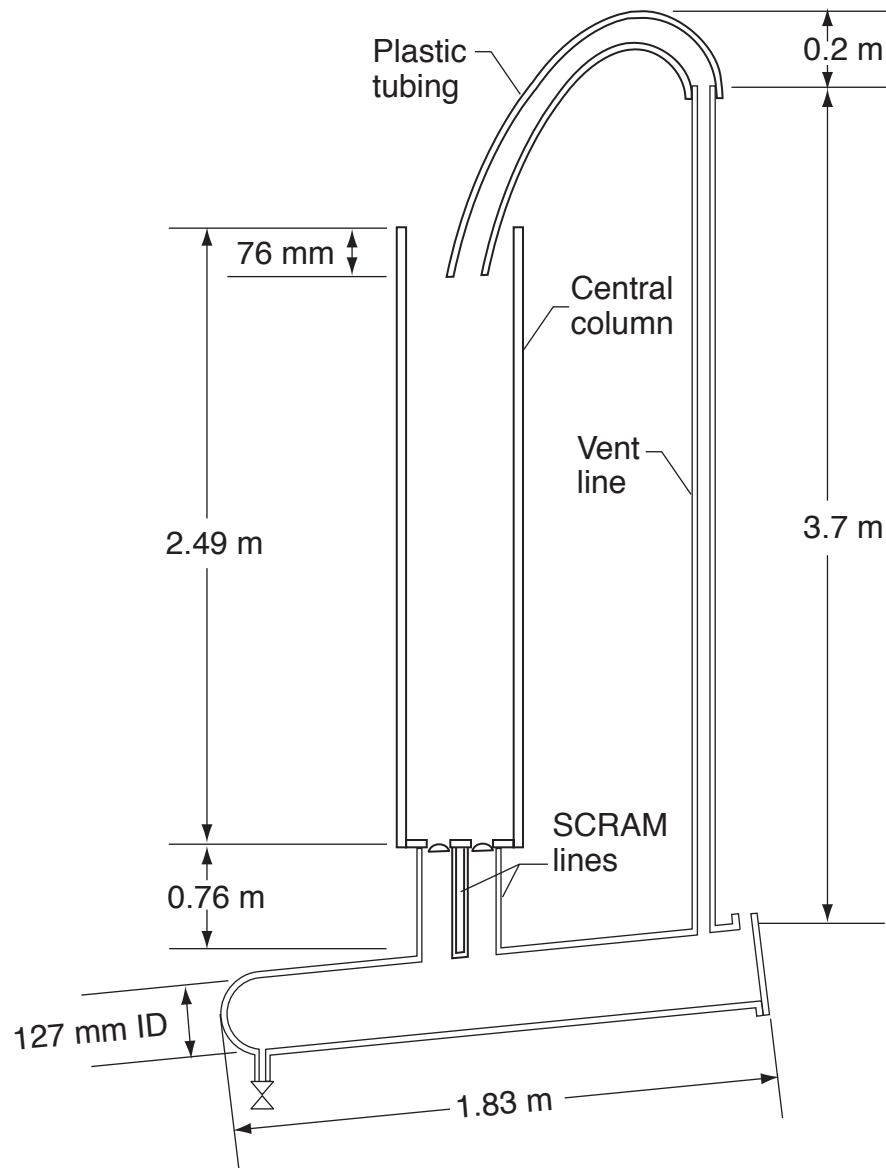


Fig. 110. The closed loop ventilation system constructed after the contamination incident had been discovered was composed of the central column (left), the SCRAM valves and SCRAM tank (bottom), the vertical ventilation riser (right), and the clear plastic hose (top) which passed solution back into the central column. These two SCRAM lines actually had two 90° bends each and a total length of 1 m.

### ***Experimental Component Falls***

The second problem occurring during this program was a design flaw. The experimental study involved a number of arms branching off a "Central Column." One arm branching off the central column slipped on one occasion and collapsed toward the arm below it. This event occurred during the 103<sup>rd</sup> experiment in this series. The date was January 22, 1968, less than two months after the discovery of the Vent Line Overflow problem. In particular, the slippage occurred during the filling of that arm with fissile solution but before the arm was anywhere near full. The event was caused by inadequate support under the arm which failed.

The experiment in question consisted of 12 horizontal arms with vertical stacks of three arms branching off each of the four faces of the Central Column. The spacing between them equaled the outer diameter of each arm: 168.3 mm. Arms extending in opposite directions were colinear with one another; and horizontal arms orthogonal to them were similarly spaced but offset by that same diameter.

Each arm was supported above the arm below it by either wood or metal supports. When metal supports were used, they were *probably* short sections of slotted angle bolted between a vertical framework. When wood supports were used, they were rectangular blocks of 38.1-mm-thick wood precisely cut and sanded to yield the desired separation between arms. When wood was used, it is recalled to have simply raised the arm above an otherwise stable arm. The wood blocks were held in place simply by the weight of the arm it supported and any fissile solution it might contain.

There were two supports per arm. One was nearer the Central Column, the other,

somewhere close to the far end of each arm. Regardless of the unrecalled details of arm support in general, at least one arm in this experiment had at least one end supported above the supposedly stable arm below it by a wooden block. During routine filling of the apparatus, that wooden block slipped out of place and fell to the floor. This, in turn, allowed the arm to fall onto the arm below it. This metal-to-metal contact made a loud sound which was heard in the Control Room through the audio communications in use at the time. An immediate glance at the neutron flux measuring instruments showed that there had not been an increase in neutrons; so no criticality accident had occurred. Still, something unplanned had happened. The experiment was shut down; and the Assembly Room was entered for investigation.

Upon investigation, one arm was found resting against its lower neighbor at the *outer* end of the arm. The wooden 38.1 mm spacer block had slipped away. The failed arm was still properly supported at the end nearer the Central Column. All other arms appeared to be as stable as at the beginning of the experiment.

The failed arm fell at some point during its filling. It is recalled to have been between one-third and two-thirds full at the moment the wooden block slipped. Evidently, the block was sufficiently stable when the arm was empty but obviously not under the added weight. The cause of the failure is probably due to the changing weight of the fissile solution entering the arm during filling. The failure may have had a dynamic factor, too. These could stem from two sources. Electrical solenoids holding SCRAM valves closed may have set up vibrations throughout the apparatus. Second, the dynamic act of pumping solution may have caused a sloshing effect; and this movement may have caused the weight to shift accordingly.

Nevertheless, the arm fell with a loud sound. Because the wooden block happened to have been under the *outer* end of the arm, the solution flowed to the *outer* end of the collapsed arm. That meant that the solution flowed *away* from the Central Column. This direction would probably tend to *decrease* reactivity of the system; and that was, evidently, the case. Had the wooden block been under the end nearer the column, fissile solution would have flowed uncontrollably *closer* to the column; and this *could have caused a criticality*. Positioning the blocks had been purely a matter of choice; so simple good luck may have prevented a criticality accident.

Whether or not a criticality accident would have occurred had the arm fallen in the other direction is not known. The neutron reproduction factor for this accident condition could be calculated, although assumptions would have to be made as to which arm fell and how much solution was in it at the time. Nonetheless, a valuable lesson was learned that all experiments must be adequately supported to withstand any and all static and dynamic forces coming into play throughout an experiment.

The failure occurred about 3:30 in the afternoon; and the text of the log book goes on to record:

*6:15 PM Restarted experiment and finished it at 7:15 PM. It was subcritical with a multiplication of about 20.*

This remark is included to illustrate differences in philosophy between the 1960s and the 1990s in the conduct of operations involving fissile materials. In retrospect, this entire experimental study should have been summarily terminated until a better way of stabilizing the apparatus had been designed and implemented. Instead, a simple modification was made on the spot and the experiment continued.

### ***Uranium Solution Leaks Into Cable Trenches***

Less than a month after the fallen arm, the next uranium solution incident occurred. The date of this leak was February 16, 1968. One statement reports about 1140 g of dilute uranium solution passed onto the floor of the experimental room and into its cable trenches; but another identifies the amount as  $1137 \pm 145$  g of *uranium*. Whether or not the former is merely rounded-off and whether the weights refer to *solution* or *elemental uranium* is not immediately clear. Three decades later, those facts are not as important as the cause or the consequence.

The leak occurred during pre-experiment activities pursuant to the next program. A newly-installed experimental tank had been filled to a depth of only 10 mm with 450 gU/ℓ fissile solution. After returning the solution to storage, the room was reentered to inspect the apparatus for any anomalies. This disheartening inspection revealed uranium solution in the areas shown shaded in Fig. 111. Unexpectedly, some of this solution had diverted into a nearby tank through a valve which had been unknowingly left open. The liquid then found its way onto the floor through an unplugged instrument opening on that tank. The 218-liter, Raschig-ring-filled, storage Tank #540 was located in the same room as the experimental apparatus and connected to the newly installed experimental apparatus as displayed in Fig 112. Thus, *two* errors contributed to this problem: (1) The unplugged opening was supposed to have had a liquid detector screwed into it. (2) The circled manual valve had accidentally been left open so some solution from storage found its way into Tank #540 as well as the Experimental Vessel.

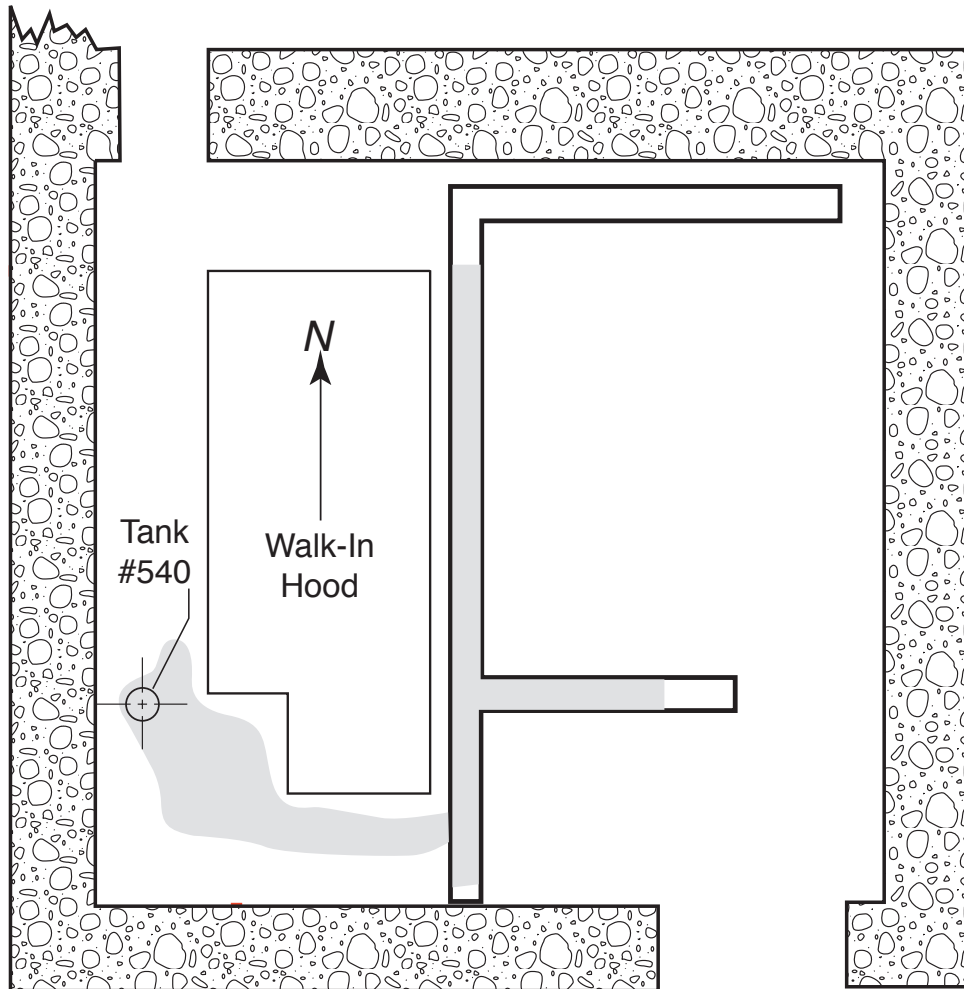


Fig. 111. The interior of the Assembly Room shows where the floor and its cable trenches were contaminated by the incident of February 16, 1968. The contaminated area is shown lightly shaded. Uranyl nitrate solution flowed out of an open instrument connection on Tank #540. In addition to that missing connection, a manual valve was inadvertently left open contributing a second error.

Solution on the floor area was not a criticality concern; a slab thicker than a few millimeters would be hard to generate. The trenches, on the other hand, *did* pose a criticality concern. They were less than half a meter wide by the same depth with a U-shaped bottom. Had a much larger amount of solution been involved, the leak might well have led to a criticality in the trenches. Fortunately, in this case, only a little solution had been pumped into the new apparatus.

Cleanup was begun by scooping up liquid where possible and collecting that into two-liter plastic bottles. Then, more errant solution was absorbed into paper towels. These, too, were placed into similar bottles. Decontamination was begun next. Quantities of warm water was used to wash both trench and floor. Altogether, liquids and soaked towels were collected in 17 bottles. Decontamination was “accomplished in 8 hours” according to one report; but how thorough that decontamination



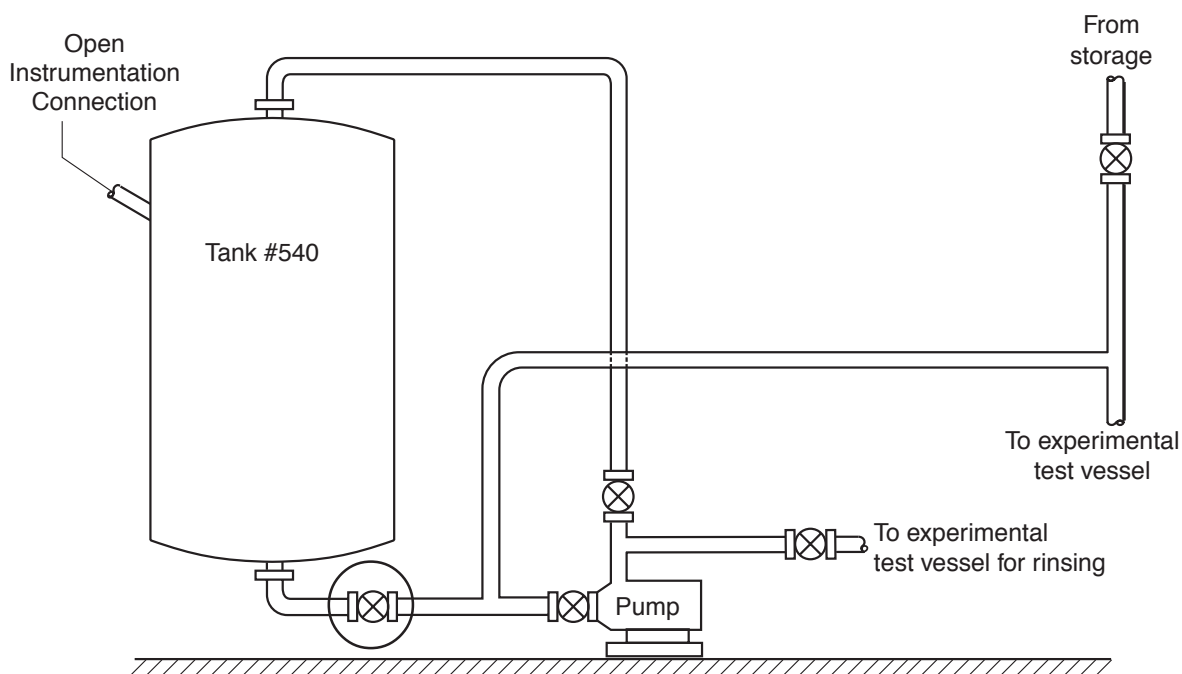


Fig. 112. An elevation schematic drawing of the incident of February 16, 1968, shows the open instrument port out of which the uranium solution leaked onto the floor. A manual valve, highlighted by the circle, was inadvertently left open. The line to its right splits and leads to storage and to the experiment.

was is questionable. Trench walls, although painted, were rough in texture; and many places were extremely hard to reach. These trenches probably still harbor some contamination; and those dismantling the facility were warned to exercise caution.

The potential for a criticality accident in these trenches was brought to light by this spill; and corrective actions were immediately taken. After washing the trench and its contents *as well as possible*, cables and other equipment needed for the conduct of experiments were temporarily removed so the trench could be mostly filled with fresh concrete. The new concrete was brought to a level about 80 mm below the floor's surface. This left a shallow trench but one that was critically safe. Still, enough room remained for the cables

and other paraphernalia. This trench was used for a number of years with no further fears of a criticality accident. Later, however, a new set of commercial metal cable trays were purchased and installed. These long troughs resided well above the floor. They were, in fact, well above head height along walls close to the original trenches. Perhaps the concern was for better contamination control; but the specific reason for these new cable troughs is not recalled for certain. All cables were moved to these elevated trays; and the remainder of the trenches filled in with still another layer of fresh concrete. The concrete was brought level to the rest of the floor's surface. This final location of the cables happened in the late 1980s.

Workers at Rocky Flats dismantling the CML were well warned to recognize the possibility of uranium contamination in the area of these trenches. They could never have been cleaned thoroughly because of the roughness of the concrete and difficulty of access. Any residual contamination has been buried under two layers of concrete. Caution was exercised when breaking up this area.

The total weight of recovered solution in the 17 bottles was claimed to be about 19.75 kg although considerable uncertainty ( $\pm 1300$  g) is associated with that estimate. Details of this leak are documented in a 10-page-long report to plant management [LANL: box 28, folder 9]. Table X, copied from that document, gives the total weight of each bottle including its contents, the bottle itself, and the bag and tape used to contain contamination. The last column gives the weight of uranium solution and paper towels.

### ***Workman Causes Small Solution Leak***

A painter bumped his knee against a small plastic pump incorporated into the uranium solution storage system while painting other equipment. The impeller unit broke and allowed a small amount of uranium solution within the pump to spill onto the floor. The leak was only about 60 mL; but the painter's knee became contaminated and required decontamination. This minor incident occurred on Saturday, May 11, 1968, in the morning [LANL: box 28, folder 10].

**Table X. Estimated Weights of Contents of 2-Liter Bottles Collected from the Vent Line Overflow Problem of 1967.**

<b>Bottle Number</b>	<b>Total<sup>a</sup>, g (<math>\pm 5</math> g)</b>	<b>Solution + Towels, g (<math>\pm 9</math> g)</b>
1	2430	2120
2	1210	900
3	1870	1560
4	2000	1690
5	2375	2065
6	1610	1300
7	1840	1530
8	510	200
9	1915	1605
10	1125	815
11	780	470
12	2500	2040
13	1690	1380
14	1750	1440
15	1130	820
16	1205	895
17	1730	1420
<b>Total</b>	<b>27,680 g</b>	<b>22,250 g</b>

Each empty bottle weighs  $160 \pm 5$  g.

The total weight of all towels is  $2500 \pm 1300$  g.

Each bottle is contained in plastic  $150 \pm 5$  g.

Total weight of uranium solution  $19,750 \pm 1300$  g

<sup>a</sup>Weight of solution, towels, bag, bottle, and tape.

### ***Large Discharge of Uranium Solution to Mixing Room Floor***

The largest leak ever involving the enriched uranyl nitrate solution occurred the morning of Friday, May 9, 1969. The incident occurred during an experiment; and, again, this author was involved. Manual valves in the solution storage room, Room 103, had been properly set (supposedly) to permit a large volume of 107.4 gU/ℓ uranyl nitrate solution to be pumped remotely from that room into the experimental tanks. A total of 1133.8 liters of this concentration solution resided in three storage tanks at the beginning of the experiment. This was anticipated to be more than adequate for the planned study.

Throughout the experiment itself, the increasing solution height in the experimental apparatus was viewed via closed-circuit television from the Control Room. The experiment appeared to be proceeding normally when, unexpectedly, the solution ceased to increase even though the pumped-transfer process was still activated. This behavior implied the storage tanks had been pumped dry; but that possibility was not at all consistent with the solution height in the experimental tank. That possibility was supported by the observed dynamics of solution movement. Small increments of solution would enter the tank erratically suggesting that residual amounts of solution dripping off the Raschig rings of an otherwise empty storage tank were being pumped into the experiment.

#### *Discovery of the Problem*

The experiment was interrupted so the cause of the mysterious dilemma could be investigated. The storage room was entered about 11:20 that morning; and a most depressing sight unfolded. Almost the entire depressed floor area (about 20 square meters) which housed the set of seven storage tanks was covered with a layer of uranyl nitrate solution. The deepest depth appeared to be less than 20 mm which was quickly assessed by this author to be safely subcritical. An excursion was not eminent. This depth feathered out to a “shoreline” that left a little of the floor area unaffected by this gigantic leak. The extent of this leak is shown by shading in Fig. 113. Later analysis reveals the *average* depth to have been 12 mm, much below the estimated 84 mm which would have produced a criticality accident.

The situation was left undisturbed while the incident was reported to C. L. Schuske, the Nuclear Safety Director. His response was controlled calm in spite of the magnitude of the event. He quietly admonished this author that the errant solution had to be recovered that same day. The risk of airborne contamination would become a significant hazard to personnel as well as the environment if the solution were allowed to dry. Schuske also quickly appointed an investigating committee. His closing comment to that first discussion still rings with ominous portent: “You stay tonight until the solution is completely recovered and the floor washed a couple of times. Then, *next week, we’ll talk about the professional implications of this situation!*”

The solution still residing in the experimental tank was returned to storage tanks #441, #443, and #447. The first two were ones from which the solution had been pumped earlier that morning. The latter, only a 250ℓ capacity, had previously been empty. This, at least, shut down the experiment safely with the return of its solution to storage according to standard procedure. Only the mess on the floor remained.

#### *Solution Recovery*

A commercial, tank-type, stainless steel vacuum cleaner was hastily outfitted for the initial cleanup. A manual valve was installed near the bottom at one point of the cylindrical wall. The body of the vacuum was filled with Raschig rings leaving only a thin space between the glass and the blower mechanism. The compatibility of the plastic hose with dilute nitric acid was established. Finally, an administrative plan was verbally agreed upon to empty the vacuum cleaner periodically well before recovered liquid might reach the top of the glass. Recovered solution would be

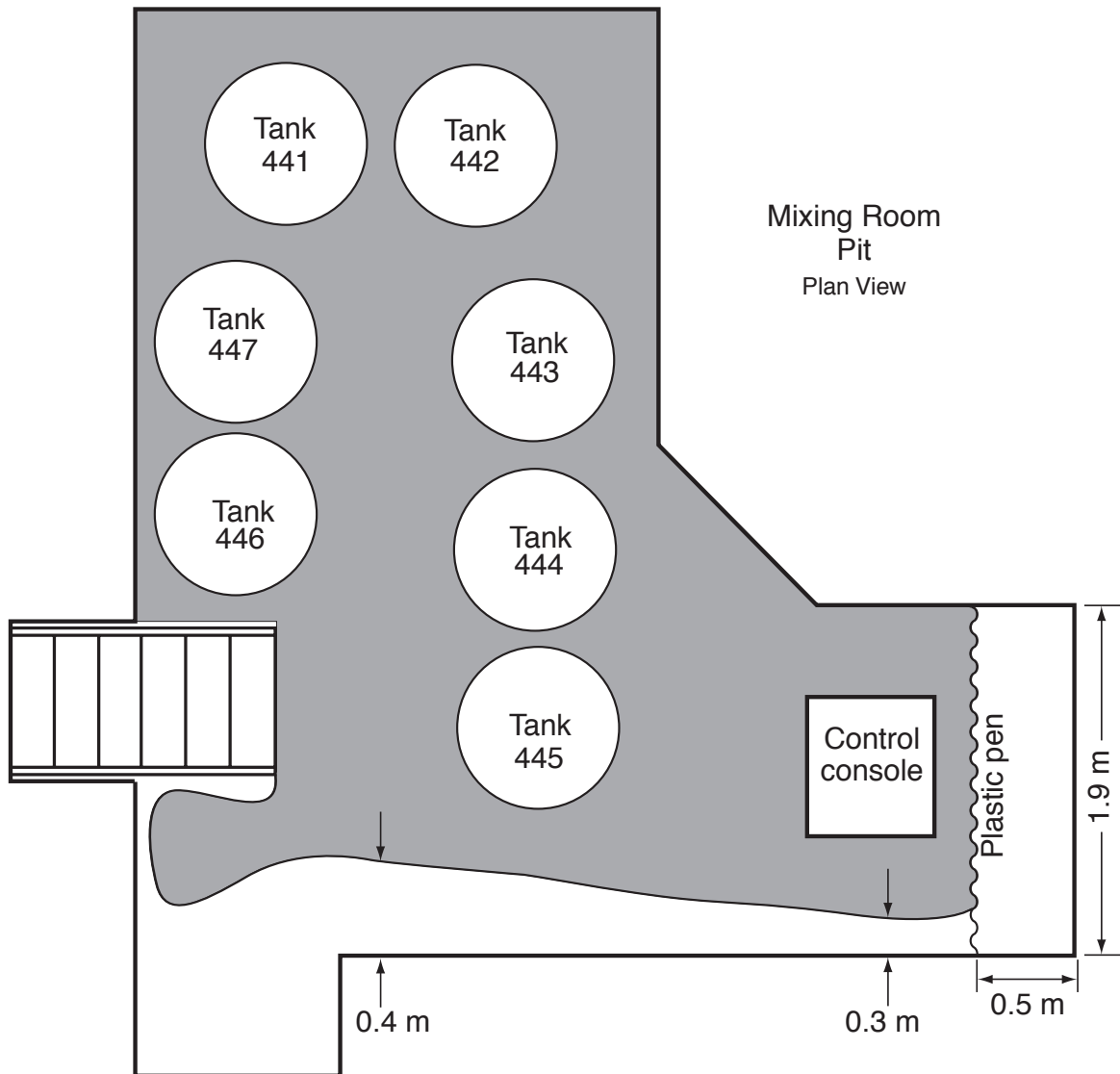


Fig. 113. The sunken floor area of the of the Mixing Room, which housed seven tanks, was heavily contaminated in a spill occurring May 9, 1969. Over 150 liters of high-enriched uranyl nitrate solution flooded the shaded area. Some small amount of groundwater had previously seeped into a small pen seen to the far right; but the pen managed to exclude the solution. The only uncontaminated floor existed near the bottom of the drawing. The cause of this spill was an improperly closed input (manual) valve on Tank #446.

emptied through the manual valve into two-liter, wide-mouth, plastic bottles. The contents of these bottles would then be poured back into just one tank (#446) which had previously housed that concentration solution. It was one that had been emptied during the ill-fated experiment. Therefore, it became a holding tank for

solution of the same nominal concentration as now stored in the other three tanks; but this solution might have suspect levels of impurities. A valved stainless steel funnel on top of each tank permitted that operation. This process would be repeated as often as necessary until the vacuum cleaner had sucked the floor as dry as possible.

This author prepared himself for the task by donning company-owned protective clothing. He covered his shoes in plastic bags which extended well up the shin. Non-slip canvas shoe covers were slipped over the bags; and these were considered disposable as they would be immersed in uranium solution. A respirator was worn; but, inconsistent with today's safer practices, the usual "half-mask" respirator was the style adopted.

The first step into the yellow sea seemed surreal. Waves propagated out from the foot with each cautious step. Uranyl nitrate solution should never be encountered under such an environment. Waves had been anticipated; and it was determined that even these surface effects would not cause a criticality. That fear was not the cause of emotions in effect at the time.

The vacuum pickup proceeded smoothly. After a few moments of vacuuming, the vacuum was emptied as described above. The number of two-liter bottles transferred after a short time helped establish a longer time for vacuuming between transfers. In time, the operation became quite routine. The last of the solution became more difficult to vacuum up. Solution would flow from more-difficult-to-reach places under tanks and behind legs down to the lowest point of the slightly sloped floor. Fortunately, this lowest point was in a readily accessible location. The vacuuming was completed by 4:00 PM the same day.

The floor was washed twice that evening. Experience allows that not all contamination would have been removed from all nooks and crannies; but upset conditions were largely stabilized before the end of the day. A tired crew returned to their homes that night. That first decontamination had been completed by

9:00 PM. Additional cleanup probably continued the next day; but this detail is not clearly recalled this long after the fact. The floor and equipment touching it, such as tank legs, were subsequently painted over to seal any residual contamination in place. This task occurred either the next week or shortly thereafter. The entire cleanup procedure apparently was successful because no incidents in later years can be recalled where latent contamination worked its way through layers of paint. This plant-wide procedure of cleaning up following a contamination incident as well as possible but, then, repainting the affected area as a final contamination control should constitute a warning to those charged with later removal of older facilities.

A total of 150.1 liters of 107.4 gU/ℓ uranyl nitrate solution had passed onto the floor. If those numbers are accurate, 16,121 g of enriched uranium had been released. Many days later, the contents of Tank #446 was measured and analyzed and found to contain  $162.7 \pm 1.0$  liters of uranium solution with a concentration of  $99.10 \pm 0.11$  gU/ℓ. Those parameters suggest that  $16,124 \pm 101$  grams of uranium had been recovered. Evidently, the recovery had been essentially complete with very little uranium lost. Another 67 g of uranium was recovered from squeezing some paper filter media; and this liquid was also returned to Tank #446. The squeezed filter media contained 117 g. Only 12 g of uranium was discarded as waste. The total inventory of 107.4 gU/ℓ solution which began that day in three tanks (#441, #443, and #446) had been  $121,727 \pm 1853$  g of uranium. After the event, collected solutions returned to tanks #441, #443, and #447 plus that vacuumed off the floor and placed into tank #446 plus any waste to be discarded

came to  $121,905 \pm 1298$  g of uranium. The agreement between pre- and post-leak inventories is remarkable. The agreement is so good that it is statistically hardly credible. All these parameters as well as other aspects of the leak are preserved in the LANL Archives in box 28, folder 11.

Surprisingly, recovered solution had not dissolved any significant amount of impurities while on the floor. The average total impurity content prior to the leak, based on only a few samples, had been 2675 ppm. Four samples taken of the recovered solution in Tank #446 showed the impurity level had risen to only 2752 ppm. These two numbers are statistically not different from one another given the uncertainty in impurity measurements. Evidently, the floor had been relatively clean prior to the leak. The conclusion was reached that this solution could be blended with any other solution in the storage tank farm. No need existed to segregate it from the rest of the inventory.

#### *The Cause of the Problem*

The cause of this incident was an improperly set manually-controlled valve (henceforth referred to simply as a “manual valve”). Both experimenters performing that day’s experiment checked and double checked all manual valves associated with this particular study. That included more than a dozen valves in two rooms. This was done as part of the routine “pre-run check” which preceded every day’s experimentation. Manual valves fell into three logical categories with respect to their position: those which must be *open* to perform the experiment, those which must be *closed*, and those for which their status did not matter. This last set consisted of valves associated with an uninvolved tank *and*

which were also beyond a closed upstream valve. A general policy at the CML regarding *all* manual valves was that they should be closed at all times unless a specific operational reason existed to open them. Exceptions to this rule were the few valves which tended to ventilate tanks to the atmosphere. These valves were generally left open unless there was a compelling reason to close them.

The cause of the leak was that one manual valve on Tank #446 was *thought* to be closed when, in fact, it was *partially* open. The valve in question is called the “input valve” to that tank and physically stands at about the middle of the height of the tank. Manual valves have their handle parallel to the line in which it is located when the valve is “open.” Conversely, the valve is “closed” when the handle is orthogonal to the line. This valve was claimed to be closed by both experimenters during the routine “pre-run check.” In particular, one announced his intention to close the valve while the other watched him perform that task; and that was considered to be a sufficient “check.” The one closing the valve, however, did so from an awkward position. Rather than looking straight at the valve and its handle, he watched himself push the valve handle “closed” looking along the line containing the valve. From this perspective, it was difficult to distinguish between a fully closed valve and one only partially shut. Had he observed the valve properly, the slight tilt of the handle would have been noticed. Later reenactment revealed that these valves require considerable force (about 70 kg) to move the handle. Evidently, the person closing the valve thought it had reached its limit of travel when it had not. Therefore, it was not fully closed and, so, was partially open.

The consequence of this partially open valve was that a portion of the fissile solution intended for the experiment was unintentionally diverted into Tank #446. The diverted fraction was insufficient to cause a noticeable decrease in the rate of solution delivery to the experimental apparatus. Thus, no cause for concern existed until one storage tank appeared to empty prematurely. The diverted fraction did, in time, fill that tank (446). The process continued until it could not contain any more solution. The rising solution soaked the paper pre-filter located just above the tank and passed into a common ventilation header to which all tanks connected. This line ran close to the ceiling but turned downward at one point and opened to atmosphere about one meter above the floor and reasonably close to a room exhaust air filter. The intention of that ventilation scheme was to exhaust possibly contaminated air exiting a tank being filled almost directly into the room's exhaust system. In this case, fissile solution—and not just contaminated air—passed through the line; and this is the solution that spilled onto the floor.

Each tank possessed a “liquid level detector” near its top. The installed purpose of this instrument was to detect a tank filled to about 95% of its capacity and to indicate that fact locally to any person in the room at the time. It did not indicate that status remotely nor precipitate any other action. These instruments were Teflon-coated metal probes which acted like an electrical capacitor. The presence of any liquid altered the dielectric constant and caused the capacitor to initiate an electrical signal.

### *Engineered Corrections*

Several “operator errors” had played a role in this situation. The need for greater care in all aspects of using this potentially hazardous material was one lesson learned through this experience. Still, perhaps some mechanical improvements could be made to the solution handling and storage system to prevent similar releases. Three corrective actions were designed and implemented; and these are discussed below as well as in the 14-page-long internal report to building management.

First, the electronic liquid level detectors were rewired such that any activation immediately initiated a full SCRAM of any experiment in progress. That action disabled all solution transfer pumps whether or not they had been operating at the time. It also closed all automatically-controlled valves which could allow solution to move into the experiment by any route. Manually controlled valves could not be functioned by this means; but the closure of all automatic valves made further additions of solution to the experiment impossible. On the other hand, any valves leading *away* from the experiment were automatically opened. This would allow solution to flow away from the experimental tank; and that solution would pass into the SCRAM tank(s). In most experiments, this latter function simply opened the two large-diameter, fast-acting, spring-loaded (to open) valves called the SCRAM valves.

The second corrective action was to redesign the tank's common ventilation header. Prior to the accident, each tank had its own small filter plenum; and the exhaust from these manifolded to a common line just barely above the tanks. The output of that vented to room atmosphere right in from of a room exhaust filter. The change eliminated individual filters atop each tank

altogether, and the tank vents were connected to a common horizontal header line raised several meters above the coplanar tops of the seven tanks (instead of just above that plane). The reason for making this header so high was to eliminate possible gravitational cross contamination of one tank by the solution of any other. The most dilute fissile solution might have a solution density close to  $1.0 \text{ mg/mm}^3$ ; the greatest density ever seen for any of the uranyl nitrate solution was a little over  $1.6 \text{ mg/mm}^3$ . An inadvertent cross connection of two such tanks, assumed full, could push the lower density solution about 60% higher than its initial plane. This manifold exceeded that height.

Still, pumped solution could exceed even that height. Consequences of this kind of mistake were mitigated by directing this common ventilation header into a thin pencil tank with a liquid level detector installed in its bottom. This formed the third corrective action. If solution found its way into this tank, the new detector would also initiate a full-fledged SCRAM. This pencil tank contained no Raschig rings but was critically safe by its diameter (about 100 mm). Even this tank needed to be vented to allow air to move into and out of it; and this vent again rose to a height well above the top plane of the tanks. There, it turned 180 and opened to the room's atmosphere as before. Figure 114 shows this improvement with uninvolved piping omitted for clarity. A filter housing at this final point limited airborne contamination to the room; and the outlet point was, again, located immediately in front of one of the room's exhaust filters. Finally, any solution that might have found its way into this "vent overflow collection pencil tank" could be recovered simply as shown by the figure. No solution was ever detected in this tall, thin, pencil tank from

that time (1969) until the system was completely dismantled in the mid-1990s.

The last corrective action was an administrative one. The importance of a much more careful inspection of all aspects of any operation involving these potentially hazardous materials was stressed. In addition, five independent review teams were formed. Their goal was to examine the entire solution storage and handling system in search of any other potential problem areas. Their review assumed a variety of reasonable human errors, evaluated consequences of performing certain operations while making these errors, and proposed preventive measures to mitigate against these problems. No significant changes were mandated through this review.

#### *A Professional Reprieve*

One final observation proved significant in this author's professional career. Schuske had stated the day of the event that "Professional implications of this incident will be discussed next week!" He had every right to be annoyed with his employee's inattentiveness. This author spent the weekend in contemplation of alternate careers. Then, on Sunday, May 11, 1969, Rocky Flats experienced the worst industrial fire in the nation's history, as mentioned elsewhere. The whole plant was involved in various aspects of the fire beginning the following Monday. This included the Nuclear Safety Group and especially Schuske. The fire was of such importance in the history of the plant that the mere leak of 150 liters on solution onto an enclosed area of floor inside a building paled into insignificance. Schuske never mentioned the incident again.



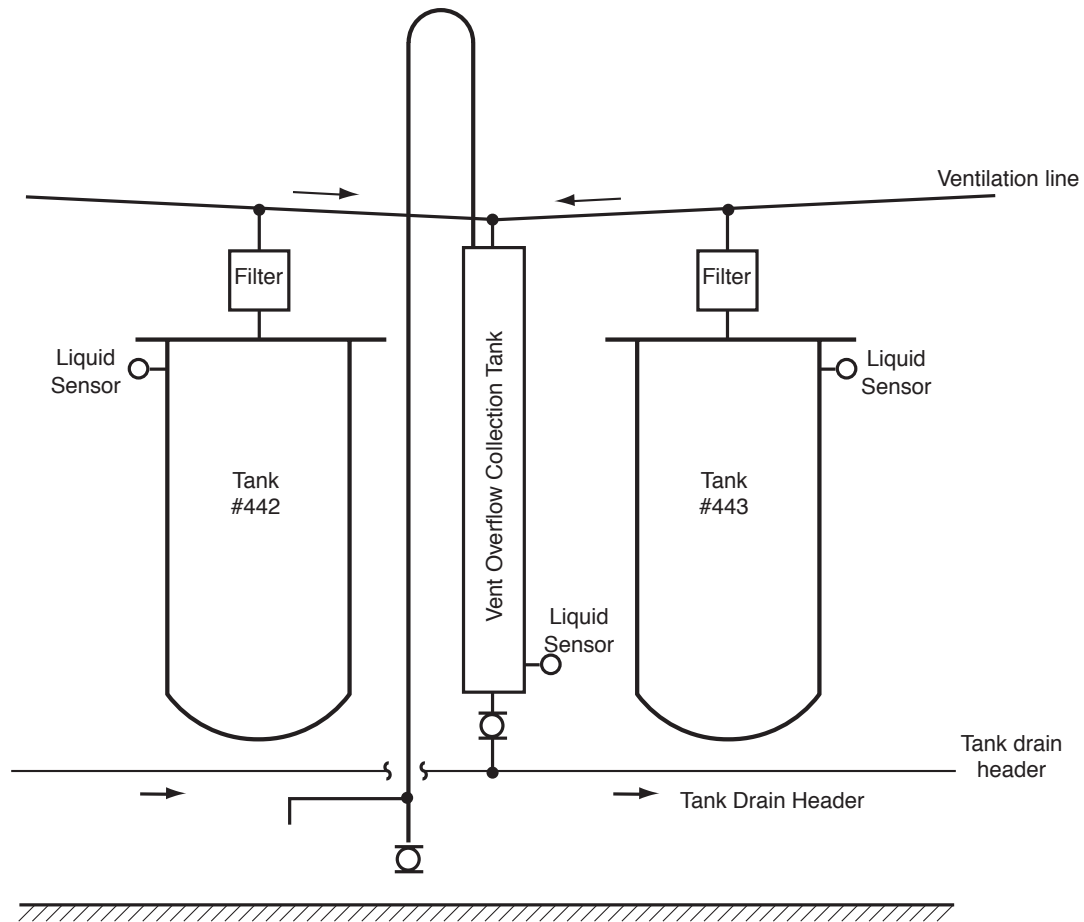


Fig. 114. The tank's ventilation configuration was changed after the incident of May 9, 1969. The change would prevent solution from ever passing onto the floor because of a similar problem. The Vent Overflow Collection Tank, left of center, was a 100-mm-diameter pencil tank. It vented, in turn, via a very tall line which then returned to the floor to exhaust to room air just in front of a room air filter. Sometime later, the improvement was improved even further as described elsewhere. Tank connections to drain lines are omitted from this drawing for clarity; and arrows point down slight slopes.

### ***Uranium Metal Handstacking Controversy***

The next questionable practice involved the CML's set of precision-machined, enriched uranium, metal, nesting, hemispherical shells. The goal was to do a "Handstacking" experiment to determine the critical wall thickness of a large, thick-walled, hemispherical shell of metal. The outside radius of this assembly was to have

been 120 mm. Handstacking experiments are similar to *In Situ* experiments discussed elsewhere in that they are performed manually with experimenters making a careful approach toward criticality. The allowed administrative multiplication limit was also ten. Details of these shells are discussed elsewhere in this paper; but each was 3-1/3 mm thick; and the average density of an assembled geometry was about 18.1 mg/mm<sup>3</sup>.

This author and another CML staff person conducted the experiment in question on July 15, 1969. The fissile fuel could have been built two ways. Smaller shells with their pole facing up could have had larger ones slipped over them until the multiplication limit was reached. The opposite tact was chosen for no special reason. The largest shell (120 mm) was placed on a cork ring with its pole down. Subsequent shells were smaller and slipped into place inside the outer one. This process was to be continued until the multiplication limit was reached; and the critical parameter estimated by extrapolation. Figure 115 shows the data collected through 20 hemishells. The extrapolation

line, based on the last three points, suggests 26 shells would have been critical. The radial thickness, then, would have been 86 mm; and the critical mass implied would be about 64.1 kg. The extrapolation shows that the construction could have continued two more shells to 22 hemishells before reaching the multiplication limit.

The step-by-step procedure had been to remove the neutron source each time a new shell was added and then return it to obtain the next data point. Both experimenters, however, noticed an ever-increasing instantaneous growth in neutron flux whenever the neutron source was returned. The effect got larger as the remaining cavity got smaller. The experiment was terminated

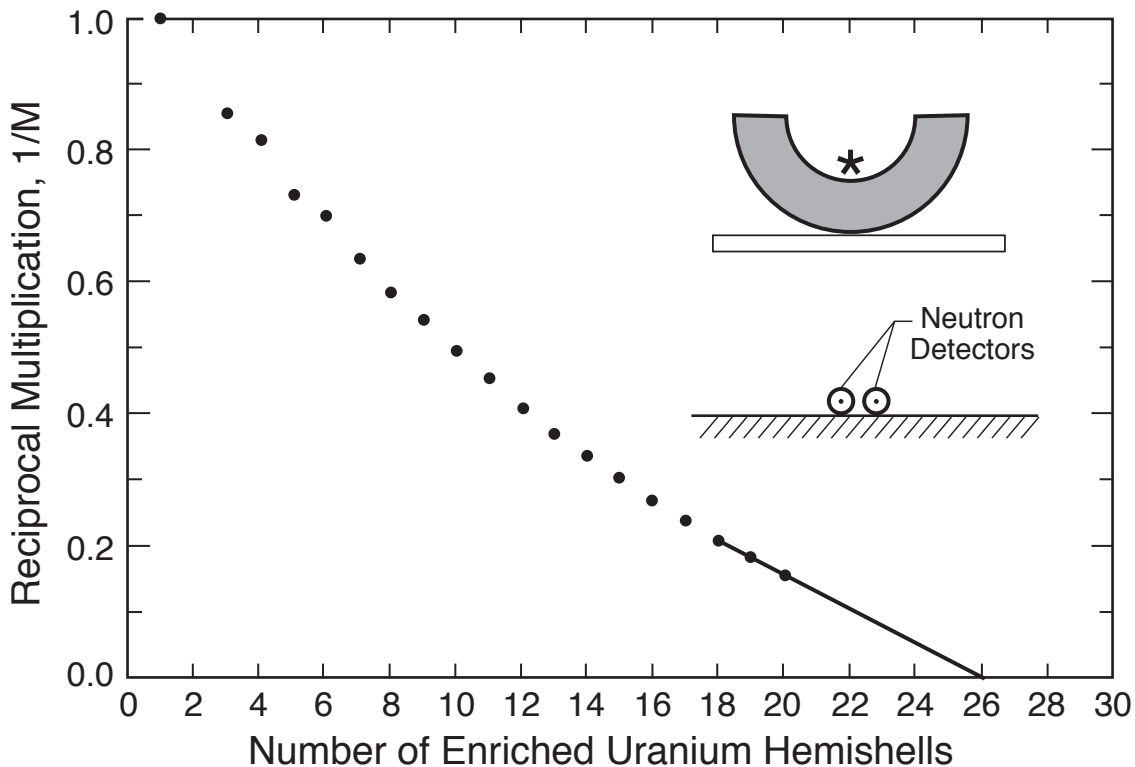


Fig. 115. The reciprocal multiplication curve, generated through 20 hemishells of enriched uranium, extrapolates to 26 nested shells at criticality. The allowable limit (a multiplication of ten) would have been reached with 22 shells based on a linear extrapolation through the last three data points. Unusually high neutron fluxes were encountered each time fingers were used to move the neutron source (shown as a five-sided star); so the experiment was terminated after just 20 shells.

because that phenomenon was not completely understood by the experimenters. C. L. Schuske was called in to discuss the situation; and he expressed considerable agitation over the manner in which the experiment had been performed. He argued that handstacking experiments are to be conducted with only one parameter varied at a time. He objected to the fact that, in this procedure, the radial thickness of the uranium was growing at the same time that the distance between the source and the detectors was changing. Thus, two parameters were being varied. He contended that the experiment should have been done pole up starting with smaller shells and adding larger ones over the growing unit. The neutron source should have been in the central cavity (as it was); but the counters should have been placed overhead so the source/detector geometry remained fixed. This controversy was rekindled several times over the next few weeks; but no long-term consequences ever developed. Unwisely, this frequent handling of that external source was performed with the fingers.

Several mistakes were made. First, the exact procedure to be followed was not discussed with others prior to the work. Such consultation was often done even though formal written Experimental Plans were not required at the time. Secondly, two parameters were, in fact, being changed which violates standard *in situ* practices. Still, this author contends that the incremental increase in source/detector separation was very small compared to the distance between the metal and the detectors (greater than 1 m). He also points out that the reciprocal multiplication curve is both smooth and appears conservative. The possibility that the curve could have turned convex at any point is duly acknowledged. Another failing was the use of fingers to

move the neutron source; and this raises two safety concerns. His fingers were unnecessarily exposed to radiation; and, even worse, the tissue of his digits moderated neutrons to an energy much more conducive to causing fissions. The worst scenario would have been that this added moderation may have pushed a subcritical assembly to criticality. Subsequent to this controversy, many manual assemblies of both enriched uranium and plutonium were performed at the Rocky Flats CML; but they were always built keeping all parameters but one fixed.

### ***Uranium Metal Shell Falls to Floor***

These machined hemishells had very close tolerances in order to enable them to fit together with such high density. Considerable concern developed over the future value of the entire set the day one of these shells was dropped. The shell was an important one often used when building either nearly solid hemispheres or hemishells of quite large inner radius. Loss of this component would have been a blow to future experimental programs at the CML. The accident happened sometime during the 1970s; but a more definitive date cannot be recalled.

The bent hemishell could not fit inside the next larger shell nor slide over the next smaller one. The defective shell was examined in great detail and many measurements of various “diameters” were made. The largest diameter seemed to be the same amount larger than the original diameter as the smallest diameter was smaller. The shell was carefully oriented between the jaws of a very large bench vise as might be found in a well-equipped machine shop. The vise handle was carefully turned to close on opposite points

along this largest diameter. Frequent measurements were made as the smaller diameter grew back toward its original value.

The procedure worked perfectly. The repaired shell, again, slipped easily around both of its neighbors. It has been used subsequently in hundreds of critical experiments. No evidence exists that it was ever bent; a nested thick-walled hemispherical assembly including this component reveals no aberration belying the defect. The accident is considered so minor that no record (other than this document) exists that it ever happened. To this day, no one can remember which shell was the one dropped.

### ***Plutonium Metal Shell Decomposes***

The nesting plutonium shells gave rise to one highly unanticipated problem. These shells were routinely stored in ordinary commercial pressure cookers with a lithium/silicone grease applied to their surface as a means of contamination control and to prevent their sticking together when nested. The glovebox and its associated down draft room contained ordinary breathable air. The inside of the pressure cookers also contained air. Rocky Flats, as a company, did not know, in the 1960s, the very best way of handling and storing bare plutonium metal safely—safely for personnel as well as the material itself. Some conjectured it should be kept in an inert atmosphere. Others believed dehumidified air would be acceptable. A third camp thought the grease coating would be adequate. Everyone agreed that ungreased plutonium metal shells should never be exposed to normal humid air.

These shells, like the uranium ones, had been used in many experiments with the metal immersed in an hydrogenous oil. The oil residue probably helped preserve the parts quite a while. One day, however, D. C. Hunt and this author were preparing to nest a number of plutonium shells for the day's experiment. Similar to many other days, pressure cookers were removed, one at a time, and placed on a "Down Draft Table." This is an opened-mesh table top with a strong current of air drawn through the mesh to collect any loose particles which might otherwise contaminate nearby objects. With the cooker resting on fresh paper on the mesh, the lid was removed and the plutonium part residing therein removed and slid through a momentarily-opened doorway into the glovebox. This process was repeated as often as necessary to collect a planar array of the shells to be nested in the glovebox in preparation for the day's experiment. This one fateful day in the early 1970s (the exact year is no longer recalled), Hunt opened a cooker expecting to extract a good-sized hemispherical shell for part of the eventual assembly. To everyone's surprise, all that was found within the cooker, however, was a large mound of yellow-green compound! The shell had completely decomposed since its last use into some sub-oxide form of plutonium. More than a kilogram of plutonium sat in the form of a finely-divided powder which had the potential for contaminating a very, very large area and providing severe lung burdens to any unfortunate soles who might breath in the powder.

No one was hurt. No contamination existed outside the interior of the pressure cooker. The lid was returned to the cooker and the cleaned cooker returned to its

storage shelf. Still, the decision was reached that same day to return all the plutonium inventory back to the Rocky Flats production stream. Whether or not any other shells were decomposed or not was not known, but the same potential existed for this to happen again at some unpredictable time. Evidently, bare plutonium metal should not be stored in an oxygen-containing atmosphere. The CML was indeed fortunate that this decomposition happened under such controlled conditions as inside a closed pressure cooker.

### ***Raschig Ring Void in Storage Vessel***

The next undesirable situation did not occur for several years after the last problems; and, as importantly, it was not nearly so severe. It did not even involve fissile material directly. Rocky Flats had put in place a number of routine safety inspections by the 1970s. These were intended to enhance criticality safety throughout the plant. One was the periodic inspection of Raschig-ring-filled vessels to make certain their rings were intact and fully serviceable. The plant had some 250 such tanks scattered throughout its many buildings. These inspections proved that the glass retained adequate amounts of boron to absorb neutrons, were strong enough to withstand the rigors of use, were free of accumulated precipitates laden with fissile material which might affect their use as a nuclear poison, and completely filled the vessel such that an inadvertent overfilling of the tank could not attain criticality in a poison-free region.

The last aspect became the focus of a problem on April 8, 1976 [LANL: box 28, folder 3]. A void had been discovered near the top of Tank #440, a waste water collection tank located in the Holding Pit and discussed in an earlier situation. That tank had been filled with 24,800 Raschig rings on March 3, 1965; and, according to a log of visual inspections, had not shown any tendency for the rings to settle with time.

All of the rings had been removed for cleaning on July 17, 1975, and returned by August 7<sup>th</sup> the same year. Whether or not the number of rings removed were returned a month later is not recorded. Quite possibly, that was not the case because the packing fraction of these glass cylinders varies considerably. The tank had been inspected visually over four months after return (December 22, 1975); and no settling had been observed. Nonetheless, rings did settle subsequently causing the void discovered in April. It required 1,227 rings to fill. Fortunately, the tank was almost never used, was certainly never filled to capacity, and liquids admitted were very low in uranium concentration. A criticality accident was not at all imminent.

Still, one important safety lesson was learned. Glass rings do pack differently depending on how they are added to a tank. A tank can appear full and the rings settle with time. This is especially true for rings packed dry. The first introduction of liquid can cause the glass surfaces to slip on one another causing settling. Raschig rings should always be loaded to their maximum attainable glass density. A photograph of this tank, properly filled with Raschig rings, was taken on April 14, 1976: (Fig. 116).



*Fig. 116. Raschig rings in the Waste Water Holding Tank (Tank #440) in the Holding Pit as they existed after filling the void discovered April 8, 1976. The void took 1227 rings to fill. The tank's lid is just about to be lowered into place and bolted down.*

### ***The Destruction of Uranium Oxide Can #5***

A series of experiments were conducted at the request of the Nuclear Regulatory Commission (NRC) between 1976 and 1982. These involved cubical cans of low-enriched uranium oxide heavily compacted and injected with water to desired hydrogen-to-uranium ratios. These cans are discussed in another section. Sometime around 1980, an accident happened with one of these cans. The exact date is lost to memory and was probably never documented; but that information is also not very important.

Over 100 cans were nearly identical in composition; so the loss of one can was not nearly so important as the one hemispherical shell bent out of shape. The accident happened to can #5. During some of the

pre-run operational checks performed each day, that can had been left sitting on one surface of the Horizontal Split Table. That was the reactivity addition device used in these NRC studies. One of the pre-run checks was to test the table closure rates to confirm they fell within expected ranges. During this test, some (now unknown) protrusion resting on the other half of the split table moved closer to can #5 as the table halves approached one another. That protrusion contacted the can, pushed it toward the edge of the table, and caused it to fall to the floor. The can bent out of shape and spilled some of its contents onto the floor.

The can, itself, was dispensable; but the uranium oxide was accountable. The powder was collected and stored with the remainder of the now-destroyed can in one of the fissile material storage rooms. It was

housed in a larger metal container; and it remained there until the oxide was finally shipped out of the facility some time in the 1990s.

### ***Uranium Oxide Cans Gain Weight Mysteriously***

The low-enriched uranium oxide cans were inventoried by periodic weighings. Separate weights of the oxide, itself, the aluminum can and lid which contained it, the plastic bags used to encase compacted briquettes, any moisture originally present in the oxide, and additional water injected to produce a desired hydrogen content had been carefully recorded when the cans were first prepared. Analysis of all materials was believed known accurately at that time. Subsequent accountability of the material was confirmed by merely weighing each can. Over a couple of such weighings a few cans differed by one or two grams from their original value; but no changes outside the measurement uncertainty were observed.

By the third or fourth weighing, a few cans were, surprisingly, *gaining* weight. Mechanisms for losing weight included evaporation of water and the gradual loss of uranium oxide powder through handling. The only mechanism for weight gain hypothesized was the adsorption of moisture. This could occur through possible pin hole leaks in the vinyl tape covering the water injection holes. This conjecture was put to the test. Four different cans were selected. Each was isolated in its own sealed container and left undisturbed for several months. Each container housed one can of oxide and something to facilitate the test. One was an open container of water alongside the supposedly sealed can in one container. Another had a bowl of desiccant which would deprive the atmosphere inside

the container of any moisture at all. A third container was evacuated to house the oxide can in a vacuum. The fourth container was equipped with a fitting to permit the its interior to be flooded continuously with pure oxygen.

The results of this several-month-long study were surprising. The only can to exhibit any change in weight—specifically, a weight gain—proved to be the one exposed to excess oxygen. The other three cans did not change weight at all. The conclusion of this peripheral study was that the uranium oxide was very slowly oxidizing within the cans.

A theory was conceived by this author to explain the observation. If it lacks credibility, the blame is his alone. That theory involves the several possible states of uranium oxide:  $\text{UO}$ ,  $\text{UO}_2$ ,  $\text{UO}_3$ ,  $\text{U}_2\text{O}_3$ ,  $\text{U}_3\text{O}_8$  and, possibly, some others. The contention is that the uranium oxide was manufactured in Ohio by calcination as  $\text{U}_3\text{O}_8$ . That is, the stoichiometrically stable form of uranium oxide formed at high temperatures is believed to be  $\text{U}_3\text{O}_8$ . Over a long period, the oxide in the cans may “burn” turning the state into  $\text{UO}_3$ . The chemical reaction proposed is that  $\text{U}_3\text{O}_8$  may be viewed as a collection of three oxides:  $\text{UO}_3 + \text{UO}_3 + \text{UO}_2$ . If this were true, the  $\text{UO}_2$  component could acquire another oxygen atom forming three molecules of  $\text{UO}_3$ . This is not an important point; but it does illustrate the variety of mental disciplines called into play in the nuclear industry.

This subject matter does not appear in the LANL Archives as a separate record. The topic is discussed in some depth in three quarterly progress reports (Refs. 301–n) published for the NRC by the Rocky Flats CML between July 1978, and March 1979.

### ***Boron Oxide Cannot Replace Sand in Making Concrete***

Including elemental boron in concrete is not as easy as it may seem; that lesson evolved along humorous lines. The first of two programs involving annular tanks were to include internal cylinders, referred to colloquially as “plugs.” These plugs would be lowered inside the annulus; and the boron would absorb neutrons. Plugs composed of earthen materials containing a designed amount of boron were engineered. The earthen materials were concrete and plaster. Three levels of boron were to be included: 0%, 1% and 3%.

Boron oxide ( $B_2O_3$ ) is cheap, readily available, and non-toxic. The first thought was to replace some of the sand with boron oxide. The plan sounded reasonable. Sand is silicon dioxide; so one oxide would replace another. A test mixture was prepared in a wheelbarrow. Sand, boron oxide, Portland cement, and an aggregate were mixed dry. Water was added while a worker mixed the ingredients. Shortly, the worker was seen shielding his face from heat and working with one hand extended from his body. He needed to remain a distance from the test mixture because of the heat. Something was wrong.

The mix remained dry longer than expected and then suddenly turned “soupy.” Next, a very surprising thing happened. The concrete appeared to set almost instantaneously as it radiated uncommon amounts of heat. The mystery was left overnight. The next morning chunks of the “set” concrete could be pulverized to powder in the bare hand. It had almost no strength.

The phenomenon was discussed with local experts in fabrication with concrete. They laughed but pointed out that boron oxide and water produce boric acid. Concretes cannot tolerate a great deviation

from a neutral pH; and this acid had shifted the mix to be highly acidic.

Tests were performed at the CML out of pure curiosity. Paper cups were filled with small mixtures of both concrete and plaster containing various amounts of boron oxide. None of these had any strength as illustrated in Fig. 117. Very little handling was needed to abrade the castings as shown. Boron oxide was *not* the right compound to use.

The problem was easily solved. Instead of replacing sand by some other oxide, some of the aggregate was replaced by minerals known to be rich in boron. These minerals had to be inert in water. Specifically, a commercial product called Gerstley Borate satisfied all requirements nicely. This is a combination of two minerals: Colemanite and Ulexite. One is a calcium borate; the other, a sodium-calcium borate. Several concrete and plaster plugs were successfully cast using these materials. Later, in another program, concrete slabs, to serve as neutron-absorbing reflectors and moderators, were cast containing boron by the same means.

### ***Concrete Casting Fails During Wet Pour***

One other event occurred during the preparation of these plugs. Over two dozen would be made; and these varied in outside diameter, inside diameter, radial thickness, and boron content although all were the same height. The outside forms were paper cylinders engineered for casting large, tall concrete pillars. These forms have a protective coating on the inside, but not the outside, to prevent moisture from the wet mix from soaking into the paper. All but three of the inner forms were the same kind of paper tubes. Those three used a metal sewer culvert stock. All sizes of forms were used; but two are illustrated in





Fig. 117. An attempt was made to cast boron-loaded concrete substituting boron oxide for some of the sand (silicon dioxide). Test samples in paper cups did not work because boron oxide and water form boric acid which changed the pH of the mixture. They had no strength whatsoever; the mix at the lower left had 3% boron and could not even maintain its shape.

Fig. 118. Concrete has just been poured into both of them.

In one case, the moisture of the wet mix softened the paper of the inner form—without the benefit of a protective coating against moisture—causing it to collapse. This happened on a thick radial thickness plug with a large outside diameter. The weight of the wet mix simply overcame the capability of the paper to resist water. That one plug ended up a strange hybrid geometry.

### ***Lifting Anchor Breaks***

Several programs over the course of many years at Rocky Flats were to be reflected by thick-walled concrete slabs. These panels would simulate walls in a production facility which also reflected neutrons back into a fissile assembly. Well in advance of the beginning of one study, a number of concrete panels were cast for this purpose. They all would be 2.44 m tall and 203 mm thick. Four of them would be 1.22 m wide. During subsequent experiments, these panels would have to be lifted



*Fig. 118. Boron-loaded cylindrical “plugs” were successfully cast using an inert boron-rich mineral instead of boron oxide. The mineral replaced aggregate instead of sand. Many were cast in different outside diameters and different radial thicknesses. They were cast at three nominal boron concentrations (0%, 1% and 3%) and of two earthen materials: concrete and plaster. These two concrete plugs have just been poured. One used a steel culvert as the central form.*

high in the air inside the building to be moved overhead into desired positions. They needed to be equipped with suitable lifting devices cast into the concrete.

One commercial “concrete anchor” was a product that resembled a truncated cone with a threaded reentrant hole. These would be cast into the wet concrete such that the smaller diameter circle and the hole ended up flush with the surface. The commercial product was called Starr Concrete Anchors. This style had been used a couple of times earlier in similar applications on experimental programs. They had proved to be very satisfactory.

The Rocky Flats Engineering Department was asked to engineer these slabs. Professional engineers would select rebar size and location and other aspects of the final product. One engineer selected a lifting device of a different design; and he remained firm in his resolve in spite of the past success of the conical design. The new device resembled a heavy coiled spring welded to four rod-like L-shaped brackets. Then, a specially designed “screw” with concave grooves to match the coiled spring would be screwed into the embedded unit for lifting. This design was used in spite of objections by CML staff. They pointed out the bottom legs of the four brackets might define a plane within the finished concrete that appeared, intuitively, to weaken the concrete.

Several panels were cast in the early summer of 1980. The work was done out-of-doors during a stretch of dry, sunny weather. The concrete was allowed to set undisturbed a number of days. Wooden forms were removed on June 6<sup>th</sup>; and a fork-lift truck, rigged as portable crane, was used to move these heavy panels about. One corner of one panel broke away from the rest of the slab during this initial handling. The break happened, as predicted, along the weakened plane at the

lifting anchor. A photograph of this situation is shown in Fig. 119. The design of the untested anchor is clearly visible; and the association between the metal and the location of the lifting device seems equally clear.

The lesson taken from this experience is to reuse proven technology and to be wary of untested new methods. In defense of these lifting anchors, no other problems developed even though other panels were lifted dozens of times in subsequent months using these devices. All remaining panels having these embedded devices were *probably* load-tested a number of times before use to ensure their serviceability when moved indoors. This action is not specifically recalled but would have been consistent with CML policy given the circumstances. The breakage is probably not to be attributed to any failure to allow adequate time for the fresh concrete to set. No other panels broke; and this was not the first one handled. One extenuating circumstance *may* have contributed to the failure; but this is not recalled confidently. The photograph shows one tine of the fork-lift truck near its top. This may have been used—like a crane—to rotate the set slab; and this action, in turn, may have subjected the anchor to a tangential force along the concrete’s surface. The design is, of course, intended to be used in pure tension applications. Still, the other embedded concrete lifting anchors had been used many times in non-tension applications; and they never broke the concrete. A second lesson is to use commercial products in a fashion for which they were intended.

Finally, even this breakage would probably not have occurred if whatever embedded anchor product had been welded to one of the rebars buried in the concrete. This weldment was specified in all later designs. This breakage was never documented previously; so no other references can be given.



*Fig. 119. This lifting anchor cast into a concrete wall section formed a weakened plane where four L-shaped rods fanned out. This break happened during manufacture before the wooden form could be removed.*

### ***Pigeons and the South Door of the Assembly Room***

The south door of Room 101 exposed a potentially contaminated room directly to the out-of-doors. The pair of steel doors and the cast concrete shield door are described elsewhere. The Shield Door was driven by a 3.5 horsepower electric motor causing the door to roll slowly along a rail. Several small-diameter wheels supported the weight of this heavy door as it opened slowly.

On one occasion after a few years of disuse, the door refused to respond to attempts to open it. The motor was not burned out; it could be heard groaning. The door tried to respond but simply would not move more than a few millimeters. The problem was traced to a plethora of pigeons having roosted there for many years. Their accumulated droppings built up a barrier strong enough to stop even that strong motor. A metal shield, designed to protect the mechanism from the elements, served two other purposes. It also protected the birds from wind and rain; and it did not allow anyone to notice the slow buildup of droppings. Once cleaned away, the door functioned perfectly.

The metal shield was returned to service; but a second (open-meshed) screen was designed and installed to fit around any open space. The birds were denied a home. The open-mesh screen was also designed to be easily removed temporarily when the door needed to be opened. The solution worked well.

### ***Improperly Reassembled SCRAM Valves***

The two large-diameter SCRAM valves used with uranyl nitrate solution experiments were responsible for the next problem. About 7 liters of 380 gU/l passed onto the stainless steel floor of the Assembly Room Hood in the experimental room. This occurred on November 25, 1980, during an experiment. The cause was a recently reassembled SCRAM valve which had been improperly rebuilt [LANL: box 28, folder 12].

Four days earlier, experiment #2-9-23 had been aborted because solution had leaked through one of the SCRAM valve's seat, allowing the solution to enter the SCRAM tank. This was not a leak *out* of the closed system; so no contamination was associated with this November 21<sup>st</sup> problem. The leak did impact the ability to perform experiments. This leak into the SCRAM tank prompted it to respond as though it were "not empty." This, in turn, caused both SCRAM valves to open. An experiment cannot be performed with the SCRAM valves open; so workmen were called in to refurbish the two SCRAM valves. They installed new O-rings and generally cleaned up the valves.

The later leak was traced to an incomplete reassembly of the valve after it had been serviced. All bolts had been reinstalled and their nuts tightened only finger tight. They had not been tightened with a wrench. The valve *looked* assembled; but it wasn't. Maintenance personnel were embarrassed.

The errant solution was vacuumed up in the same vacuum cleaner used in an earlier incident. Unfortunately, the glass rings were quite dirty. The decision was made to pick up the small amount of solution into dirty rings rather than wait for

clean rings to be installed. The collected solution was described as “an olive-green liquid with a grey scum floating on top and a grey sediment at the bottom.” This liquid was filtered and returned to one of the storage tanks. The only discarded uranium was in the precipitated solids and materials associated with decontamination.

### ***Aluminum Pin Sheared During Demonstration***

The next lesson learned was really not a problem at all. It was, instead, a glowing example of the experimental safety preview process working at its best. The incident has some humorous aspects. It has never been documented before this writing so it cannot be found in the literature.

A study was planned involving arrays of plutonium metal cylinders. As many as 27 cylinders were to be held in a 3×3×3 array in a large tank; and that array was to be reflected and moderated by water. These experiments, then, would involve 81 kg of plutonium metal in a tightly packed array and submerged in water. Criticality safety specialists will recognize the gravity of such a configuration. Each plutonium cylinder was canned in two containers, one inside the other, to preclude the adverse effects of water contacting fissile metal. The first container was aluminum and mild steel. The second containment was a thick-walled, machined, stainless steel container consisting of two halves glued together. Vertical stacks of three fissile components were to be slipped into a carefully rolled “sleeve.” The sleeve was made of perforated aluminum metal. The inside diameter of the sleeve fit closely around the stainless steel outer containers.

The vertical spacing between units would be maintained by passing metal pins

through diametrically opposed holes in the perforated metal. Water could pass freely through perforations ensuring that the neutronic influence of each increment of water would be promptly seen by the detectors. Even though the outer container was machined from stainless steel, the hope was to minimize the amount of this material in the experiment. Lengths of 3.18-mm-diameter aluminum welding rod stock were selected to serve as the pins. They slipped nicely through the 3.2-mm-diameter holes punched in the perforated stock.

Well in advance of the first experiment, the entire written Experimental Plan was subjected to a safety review by a consortium of knowledgeable Rocky Flats employees. The intended plan was presented for their approval. One of these asked how the plutonium cylinders would be spaced vertically from one another. A demonstration was offered. One doubly-contained unit had been prepared with the plutonium (19.6 mg/mm<sup>3</sup>) replaced by a lead cylinder (11.6 mg/mm<sup>3</sup>). The model showed how the fuel units would be prepared and could be used in any such demonstrations. The lead substitute was placed at the top of a sleeve with an aluminum pin inserted near the bottom. The stainless steel cylinder was allowed to slide down the sleeve toward the waiting pin. The sharp machined edge of the machined piece sheared through the aluminum pin as though cooked spaghetti had been used. Members of the review panel laughed and this author blushed. Stainless steel was used in spite of adding to the amount of that unwanted substance in the experiment.

## ***The Plutonium Cylinder Contamination Incident of 1983***

The plutonium metal cylinders had come from Lawrence Livermore Laboratories (LLL) in the 1970s. They had been used there in a number of experiments and were transferred to Rocky Flats for further experimentation. As received, they were contained in the thin-walled aluminum cans with steel lids; and all this has been described in another section. Staff at the Rocky Flats CML designed the two-piece, stainless steel, secondary container. These, too, were described elsewhere. These doubly-canned plutonium metal cylinders had been used in a great many experiments at Rocky Flats. Almost all of these experiments involved immersing the sealed units in water; and that procedure led to one of the most serious contamination events in the CML's history.

Several factors combined to produce the dreadful events discovered January 12, 1983. Some small contamination had been detected on the floor as early as December 20, 1982; but this was not even initially attributed to plutonium. The January discovery really marked the beginning of this incident. Plutonium metal is a copious alpha emitter. These alpha particles give up their energy as they come to rest within the metal. Consequently, plutonium metal is quite warm to the gloved touch. This heat was conducted to the stainless steel outer containers such that they, too, became quite warm. Each evening, each unit would heat up to some equilibrium temperature. The water used in the next day's experiment would thermally shock them down to the temperature of the water. This process was repeated many times over a number of experimental programs spanning many years. Thermal cycling produced stresses on the rubber glue used to hold the two

halves of the stainless steel together. Quite possibly, that bond had also been weakened by constant gamma radiation from the plutonium metal itself.

Sometime prior to December, 1982, these glue joints began to fail. Minute amounts of moisture would find their way through the secondary container and touch the inner container. This moisture was effectively stopped—for a while—by the aluminum can with the steel lid. Aluminum withstands water corrosion very well; and even steel would take a very long time to rust through. The joint between the two metals, however, was quite vulnerable to water vapor. This joint was merely a rolled connection similar to that found on a food produce can; it is in no way perfectly leak tight. Once moisture worked its way through this container, problems began in earnest. Water is highly reactive with bare plutonium metal. Plutonium compounds formed and were constrained to a volume previously occupied only by pure metal. The metal is very dense; but compounds, much less so. They had a density of only about 11 mg/mm<sup>3</sup>—considerably less than two-thirds the metal density. Neither container had sufficient capacity to contain the growing amount of plutonium compound. The uncontainable compound, in time, pushed the lid of one container away from its bottom half and spilled the yellow-green contents all over the floor of the experimental tank in use. A serious contamination incident involving plutonium had occurred.

The chronology of this event is described below in some detail. Original documents are archived at LANL in box 28, folders 13, 14, and 15. A complete set of photographs, a few of which are included in this paper, will be donated to the LANL Archives sometime during the early 2000s. At present, they reside in this author's possession. Another quite

complete documentation of this entire situation is contained in a fairly recent document in the literature (Ref. 2).

### *Discovery of the Problem*

The morning of January 12, 1983, dawned ordinary. Experimenters from the CML reported to work prepared to perform another in the series of critical experiments involving plutonium. The previous array, containing a little over 81 kg of plutonium, had been unchanged since water from the last experiment had been drained away. The 27-unit array occupied a cubical space less than half a meter on a side and stood centered in an open-top, thick-walled, clear, plastic tank.

An inspection of the experimental apparatus that morning revealed an alarming sight. A small handful of a light yellow-greenish dust lay strewn around the floor of the tank. This powder can be seen just to the right of center in Fig. 120. The substance was unevenly distributed within an irregular region about 0.3 m across as shown eight days later in Fig. 121. It lay just below one corner of the array and could easily be seen through the thick, but clear, walls. The first thought was to wonder what foreign substance had fallen or blown into the tank.

Scanning up the corner sleeve, an uncharacteristic outward dent in the vicinity of the middle can in this sleeve was quickly noticed. The aluminum was sharply bent. Naively, the two abnormalities—powder on the floor and a dent in the sleeve—were not connected at first. A still-closer look at the sleeve revealed a wedge-shaped band of the same green granules at about the mid-section of that same can. This situation is shown in Fig. 122, although the loose plutonium compound appears grey in this black/white photograph. The two events were now

connected. Something was definitely abnormal.

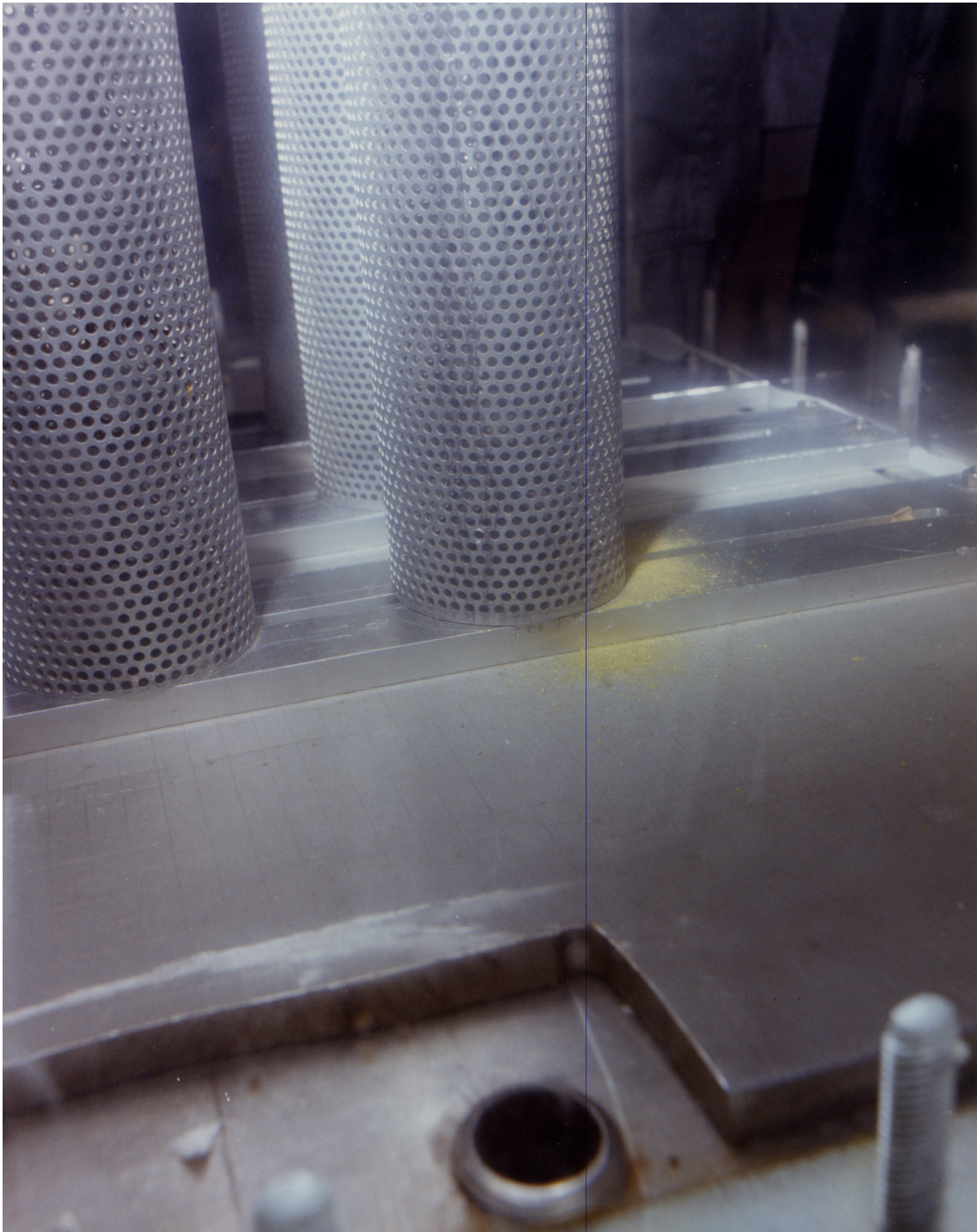
The top half of the stainless steel can had been pushed upward and canted jauntily to one side. It was this tip of the can's lid that had dented the sleeve. With disbelief, the observers finally recognized the full scope of the situation. One can had ruptured and, somehow, a plutonium compound had formed. These have lower densities than pure metal; so they would require much more space than available within the inner can and, evidently, even within the spacious tolerances of the larger can. The compound had continued to grow until it pushed against the outer can's glued-together seam. The halves separated and dented the sleeve; and the compound leaked through the holes in the perforated metal of the sleeve and fell to the floor of the tank.

The puzzle was quickly pieced together further. Water was the most likely foreign material to contact the bare plutonium metal because the cans had repeatedly been immersed in water. The sealant had been expected to prevent this. Evidently, this expectation was not realized. The incompatibility of water and plutonium is well known.

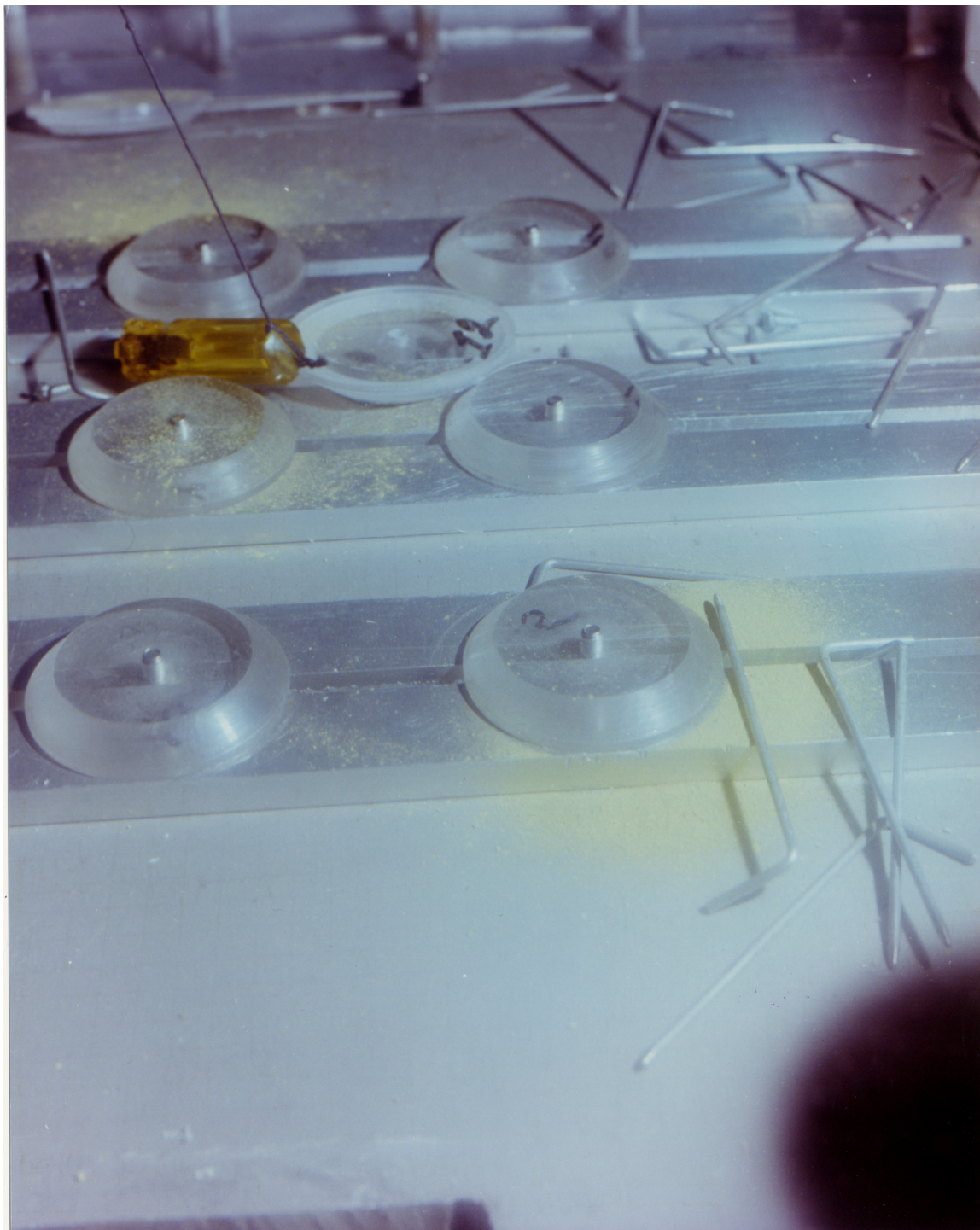
### *Initial Response*

This situation constituted a serious radiological emergency. Prompt—but critically safe—actions were called for. That the compound seemed to be well-contained at the bottom of a deep (even though open-topped) tank was quickly noticed. Another fortunate happenstance was the lack of any air turbulence within the room. The room was quickly posted to forbid casual entry, the manager of the CML was notified, and the radiation safety technician was asked to perform a careful survey of areas around the *outside* of the tank.

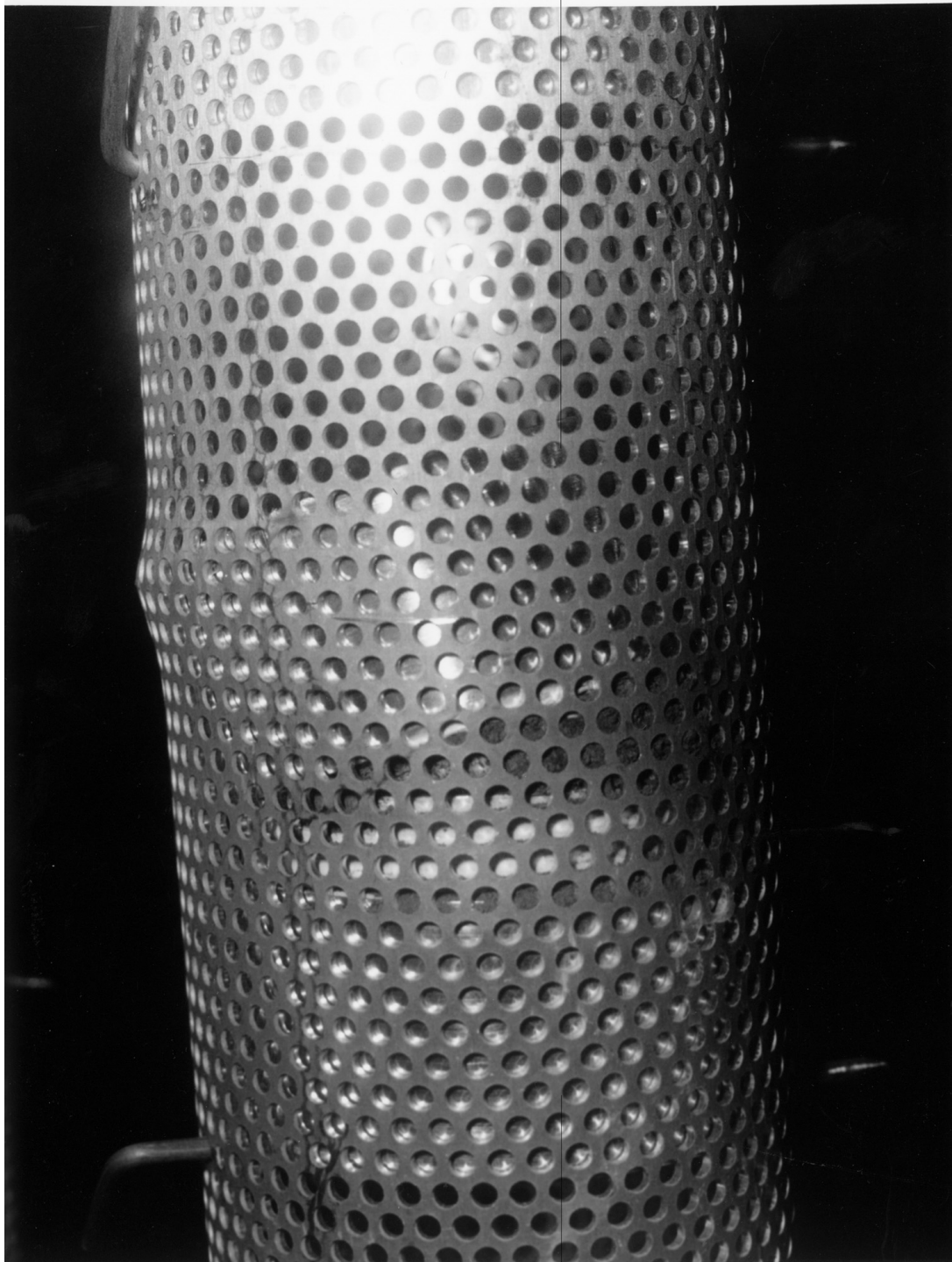




*Fig. 120. Plutonium compound was discovered on the floor of an experimental plastic tank the morning of January 12, 1983. The yellowish compound can be seen near the bottom and just to the right of the righthand forward sleeve. Each sleeve contained three vertically-spaced cylinders containing about 3 kg of plutonium each.*



*Fig. 121. Eight days later, all sleeves containing 81 kg of plutonium had been removed and the plutonium returned to the production stream at Rocky Flats. The extent of contamination within the plastic tank is clearly visible. Fortunately, contamination had been contained within the tank by a plastic sheet taped over its once-open top.*



*Fig. 122. Plutonium compound, appearing dark in this photograph, had pushed the stainless steel lid of the cylinder's secondary container upward. This tilted the lid, dented the sleeve, and permitted the compound to fall to the floor of the plastic tank. The pin used to position the cylinder vertically within the sleeve can be seen at the bottom of the photograph.*

This survey began a considerable distance from the scene and worked its way inward, a standard practice for contamination incidents. The goal of this last action was to determine if, indeed, the contamination was contained, as hoped, within the tank. Fortunately, the survey confirmed that point totally. Surveys also found no contamination on the horizontal top edges of the plastic tank's walls. The only plutonium contamination was confined to the interior of this plastic tank.

A length of flexible, heavy-weight, plastic sheet was cut to size large enough to cover the top surface of the tank and fold down over the sides a significant amount. This sheet was slowly and carefully positioned without disturbing the dust on the floor. It was neatly folded down over the edges of the tank and taped in place with wide vinyl tape. This formed a "lid" for the previously open tank.

All water had been drained back to the reservoir after the last experiment. The possibility was recognized that the water might have become contaminated depending on exactly when the leak happened relative to the end of the last experiment. Both SCRAM lines were disconnected at the reservoir end and examined. Fortunately, they, too, showed absolutely no contamination. Droplets of water clinging to the plastic tubing were, likewise, not contaminated. The water in the reservoir was also uncontaminated. Evidently, all loose plutonium was, indeed, contained to the interior of the clear plastic tank.

The immediate emergency had been stabilized; and a little more time could be taken to think through the next actions. Still, some urgency remained because the condition of the other 26 cans was not known. A careful visual inspection through the walls of the tank and the perforated metal of the sleeves revealed no other compound nor stainless steel cans with

partially separated seams. All cans could be seen clearly, even in the central sleeve.

### *Plutonium Returned*

Many plutonium experts from around the plant gathered within that first hour to map out strategy. It was agreed that all 27 plutonium cans should be returned immediately to the production stream at the Rocky Flats Plant. Their condition was a mystery. This was accomplished by carefully removing the nine sleeves, one at a time. The cans would not be separated from their sleeves until relocated to another building. Each sleeve was removed from the experimental array by hand and slowly pulled up into a waiting flexible plastic sleeve considerably larger than the metal sleeve. The dented one containing the leaking cylinder was saved until last. This entire operation was closely monitored by a team of radiation protection personnel. The removal proceeded smoothly with no further spread of contamination.

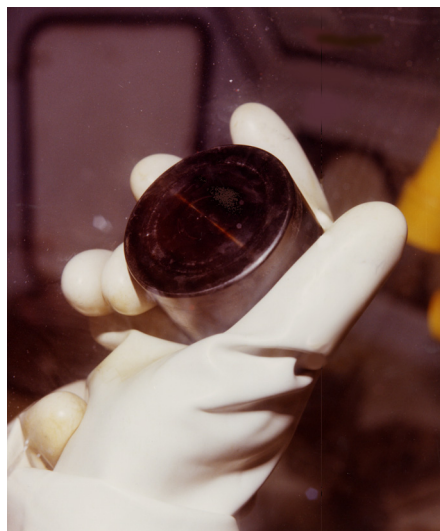
The bagged sleeves were loaded into a shipping container, although specifically which type of container was used is not recalled. They were shipped to two or three buildings on plantsite within a few hours of first discovery. To everyone's credit, *no worker was contaminated nor did contamination ever escape the tank during this entire operation!*

The status of stored cans which had not been part of the fated array was also suspect. The decision was made to return these cans, too, to the same production buildings. That is, the CML would divest itself of all plutonium metal that same day. The condition of each stainless steel can was totally unknown; so great care was exercised when handling these suspect cylinders. That long and tedious operation was completed about 4:00 AM after which weary workers returned home to sleep. Happily, the situation was fully stabilized.

*Physics of the Problem*

The following scenario is believed to be the cause of the problem. In the first experimental program between 1973 and 1976, the stainless steel cans were exposed to a great many thermal cycles. The cans did not leak because the sealant was fresh and served its purpose well. A few years passed between the two experimental programs. During this time the sealant apparently deteriorated. Sometime during this second study, a very small amount of water found its way into the outer can of at least one fissile unit. The aluminum would have resisted this water forever; but the can did have a steel lid. Evidence reveals that this steel did not rust through. Instead, the water evidently seeped through pin holes in the rolled joint between the two metals. This moisture began to attack the metal. This, in turn, led to the resultant contamination incident.

Recovery of the plutonium was very revealing. Returned plutonium metal was removed from its double containment in other buildings and, of course, within the confines of gloveboxes. This author was present at the opening of a few. Most of the bare plutonium appeared to be in excellent condition. They were black, as expected, and showed no evidence of attack from water. Figure 123, taken January 26, 1983, shows the excellent condition of one of these unaffected cylinders. Black is the surface oxide coating which quickly forms on this silver-colored metal. A few aluminum cans, however, revealed that the same catastrophe was imminent. Fig. 124 is an example where the side of the aluminum can has split open by the expanding compound. A second example shows that some inner cans were merely coated with a surface deposit resulting from water vapor repeatedly being evaporated to dryness between experiments as shown in Fig. 125. Some water attack was so bad that the cylinder fell into two pieces during the uncanning operation (Fig. 126).



*Fig. 123. All plutonium cylinders were removed from their double containment and returned to the production stream at Rocky Flats. This cylinder shows no evidence at all of any attack by moisture. It is black in color as expected. This photograph was taken January 26, 1983.*



*Fig. 124. Some plutonium cylinders showed evidence a similar event was imminent. This can's side wall had split open; but no oxide had yet filled the secondary container. This photograph was taken February 24, 1983.*



*Fig. 125. Some inner containers showed evidence they had been in contact with moisture; but that water had not yet penetrated. Because of the mechanical seal between aluminum can and steel lid, an eventual problem would have been almost a certainty. This photograph was taken January 20, 1983.*



*Fig. 126. Some plutonium cylinders had been so badly corroded by water vapor they fell in two during the uncanning operation. This photograph was taken January 20, 1983.*

## ***Plutonium Metal Cylinder Spontaneously Ignites***

The drama of this event did not end there. A second unpleasant happening occurred during post-incident activities. One sleeve containing three apparently undamaged stainless steel cans had been transferred to a Rocky Flats analytical laboratory before being returned to production. The purpose of this extra step was to determine the status of apparently unaffected plutonium. The entire sleeve was bagged into a glovebox and one can extracted from it. The rubber sealant was still strong; so its grip had to be broken loose before the inner can could be accessed. That aluminum can was opened in a glovebox; and the bare plutonium cylinder was set upon the glovebox floor.

The fissile metal was black in color, as expected; and it appeared to be in excellent condition. While uncanning debris was being gathered up, this author studied the fissile piece through the window of the glovebox. He had never seen the bare metal before; yet it had been the subject of so many experiments over so many years.

Within a moment or so, a surprising event occurred. The surface began to emit sparks—much like a 4<sup>th</sup> of July sparkler. The author, not a plutonium metallurgist and seeking to understand, inquired what might be happening. The utter astonishment of those who understood would have been comical if they had not been so serious. They immediately recognized that the glovebox contained air—not nitrogen as thought. Nitrogen is an inert gas unable to support combustion. Plutonium, it was explained, must never come in contact with air. The cylinder was about to combust in a flameless, rapid, oxidation; and nothing could be done to stop it.

The oxidation could be controlled, however; so a bag of magnesium oxide sand and a stainless steel can about the size of a shoebox were quickly bagged into the glovebox. The sand was emptied into the box forming a thick heat-insulating cushion. A metal tongs was used to lift the cylinder, then glowing a dull red, into the box and onto the sand. The glow brightened and reddened toward an orange-red while all concerned stood helplessly by. At its brightest, the plutonium cylinder and a glowing charcoal briquette at a

picnic cookout would have looked the same. The can burned itself in half as seen in Fig. 127 in about half an hour.

After the conflagration was over, a pile of plutonium oxide ash resided where the cylinder had been. The color of the burning metal appeared on the faces of the technical staff. A mistake had been made. The wrong gas resided in the glovebox. No more cans were opened in an oxygen atmosphere. Even though the destruction of this one cylinder was an unplanned event, it is important to recognize that no harmful



*Fig. 127. One plutonium cylinder was uncanned in a Rocky Flats laboratory. The glovebox selected for this operation unknowingly contained an air atmosphere. In short time, sparks began to be emitted from the surface of the now-bare plutonium. The entire cylinder turned a dull red within a few minutes which allowed time to introduce a metal box with a layer of sand in the bottom. The cylinder was placed on the sand and allowed to combust completely. It looked like a glowing charcoal briquette at the stage shown in this January 19, 1983, photograph.*

consequences resulted. No person was hurt or contaminated. No contamination outside the glovebox (which was already heavily contaminated internally) occurred. The cost of recovery was small. No plutonium was lost; all was recovered from the sand.

### ***Nuclear Reactor Period Exceeded***

The next problem was termed a “personnel error.” A claim had been made that the “indicated reactor period” specified in the Experimental Plan in effect for the experiment in progress had been exceeded during one reactivity addition increment. The date was February 16, 1984; and the reported time of the incident was 10:06 AM.

The Experimental Plan specified: “In practice, the indicated (reactor) period will be kept longer than one minute.” This administrative goal was conservatively longer (4 times) that the reactor’s SCRAM setting of 15 seconds. This, in turn, was conservatively longer than the facility’s “Safety Limit”. A Safety Limit is, by definition, the point at which some damage *could* occur if ever exceeded. This had been somewhat arbitrarily set at two seconds when writing the Technical Specifications. In reality, no damage would truly be expected from such a period. The TRIGA reactor in Denver routinely attains its power level on a two second period. Still, the successive protections of two seconds, 15 seconds, and one minute had been adopted and approved.

Near the end of the experiment in question, the neutron source was being removed in alternating increments with very small solution additions. The object of this often-performed procedure was to place the no-longer-necessary source a considerable distance away while maintaining a reasonably high neutron flux.

The third incremental solution addition following the third tiny source movement caused the indicated reactor period to dip to 45 seconds, an apparent violation of the period allowed.

Two technical factors should be understood in evaluating the seriousness of this alleged violation. One, the instantaneous neutron reactor period is truly a statistical parameter measuring the rate at which the neutron flux is falling or rising. It is so full of statistical “reactor noise” that, in reality, it varies wildly between very fast positive and equally fast negative periods. Only the time average over some reasonably length of time makes any sense at all. Viewed instant by instant, the limit would be violated all the time—even far from criticality. The reported dip to 45 seconds lasted a very short time. The defense submitted that the time-averaged reactor period was really much longer than the limit.

The second factor concerns the complex neutronics in effect as competing actions are taken this close to criticality. Source removal can introduce a very sudden and large decrease in the observed neutron flux. On the other hand, solution increments this close to criticality can result in fairly large reactivity additions. One effect masks the other; and the goal was always to balance the two so the time average reactor period remained within the limit. Very slow solution additions can be controlled in two ways. The pumping rate of the pump can be slowed down; so its electrical control can be powered more or less continually. The second way of achieving the same effect is to allow a slightly higher pumping rate but activate the pump for much shorter intervals of time. The pump in use on this date was the slowest pump available. Its output was a little more than one liter per hour.



Slower rates were not very dependable. The decision had been made years earlier to use the second method with shorter bursts at a slightly higher rate.

By 1984, reporting procedures for occurrences had become quite extensive. A Supervisor Investigation Report (SIR # 84-2-886.1) was written February 22, 1984 [LANL: box 28, folder 16]. Beyond that, no further consequences are recalled.

### ***Small Leaks of Uranium Solution***

A very small leak inside the walk-in hood within the experimental room was discovered during the Poison Tube Tank program. Events related to this study spanned July 9 to 20 of 1984 [LANL: box 28, folder 17]. A small quantity of dried solution salts had been noticed on the floor of this hood. That was not too disturbing since containment of such small leaks was one purpose of the hood. On Monday, July 16, two workers noticed a “somewhat large” quantity of salt crystals on the floor. These were underneath a flange near the sight gauge and in the southwest corner of the hood. These workers estimated 400 g of salt crystals had collected. The next day, a worker arrived to tighten the flange; and about an additional liter of solution spilled onto the floor. This occurred while he was repairing the leaky flange.

The combined spills were being cleaned up that afternoon when an unrelated event happened. This combination of occurrences is one of two reasons for including this otherwise rather routine event. Perhaps there are lessons to be learned. While cleanup was in progress, the Instrument Technician accidentally caused a Building Alarm while doing some unrelated testing on one of the instruments.

Response to this alarm is mandatory. It calls for immediate evacuation to an outdoor location well removed from the building. The combination of these two circumstances placed four possibly contaminated workers in this out-of-doors setting. Quite possibly, work on an instrument which could reasonably initiate such an alarm should have been deferred to a time when other workers were not dealing hands on with fissile material.

The two-page-long handwritten report states that there was “only minimal contamination removed from the hood.” Although not recalled for certain, the four possibly contaminated workers were probably segregated when they arrived at the outdoor assembly area. Again, good fortune may have prevented a serious environmental impact.

The repairman returned on Thursday, July 19, to complete his task. In spite of his very cautious efforts, an additional half-liter of solution leaked onto the floor before he could close the flange once again. At this point the CML staff person, a relatively inexperienced one, realized his mistake. Two identical leaks had occurred in a short span because of the same oversight. Because the experiment was in the SCRAM mode, valves had closed automatically and had trapped fissile solution in the horizontal line to be worked upon. Under these conditions, the worker’s efforts to work on the flange would *always* precipitate a leak. He then drained the lines in question by opening appropriate valves; and the flange was repaired without further incident. The entire maintenance task had not at all been thought out nor discussed with others.

### ***Boron Oxide is Hygroscopic***

The Poison Tube Tank experiment became the basis for another humorous event which belies a lack of understanding basic chemistry. Thousands of paper tubes were purchased to be filled with a number of neutron-absorbing powders, chemicals, and minerals. Paper tubes were long hollow pencils designed to slip-fit inside the stainless steel tubes of that program. About 450 of each material were prepared; and many contained boron. One boron compound was boron oxide. The warm, humid summer of 1984

demonstrated that boron oxide is a desiccant. Absorbed humidity weakened the paper tubes causing them to split apart at the seams. Figure 128 shows the sagging tubes on the left. Unaffected tubes, filled with some other neutron-absorbing compound, stand intact to the right. This event occurred before these tubes ever were used; and that material was simply excluded from the list of absorbers studied.



*Fig. 128. The Poison Tube Tank was to have used a number of different neutron absorber materials. Some of these were solid; but some were powders and had to be contained. Long, thin paper tubes made of spiral-wound laminations formed that container. Several powders, such as borax, cadmium oxide, and others worked well as witnessed on the right side of this photograph. Boron oxide did not. The material is hygroscopic; and absorbed water caused the tubes to weaken and unwind as shown on the left.*

## ***A Personnel Contamination Incident***

A personnel contamination incident happened on Saturday, February 14, 1987. Two sheet metal workers were to perform operations on apparatus associated with the Shielded Annular Tank experiment. In particular, they were to remove a large, cylindrical sleeve which had been immersed in fissile solution during a number of previous experiments. A similar sleeve—not the contaminated one—can be seen suspended from a crane in Fig. 129

above the tank. This one is not yet contaminated. Sometime in the early afternoon, both workers discovered they, themselves, had become contaminated. In addition to company-issued clothing, both men were contaminated on the hands and about the face. Contamination levels were somewhat significant but not extreme. Body parts were easily decontaminated; clothing was discarded.



*Fig. 129. Stainless steel, thin, cylindrical sleeves were used as “reactivity shims” in the Shielded Annular Tank program. Improperly moving one which had been immersed in high concentration fissile solution had caused wide-spread contamination of personnel and equipment. This occurred February 14, 1987. This photograph shows a different-but-similar shim before it ever became contaminated about to be lowered into the tank. The upper part of this figure was also used earlier to illustrate another feature.*

Portions of this occurrence are recorded in the Archives [LANL: box 28, folder 18]; but the documents there are not very complete in the opinion of this author. They address the extent of the contamination, actions taken to decontaminate personnel, and a considerable discussion about the failure to use a safety review form called a Work Permit. The Supervisor Investigation Report (SIR #87-2-886.1) even states that “The source of the contamination cannot be determined.” It also states that “no further evaluation is required” and that “corrective actions have been taken.” Archived records do not pursue the matter further. They should have.

This author recalls the situation differently. The Shielded Annular Tank was a large diameter vessel open at the top. Inner and outer tanks nested to form an annular region which routinely received uranyl nitrate solution. The annular region was a little too thick to attain desired critical heights, so thin metal shells, called “reactivity shims,” had been installed to reduce the solution thickness. The shim was to be removed using the heavy-duty, overhead crane. Although it had been immersed in concentrated uranium solution a number of times in recent months, it never had been rinsed or flushed. Dried yellow cake was still obvious on its surfaces. The goal was to remove it; but no detailed plan had been discussed. Workers simply planned to raise it out of the annular region in incremental steps. As contamination became exposed, it was to have been washed. One logical flaw in this plan concerns the inside surface. It could not be reached at all.

At some time during this questionable procedure, the shim evidently was bumped, banged into the side of the tank, or some other action caused the shim to vibrate like a resonating bell. This caused dried ura-

nium salts to become airborne which, in turn, probably caused the skin and clothing contamination observed.

The shim was lowered back into the tank while the more significant personnel contamination issues were tended to. As recalled these many years later, contamination of nearby equipment and surroundings was much greater than implied in the report preserved in Archives. A long-term controversy ensued as to which organization, CML staff or the sheet-metal workers, should perform the decontamination.

### ***Another Personnel Contamination Incident***

The next incident was actually related to the previous one. The shim removal task was resumed on March 10 to 13, 1987. Health Physics personnel had “suggested” that the shim be wet before moving it to hold down airborne contamination; but the maintenance workers elected not to do that. They claimed contaminated liquid might leak onto the floor. Because of this decision, another contamination incident occurred. Body parts as well as additional floor and equipment areas became contaminated. Work on March 10 and 11 proceeded without incident; but the next two days resulted in some contamination problems.

The underlying factors behind this repeated problem seem petty and out of place in the nuclear industry. Maintenance workers were annoyed over their assignment to decontaminate the room following the earlier shim incident. Apparently, they approached resumption with some hostility. After the March 13 incident, workers filed a “Safety Concern” claiming the room’s air flow patterns were inadequately designed. The room air filters and the location of the Selective Air Activity Monitor (SAAM)

were argued to be improperly placed. This seemed to be a deliberate attempt to shift blame away from inadequate safety practices toward facilities design [LANL: box 28, folder 19].

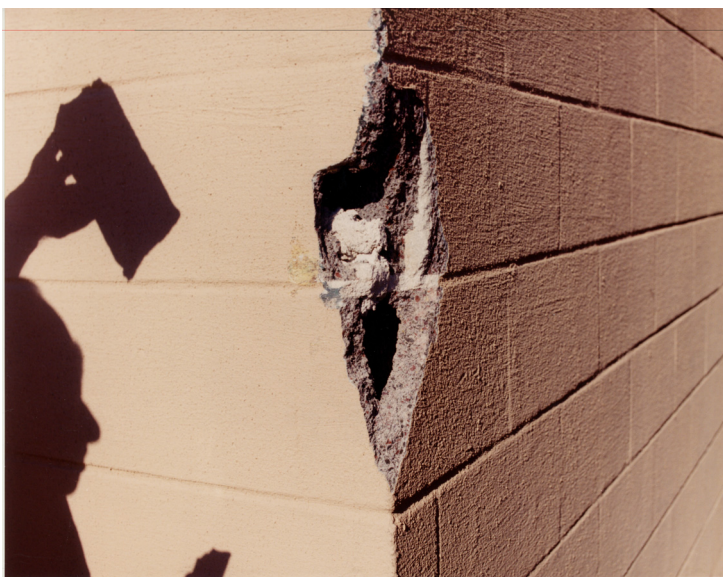
Very similar work had been performed in this area for over 20 years with no previous problems associated with either air flow patterns or filter or sensor location. The location of the sensor, in fact, had been indicated by the Health Physics Department.

In retrospect, the entire handling of this whole movement of heavily contaminated reactivity shims in and out of an experimental tank was not at all properly handled by any parties.

### ***A Vehicular Accident***

A vehicle accident occurred on March 23, 1988. A plant truck hit one corner of the building and broke the corner off two cinder blocks. The room affected on the outside was Room 102 which housed all of the CML's non-liquid fissile material. At the time, it contained a large inventory of enriched uranium metal and an even larger holding of low-enriched uranium oxide. The room probably also housed a few neutron sources. The reason for discussing this minor incident is that the affected room contained fissile and accountable materials.

A photograph of this accident appears as Fig. 130. This room-addition to the building's initial construction had been built of cinder blocks and these back-filled with mortar as discussed in another section. The presence of this mortar is clearly visible in the color photograph. The incident, initially, was not thought worthy of reporting nor recording; so, even though the accident took place in March, this photo record of the event was only made some months later.



*Fig. 130. A Rocky Flats vehicle backed into the corner wall of the outside of the storage room for fissile metals and oxides (Room 102). No damage occurred inside the room; and the revealed section view of construction materials shows the concrete which had been used to back-fill holes in the cinder block.*

### ***Tar Leaks Into Building During Roof Repair***

The next external problem to happen to Building 886 occurred around the 20<sup>th</sup> of June, 1988. The composition roof originally installed in 1964 had been declared in need of replacement; it had served about 25 years. Original materials were stripped away and a fresh coating of hot tar and gravel applied. That removal exposed numerous small holes related in some way to initial construction. Fresh tar passed through those holes and splattered all over much of the inside of the building. Most rooms affected were on the west side of the building. Major deposits were found in the Mechanical Equipment Room and the adjacent Janitor's Closet; but some additional leakage is recalled to have happened in the fissile solution storage room (Room 103). Figure 131 shows a corner of one of the non-fissile rooms most heavily affected.



Figure 132 shows the source of these small holes in the steel panel roof. Lengths of steel angle stock resembling a tent stake had been driven through the paneling. The reason for these penetrations is not recalled; they may have something to do with high winds often encountered in this part of Colorado. This figure also serves as a good illustration of the roof construction and its connection to walls. This applies to all areas of the building except the experimental testing room (Room 101).

*Fig. 131. Building 886 was almost 25 years and a new roof was to be installed. The old roof had never leaked but was removed to provide a fresh surface for a new tar-and-gravel composition. Fresh tar leaked through openings and damaged rooms inside the building. The janitor's closet had tar splattered onto walls and rolls of plastic sheeting.*



Fig. 132. Metal spikes driven through the metal pan roof formed the path for the tar to leak inside the building. The room shown is the janitor's closet.

### ***Broken Cable on Criticality Alarm System***

A broken electrical cable connection was discovered in September of 1988. The problem is apparent in Fig. 133; but the cause of the defect is not at all recalled. The problem has some importance because the equipment to which the cable attached was part of the building's Criticality Alarm System. That fact is not certain; and the figure does not clearly confirm it. The incident had been forgotten until this photograph was discovered in the Archives [LANL: box 28, folder 24]. No written information exists in that folder. The building was apparently beginning to show its age by the later years of the 1980s.



*Fig. 133. A broken electronic cable, discovered in September, 1988, was associated with the building's criticality alarm system. The damage was repaired before any consequences occurred; and alarm coverage was never lost.*

### ***Waste Water Leak at Outdoors Holding Tank***

Very low level uranium-contaminated waste waters had been transferred from the Waste Holding Tank (Tank #440) in the underground Holding Pit for the first few years of the CML. During the last few years of use, though, this very low level uranium-contaminated water was transferred into a portable tank called the Portable Liquid Dumpster (PLD). All waters passing through this tank were discarded into an open-air evaporation pond located on the Rocky Flats site. To qualify for admittance to the PLD, water had to be so low in uranium content that it could be safely drained into this pond.

In spite of such low contamination, a sign was affixed to the tank declaring it to contain "Contaminated Liquid." That

process had stopped by the mid-1970s; so the tank had not been used after that time. It had remained where it was all those years because no funds had been appropriated to remove it and decommission it properly.

This tank could have been left free of Raschig rings; uranium content was that low. The tank had, however, been filled with rings just as a precautionary measure; and that decision precipitated a "contamination incident" discovered September 26, 1989.

The tank had sat idle for about 15 years after use ended, exposed to alternating seasons. Humid air drawn into the tank in the summer would condense on the glass surfaces in cooler weather. A decade and a half was required to collect any significant



amount of water. Lack of any maintenance over the same span led to a deterioration of the gasket material of the bottom manual valve. Some of this condensation was found to have dripped onto the concrete pad on which the PLD rested.

Because of the sign affixed to the tank, the drip leak was assumed to be fissile solution. That spot was between 100 and 130 mm in diameter. *Very low levels* of contamination were found on the valve body and the concrete below it. Most of that was “non-removable” (not easily wiped up). A very little was easily washed away with soap and water. The scene after cleanup is shown in Fig. 134. The

tank was shipped away for proper disposal immediately.

Unfortunately, a minor outdoor contamination incident was required to motivate immediate action on a task which had been sought for many years. The surface layer of slightly contaminated concrete was chipped away, leaving the surface free of any contamination.

A long investigation ensued and records can be found in the Archives [LANL: box 28, folders 23 and 25]. Some of these follow-up documents date to several months after the discovery. Incidents such as this, by then, fell under the label of an “Internal Investigation Report”; and this one became IIR #89-131 886-1.



*Fig. 134. The outdoor concrete platform which had supported the Portable Liquid Dumpster tank for decades was discovered to have very low uranium contamination on it. This discovery happened September 26, 1989. The tank's contents had been discharged into an open pond for evaporation for a few years; but the tank had been out of service for the previous 15 years. Atmospheric condensation inside the tank eventually leaked through decaying valve flange gaskets causing the incident.*

**Erroneous Analytical Lab Result Leads to False Safety Concern**

The uranium inventory of the uranyl nitrate solution, conducted in late 1989, was coordinated with the periodic inspection of borosilicate glass Raschig rings in the several tanks. This was a common practice since early in the 1970s because the tanks would naturally be empty at various times; and that provided the opportunity to perform tests and inspections. One measurement—mandated by the relevant American National Standard—was verification that the borosilicate glass contained the required amount of boron. The test consisted of four rings removed from each of two locations from each of the seven tanks. The locations were the top and bottom of each tank through ports designed for this purpose. Any ring sampled must represent the initial loading and should not have been added later for any reason.

These rings had been installed decades earlier and had never even come close to failing tests for boron. Uranyl nitrate solution was known to be benign; both radiation and nitric acid levels were low. No reason existed to fail tests passed so successfully for so many years. The nominal content of borosilicate glass is about  $12.6 \pm 0.3$  % boron oxide. The Standard’s pass/fail criteria was only 11.8%. No mechanism could be conceived by which boron might be lost. That ought never be a problem.

*The Finding*

Still, results in early 1990 showed that several rings *apparently* did fail. The finding was unbelievable; and these results are shown in Table XI. The worst recorded 11.36% boron oxide while one ring measured 11.79%. Whether or not this 0.01% below a passing grade should be considered a failure given the uncertainty of the measurement is a minor side issue. A total of 10 of the 18 sets of rings submitted failed; and this caused 7 of the 9 tanks to fail this test. Only two tanks survived. Most rings appeared to have lost a considerable amount of boron oxide. This result was puzzling and not quickly explained.

The Rocky Flats laboratory performing boron content measurements simply reported their findings. No explanation was offered. No doubt raised. No questions asked. The fact that no previous failure of this sort had ever before happened was ignored. Their report was concise: most rings failed and those offending tanks had to be removed from service. Tanks were no longer “certified” for use. This prompted a dilemma. Tanks containing failed rings also contained high level fissile solution. The tanks were obviously still subcritical; but solution could not be transferred to another tank, even if that were deemed safe, because no spare tanks existed.

The paradox was unique on plantsite. Elsewhere, so many tanks were interconnected that any one could easily be emptied by moving its contents to another tank. This was not possible in Building 886.

**Table XI. Boron Oxide Contents (wt%) of Raschig Ring Samples from Rocky Flats CML Tanks in January of 1990—Wrongly Failed by an Improperly Calibrated Analytical Method.**

Tank Number	441	442	443	444	445	446	447	451	452
Top port	11.90	11.79	12.42	11.36	11.74	12.63	12.42	11.58	11.77
Bottom port	11.65	11.82	11.53	11.73	12.21	12.38	12.42	11.66	11.73

The paradox was: Solution cannot be moved because the tanks are not certified; and tanks cannot be certified because the solution can not be moved.

### *Possible Resolutions*

Plant procedures allowed minimal options. Rings could be retested; and their integrity accepted if they passed the second test.<sup>84</sup> Unfortunately, this could not be applied in Building 886. Retesting rings wasn't possible since these tanks were full; and procedures did not permit them to be emptied. A hopeless cycle existed: tanks were "out-of-service" because rings had failed; and rings could not be re-tested because tanks were in use.

Another option was to forego any retesting and simply accept laboratory results. Replacing all rings in a failed tank with new, certified, Raschig rings would solve the dilemma. This approach would involve replacing rings in seven tanks. This would prove costly, generate considerable solid and liquid waste, increase risk of contamination, and possibly subject workers to contaminated wounds as occasional glass items broke during handling. The option was unattractive if not impossible.

Even this option would not work in Building 886 because plant procedures required the offending tank be emptied of fissile solution, rinsed a couple of times, and turned over to the Ring Change Crew with only mildly contaminated rings. Here, fissile solution could not be moved because no empty tanks existed. There was no place to put the solution while the ring change was being accomplished. Even if one could

be emptied, it could not have been rinsed because no provision existed for disposing of contaminated waste waters. Another hopeless cycle existed.

The CML staff could not believe these rings had suddenly lost boron when they had proven so stable over more than two decades. This, coupled with the limitations just discussed, prompted a search for some other resolution of an apparently impossible dilemma. Perhaps test results were wrong. They questioned all aspects of the test which had produced failures. Was the apparent failure real; or simply a quirk of the test method?

### *Rocky Flats Method*

The test used was called a "Neutron Transmission" method. A nearly cubical plastic block had a hole the size of a Raschig ring near its center. A neutron detector ran axially down the center of this hole. Two neutron sources were located in the block such that thermal neutrons would be incident upon this hole. A neutron count over a fixed period,  $C_0$ , was obtained with the hole empty. Then, a second count was measured,  $C_1$ , with the test ring present. The boron in the ring would reduce the neutron flux in proportion to the amount of boron oxide present. All that was needed to complete the test was a set of rings with which to calibrate the instrument.

The testing unit was calibrated using hand-made, "secondary-standard," glass rings having various boron oxide contents. Corning Glass Company had prepared a small set of calibration standards many years earlier when the method had first been introduced at Rocky Flats. Boron oxide contents in this set nicely overlapped the expected content of a nominal ring, ranging a few percent on either side of the expected value. Because boron oxide

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<sup>84</sup>The logic behind such reasoning is questionable. The failure would seem to carry less "weight" than a pass. How a failure was so easily rationalized away has never been revealed. Nonetheless, the procedure was approved for plant-wide use.

loadings were unique for these few special rings, large batches of each were not prepared. They were manufactured, instead, one at a time by hand in Corning's New York facility. Radial dimensions of these hand-made rings were expected to vary just a little bit from a nominal ring because they were hand made; so a calibration procedure was created which would take into account slight variations in radial thickness. The tacit assumption was that even though glass might vary in outside and/or inside diameter each ring could easily be cut to proper length.

The idea was sound. This procedure had been used with great success for many years. Small variations did, in fact, exist in radial dimensions; but the set of standards were all the correct length. Procedures properly took into account radial differences; and the testing procedure seemed to be quite adequate. Therefore, Rocky Flats adopted this methodology.

No one seemed aware of the fact that the method chosen was not in compliance with requirements of the relevant American National Standard. It specified the content *had* to be measured by a wet-chemistry procedure called Manitol Titration. This, too, was standardized: ANSI/ASTM C 169-80. The national standard did permit a substitute method be used but only if it had *greater* precision and accuracy than the ASTM method. Neutron Transmission did not meet that criteria. In its defense, however, Neutron Transmission was more than adequate to measure the huge boron oxide difference between a normal ring ( 12.6 %) and the pass/fail criteria: 11.8 %.

### *New Standards*

The only difference between the 1989 results, which produced "failures," and previous tests, which never did, was that a

new set of calibration standards had been used. The new set had been purchased recently as a backup to the initial set. This seemed prudent. Why the new set was put into use without ever comparing results against the first set remains a mystery. Nonetheless, the new set was put in service by the Analytical Laboratory without question.

The CML staff asked to review the procedures followed by the Analytical Laboratory as well as to study their analytical findings. This was not a hostile challenge of their professional integrity; it was, instead, an open request to join other professionals in an honest search of an illusive truth. Only then did they learn that a new set of calibration standards had been used. This author asked to view them. He immediately recognized that the new set of standards were obviously of a different length-to-diameter ratio. A fresh pair of eyes had seen what familiarity with the problem had blinded. This happened about two years into the debate. The new standards were clearly about 5 % shorter than a normal ring or one of the first standards. The whole failure could be traced to the wrong assumption that calibration rings would be the same length as those being tested. Too many neutrons were being detected because of this shortened length; and this appeared to the instrument as though the glass, presumed of normal length, contained too little boron. The solution was so simple. The embarrassment to all was that it took so long to find.

The obvious next step would be simple. Retest the same rings using the *initial* set of calibration standards. Unfortunately this was not possible. Why the first set of standards was no longer available is not recalled; but they were not. A couple of years had passed; and the apparent failure called into question the entire procedure at

Rocky Flats. Furthermore, some of the first-tested Raschig rings—both those which had passed and those which had failed—had been used in another independent attempt to resolve this dilemma.

*Other Studies*

Before the difference in length had been discovered, an investigation had been initiated to compare Rocky Flats findings against other laboratories and against other methods as well. Accordingly, some rings from the 1989 sample of Building 886 tanks were sent to two independent laboratories to be measured by the Manitol Titration method. These other laboratories included Corning Glass, the manufacturer, and INEL, a completely independent facility. The comparison was really very complicated. Those complications revolved around three facts. First, Rocky Flats had both a testing device for uncontaminated rings as well as contaminated rings. One was called “hot”; the other, “cold.” Second, contaminated rings could not be sent to other laboratories for testing for obvious reasons. Finally, Rocky Flats did not yet have the capability of performing the Manitol Titration procedure; and the other laboratories could not reproduce the Neutron Transmission method. The Rocky Flats Statistical Analysis Group was called in to design a statistically significant comparison. How many rings should be analyzed by which laboratory using what method was one essential ingredient of the experimental design. Another issue was how to compare and cross-correlate results in a statistically responsible way. Details of this are contained in the Archives and not repeated here.

The result of this comparison was that a clear bias existed between Rocky Flats measurements using Neutron Transmission

calibrated with the second set of standards and the ASTM method from other laboratories. Results for 20 rings appear in Table XII. A large bias is clearly evident; and the statistical analysis was completed in October of 1990.<sup>85</sup> The two other laboratories agreed well with one another within the expected uncertainty of the method. The magnitude of that bias was large. Rocky Flats results were found to be 0.6% too low in their boron oxide finding. That is, the worst failed ring by the Neutron Transmission method, 11.36% boron oxide, should have an additional 0.6% added to it as a bias correction.

**Table XII. Comparison of Wrongly Failed Raschig Rings (Neutron Transmission Method) with Better Analytical Methods (Manitol Titration) at Two Independent Laboratories.**

Ring	Neutron Transmission		Manitol Titration	
	Cold System	Hot System	Corning	INEL
1	11.3	–	12.66	12.60, 12.54
2	11.4	12.0	–	
3	11.9	–	12.59	12.61, 12.62
4	11.8	12.3	–	
5	11.8	–	12.68	12.42, 12.47
6	12.8	12.4	–	
7	11.5	–	12.75	12.45, 12.51
8	11.5	12.0	–	
9	11.2	–	12.74	12.61, 12.50
10	11.4	12.0	–	
11	11.0	–	12.70	12.65, 12.65
12	10.8	11.6	–	
13	10.8	–	12.70	12.62, 12.60
14	11.4	12.1	–	
15	10.9	–	12.79	12.64, 12.61
16	11.8	12.4	–	
17	11.2	–	12.76	12.65, 12.58
18	11.4	12.4	–	
19	11.2	–	12.86	12.82, 12.83
20	11.9	12.0	–	

<sup>85</sup>D. R. Weier, “Raschig Ring Boron Content Testing Comparison,” EG&G Rocky Flats Inc. Statistical Applications, SA/90-016. October 8, 1990. This report may be found in the LANL Archives in box 37, folder 4.

This ring, then, would measure 11.96%. This ring would have passed the test with the inclusion of that measured bias. Still, even this content was lower than expected. Quite possibly, not all defects of the Rocky Flats method had yet been realized.

The statistical analysis of this inter-laboratory and inter-methodology comparison contained statistical uncertainty as would be expected. The comparative mathematics was very complicated; so that uncertainty was understandably fairly large. The Gaussian distribution had an uncertainty at the 95% confidence level of  $\pm 0.24\%$ . At this point, another unwise path was chosen.

#### *The Wrong Track*

Instead of recognizing that the Rocky Flats method was simply wrong and discarding erroneous results, these first wrong values were simply “corrected” by the measured bias. This was done in spite of the large uncertainty introduced by the complicated nature of the comparisons. A very conservative approach was taken in making this correction. The average correction (0.6%) was reduced by *twice* the standard deviation of that bias. This supposedly yielded a 95% confidence that the bias addition had not been over estimated.

Still one other complication remained. Statistically, the uncertainty should be applied non-symmetrically because no danger exists if the subject ring should contain too much boron. This unnecessarily conservative approach still left one tank with rings which apparently failed the national standard criteria.

#### *Another Approach*

Still another tact was being taken by safety experts. Computer calculations had been performed which proved that even the lower limit established in the American National Standard was unnecessarily high. People from Rocky Flats had been instrumental in writing the first of these national standards back in the early 1970s; and they had continued in this role through the publication of the then-current version dated 1986. The lower limit of 11.8% boron oxide had been adopted quite arbitrarily. No one ever expected any Raschig ring to ever come anywhere close to the limit; so no harm could come from too high a safety limit. Calculations, such as shown in Fig. 135, reveal that absorber contents as low as about 6% boron oxide would be required before a Raschig ring tank quite similar to those at Rocky Flats containing high-concentration solution would become critical. Clearly, a limit as low as, say, 10% could have been used in the Standard; but that had not been done.

#### *Summary*

In this author’s opinion, the entire controversy was handled wrong; and many share responsibility for that. Good scientific judgement was not used on a number of occasions. In summary, perfectly good Raschig rings were cast into question by erroneous test results. Tanks containing them were administratively declared “out-of-service” with no defense arguments allowed. When a measurement error was finally discovered, erroneous findings were simply “patched up” by adding an unnecessarily conservative bias rather than discarding mistaken results. Finally, a straightforward calculation showing that the entire issue of boron oxide was really irrelevant was ignored simply because of the stature

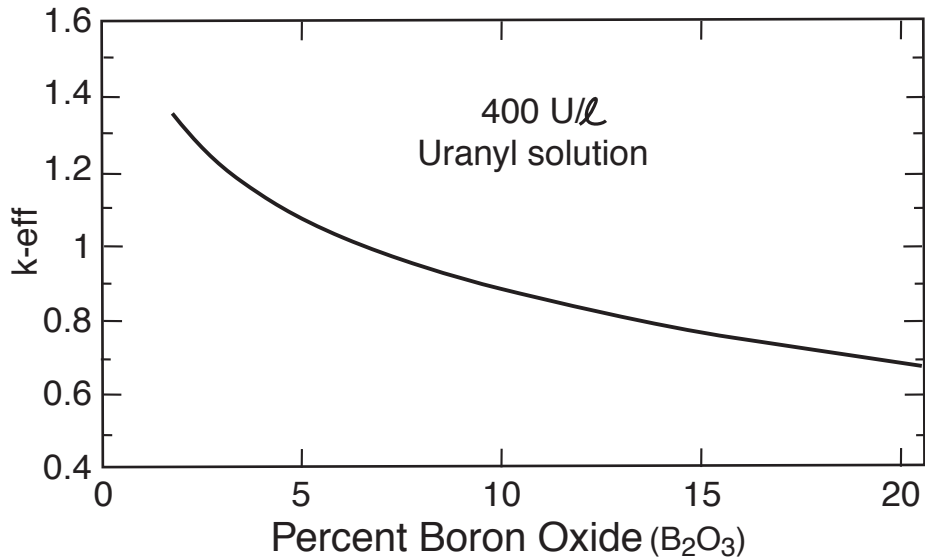


Fig. 135. Computer calculations showed how the neutron reproduction factor,  $k$ -eff, varied with the assumed boron oxide content of borosilicate glass Raschig rings. The uranium solution storage system in the Rocky Flats CML was modeled to obtain these calculated results. The solution concentration selected for this study, 400 gU/l, was greater than that housed since the 1970s; but the curve was fairly insensitive to concentration throughout the minimum-critical-volume concentration range. The lower limit specified in the relevant American National Standard (11.8%) yielded a very conservative  $k$ -eff = 0.82. The glass's nominal 12.6% corresponded to  $k$ -eff = 0.8. Criticality would not have occurred until the boron oxide content reduced to about 6%.

of an American National Standard. Even if the lowest value ever reported had been accepted at face value, these calculations reveal that criticality safety would never have been compromised.

The issue was never satisfactorily resolved. The decision to close the CML on other grounds was made before that could happen. The solution storage tank farm had remained idle for several years (1989 through 1995) because of this perceived problem; and that lack of use precipitated the next problem.

The Department of Energy had just introduced a new kind of document to be used for the timely resolution of problems such as this one. These were referred to as "Compliance Schedule Agreements." How widespread these were throughout the DOE Complex and how long this format endured is not known to this author. However,

CSA-1 and CSA-2 were written at Rocky Flats; and both revolved about this issue. The topic of the first one was "Neutron Absorption Method for Boron Content Determination." The subject of the second was "Boron Content of Raschig Rings in Building 886." Both documents evolved through many revisions. Many documents on this problem spanning *four years* have been preserved: [LANL: box 37, folders 3, 4, and 5].

### ***Static Solution Leaches Plasticizer***

The static nature of the uranyl nitrate solution over six years caused a slow-acting chemical reaction between the low-level acid and the plastic tubing used as sight gauge material on each tank. Previously, these tanks had received periodic maintenance every three years since the

late 1960s. That maintenance program has been mentioned above. In addition to obtaining samples of Raschig rings for periodic tests, the clear plastic sight gauge tubing was routinely changed. One reason for doing this was that the plastic yellowed just a little in three years. Reading liquid levels in the gauges became just a little less certain with a somewhat “cloudy” tube.

During a routine inspection of Building 886 by DOE persons, a Rocky Flats official, and a representative of the CML (not this author), on January 10, 1995, an anomaly was discovered in the sight gauges of several tanks in Room 103. That anomaly consisted of an apparent “stratification” of the liquid in the sight gauge. A thin layer of one yellow liquid clearly rested upon the top of the main column of uranyl nitrate solution in the rest of the gauge. Although several tanks had similar stratification, tanks #451 and #452 seemed the worst. The top layer was about 6 mm thick in both cases. Other tanks showed less or no stratification.

The phenomenon was not immediately understood. Several unanswered questions immediately arose: Is precipitation taking place? Is this separation or precipitation happening inside the tank as well? Could this lead to criticality if the concentration were to rise too high? The word “slurry” was used to describe the curious situation; and this heightened fears. Both “Slurry” and “stratification” were words packed with hidden meanings. Quickly, a Solution Stratification Task Team was formed to investigate the source of this mystery. They were to answer the following questions:

- a. Is there a risk of criticality?
- b. What is the cause of this anomaly?
- c. Is similar “stratification” taking place inside the tank?

- d. What surveillance measures might detect future anomalies?
- e. What changes should be made to prevent future anomalies?

The following day’s inspection proved interesting. When pinched, the plastic tubing seemed less pliable than new tubing. Intentionally pinching the tube near the interface caused the “slurry” to protrude through the clear solution and then recede to essentially the same point once the pinch was relaxed. Sight gauges of two other tanks (#441 and #442) appeared to be more cloudy than expected. Several gauges exhibited a small amount of a white particulate “flocculation” on the tube’s interior wall. All sight gauges showed varying degrees of discoloration in the air space above the liquids. Finally, all plastic tubes showed evidence of aging.

A myriad of tests were run on these tanks and their sight gauges; and a team of 20 persons met about weekly to evaluate progress. Radiometric scans were performed up the sides of the tanks; but no useful information was obtained from these gamma ray data. Neutron flux levels were not largely different than three decades of experience would suggest. The solution was not critical nor did criticality appear imminent. Remote radiometric measurements were made in an effort to determine if the solution within the tank was homogeneous; but results were questionable because of the test’s shallow penetration into the tank. Measurements spanned many weeks following initial discovery. More intrusive measurements—which might call for solution movement—were rejected for fear of upsetting some unknown condition.

No results suggested the tanks were in any way abnormal, a belief held by CML staff since the first discovery. Only the sight gage stratification perpetuated the



mystery. Rocky Flats rightly chose a very conservative approach. No one knew what was happening; so the safe approach was to proceed with caution to ensure that an unstable equilibrium would not be disturbed by some hasty action.

Sometime late in this series of investigations, a sample of the top stratified liquid was obtained. Exactly how this was accomplished is not now recalled for certain. Quite possibly, a long hypodermic syringe needle was injected right through the plastic tubing. The injection would have been made from above the solution/air interface to preclude a leak. A second possibility is that the sight gauge, itself, was carefully disconnected from its top attachment to the tank and shifted to one side a little such that a long needle could withdraw the sample. How this sample was obtained is not as important as the result.

Chemical analysis of the top stratified liquid revealed that it contained dioctyl phthalate, the plasticizer used in the manufacture of this tubing. This finding was consistent with observations collected during the early days of this investigation that the tubing appeared to be aging and that it felt less resilient when pinched. Similar problems had not happened in the past because sight gauges had been routinely changed every three years during tank maintenance periods. Old tubes had always showed a yellowish tinge.

The explanation of the “stratification” phenomenon, then, reduced to the simple fact that this plasticizer chemical was leaching out of the plastic tubing. This chemical is not soluble in the dilute nitric acid; so it rode on top of the solution in the sight gauge. That was the stratification. The actual problem existed only in the sight gauge and not at all in the tanks themselves.

All these facts were collected in a 13-page-long report<sup>86</sup> probably issued three months later. A draft of this document exists in the LANL Archives; but no copy of the final text was found there. The draft concludes that (1) No indications of solution stratification in the tank exist. (2) There is no risk of criticality. (3) The most probable explanation of the anomaly *appears* to be one of Tygon tube deterioration. (4) A working familiarity with the physical features of this solution should be maintained to preclude future situations.

Recommendations included movement of the solution as soon as possible such that each tank, one at a time, could be emptied. Then, new sight gauge tubing could be installed. The fear was that continued leaching of the plasticizer could eventually embrittle tubing so much that it might break under its own weight. Very old plastics often become brittle with age whether or not acidic fissile solutions are involved; this is recognized in everyday life. Another recommendation was that periodic recirculation of all solutions in the tanks should be performed. Lack of familiarity with a static condition caused this situation in the first place.

### ***Spring Runoff Floods Holding Pit***

The spring of 1995 was an especially wet one. The ground had become saturated with rainwater. Water poured into the underground Holding Pit (Building 828) as had happened decades earlier (see above). The flood also involved the filter plenums in Building 875, ventilation ducts, and the huge Fire Water Collection tank

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<sup>86</sup>“Building 886 Highly Enriched Uranyl Nitrate (HEUN) Stratification.” Task Team Report. EG&G Rocky Flats, Inc. (March 15, 1995). Find in LANL Archives: box 28, folder 2.

(Tank #501). Still other runoff seeped into the tunnel connecting Buildings 886 and 875; and even more ground water collected on the floor of the fissile solution storage room (Room 103) in the main building where it got about 75 mm deep. An important point is that water on these two floors had *not* gotten there by way of any contaminated route.

Rainwater filled the Holding Pit to within a meter of the very top. Both thousand-liter storage tanks also filled as water flowed through vent connections. One might expect buoyant forces to float a submerged tank; but that would not happen. The buoyant force is about 400 kg less than the combined weight of tank and glass. Furthermore, both tanks were fastened to the floor. Still, more than *one hundred cubic meters* of water inundated this pit!

The pit was vented to the Hot Exhaust Filter Plenum via a duct mounted to the wall of the below-grade tunnel between it and Building 875. The reduced pressure within the plenum literally sucked additional water into the first stage of the plenum. Water in this first chamber was about half a meter deep. This chamber very well *might* have contained considerable fissile material; it vented all potentially contaminated rooms. The chamber was quite large but not so large to keep the depth small. Therefore, under different conditions, a criticality accident *could* have occurred during this event.

Even though made of paper, filter units resist passage of water for awhile. The second stage chamber only contained water only to a depth of less than 100 mm upon first discovery. The third stage chamber contained only a little water; and that probably just seeped around filter seals. In time, however, all this water came to an

equilibrium depth in all three chambers as the paper filters soaked through.

The first chamber had been constructed with a water sprinkler system anticipating a fire might someday be drawn onto the first bank of filters. A drain for this water would be necessary; so one was designed into the floor of the first stage's chamber. That led, under gravity, to a 5000 liter, Raschig-ring-filled "Fire-Water Collection" tank. This tank, too, became completely full of spring runoff. The duct connecting the Pit to the Plenum also connected to the even-larger-diameter Hot Exhaust Duct from the main building. Water was found in the horizontal leg of this line, too, although this runoff water never backed into Building 886 because of a vertical leg between the connection and the building.

Several areas flooded with water *could* have contained appreciable amounts of fissile material. Good fortune may have had a role in the absence of a nuclear criticality accident that spring. Recovery was effected—as the season dried out—by pumping water into mobile tanker trucks. In one 3-day interval, about 150,000 liters of water were removed; the total water processed came to about 400,000 liters. All this was hauled to one of the plant buildings (Building 374) which treated contaminated waste waters. Waters were often tested for radionuclides. Activity levels in Tank #501 were reported on one occasion at 500 pCi/ℓ; while groundwater recovered from the tunnel measured 2700 pCi/ℓ. The highest level recorded was 4000 pCi/ℓ. All levels decreased rapidly as more and more water passed through.

Some documentation of this situation exists in the possession of the Criticality Engineer responsible for criticality safety aspects of recovery; but no records exist in the LANL Archives at this time.

The date April 30, 1995, appears on some of his papers; but that is probably not the date the flood was actually discovered. The holder of these documents is Paul D. Felsher; and this author gratefully acknowledges his willingness to share knowledge. Perhaps, his documents can be added to the Archives in the future.

### ***Criticality Alarm Activations***

As a close to this chapter of anomalous events at the Rocky Flats CML, the subject of unplanned criticality alarm evacuations should be discussed. These *did* happen occasionally over the three decades of laboratory history. Records may exist somewhere to give a more precise number; but this author recalls such occurrences happening one or two times every couple of years.

They were always ‘false alarms.’ Rocky Flats never experienced a nuclear criticality accident. This alarm—as well as proper personnel response (evacuation)—was periodically tested; but this, too, is excluded from the current discussion. A few of these “crit alarms,” as they were called, were triggered during maintenance work involving electronic instruments capable of initiating such an alarm. Some alarms happened under the general description of “operator error.” For example, an instrument’s range selector switch may have been turned the wrong direction. Another time, the instrument technician bumped the “test” button as he squatted to perform some other function. No alarm ever happened for which some explanation could not eventually be offered, although sometimes some investigation was required. Detailed information about accidental trips over one ten-year interval are presented in another chapter.

A few of these happened during nuclear

experiments. That alarm was *not* wired to initiate a SCRAM automatically of whatever experiment might have been in progress. Perhaps that would have been a good procedure. Whenever those two events did overlap, the experimenters always had the presence of mind to SCRAM the experiment manually as they evacuated the Control Room enroute to the Assembly Area out of doors.



## *The New Millennium*

This is a lengthy book full of disconnected facts about one particular component of the nuclear industry in the United States over a span of three-plus decades. Additionally, it is infiltrated with this author's personal opinions on a myriad of unrelated subjects. It is also splattered with smatterings of humor and personal interest. Reduced to simplest terms, this document is a loosely-connected manifestation of the observations of one scientist in one place at one moment in history as he attempts to write down the combined efforts of a small band of often-talented professionals. No one is expected to read this entire volume as a recreational novel.<sup>87</sup> Still, information is contained within these pages that should never be kept hidden. Personal safety to Rocky Flats workers and future unspecified citizens—possibly ignorant of the region's history—can be enhanced by paying attention to certain aspects of this document. Even if one nuclear accident or contamination incident, at Rocky Flats or elsewhere, could be prevented by heeding observations contained herein, this effort will have proven worthwhile. Highlighting potential problems about the site once-occupied by Building 886 is one succinct purpose of this chapter.

The Assembly Room of Building 886 was explosively weakened on Saturday, April 12, 2002, and reduced to rubble the next day. Problem areas contained therein had already been successfully cleaned up before the building's demise; and their mention becomes merely a documentation

of recent history. A great many of these points had already been discussed verbally between this author and decommissioning and demolition workers in the years leading up to demolition; and these matters, therefore, were well in hand prior to that moment. The importance of this chapter—and perhaps the entire book—may lie in those few previously unreported, unknown, unrecalled, or underestimated problems. That these issues were satisfactorily resolved before demolition are underscored below.

This author's premier concern right up into the new millennium was the buried duct under the floor of Room 101 and through its thick west wall. This was a very long run of 250-mm-diameter pipe totally inaccessible to human reach. It had been cleaned of many kilograms of high-enriched, dried, yellow-cake salts by a rudimentary expedient—a child's roller skate and a make-shift parachute! The roller skate had been drawn deep into this horizontal pipe; and then drawn back to the opening via a length of string. A simple scraper blade collected what salt it could. Even though modern analytical techniques "proved" this duct to be relatively free of loose contamination and limited to mere surface contamination, discussions about this matter urged caution right up to the end. The situation was treated as though some sizeable collection of uranium salts may have remained. Criticality was probably never an issue; but contamination control was the watchword here.

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<sup>87</sup>Except for the unfortunate souls peer-reviewing it.

The entire collection of nine storage tanks were gone by the start of this century. That was successfully completed with careful respect for contamination hazards. The tanks were no longer a concern. The remaining components of the uranium solution handling system, however, had to be recognized to contain possibly quite high levels of contamination—even residual fissile solution. This assortment of pipes, pumps, and valves existed in Rooms 103 and 101; and some of this piping was even contained within the very thick wall between the two. Vertical lines could be assumed empty of solution hold-up and would only have high levels of internal contamination. Horizontal runs of pipe, however, were not always obviously empty. Even when they sloped toward a lower point and emptied into a vertical pipe, some “horizontal runs” had slight depressions in them which could have held residual quantities of fissile solution. These dips were formed unintentionally during fabrication in the 1960s. Welding can cause stainless steel pipe to “creep” and “crawl”; and this produced these depressions.

Tanks #441 to #447 and #451 and #452 were gone; but some other tanks yet within Building 886 still contained fissile materials. Still-present tanks were known to be internally contaminated to a high degree. In particular, the large-diameter tank used in the last experiment, the Shielded Annular Tank, was known in the mid-1990s to contain thick, visible, deposits of uranium salts. Residual liquids, salts, and contamination had to be dealt with before demolition could proceed. This was systematically and professionally accomplished; but considerable information contained in this book proved instrumental to that effort.

The interior of the stainless steel glovebox in Room 103 was heavily contaminated with plutonium for decades

before demolition. Large sized pieces of machined bare plutonium metal shells were known to have been slid back and forth across the floor of that box. Loose oxide had often been abraded off their surfaces as the tiny sparks associated with the combustion of these flakes is vividly recalled. The inside of that box was heavily contaminated. Its cleaning in the 1980s was performed by two scientists—really inexperienced decontamination workers—using the most primitive equipment. Cleaning solution was smeared on the interior surface working through thick rubber gloves, reaching only as far as the arm could. Even this arm movement was awkward and restricted. The eventual removal of this box, too, had to be accomplished with caution.

The walk-in hood in the Assembly Room produced another point of caution. Although built of stainless steel, enough uranium solution had found its way onto the floor of that box over three decades to seep into weldment seams and any cracks in welds. Several liters of high concentration uranyl nitrate solution had leaked onto this floor on a small number of occasions. The floor pads under the four legs of the Solution Base certainly contained crusted uranium salts. This danger was discussed frequently prior to demolition.

Trenches in Room 101 were still another source of hidden contamination. One unplanned incident had deposited dozens of liters of high concentration solution along the bottom of the trenches. Trench bottoms were rough and irregular. Furthermore, electrical and electronic cables and sometimes copper tubing lay haphazardly all along the bottom. A good cleanup at the time was next to impossible. Years later, cables were removed and (still-contaminated) trenches filled with wet concrete leaving a depth of about 50 mm for a new cable path. This wet concrete

trapped residual contamination in the much-painted-over bottom surface of the original trench. This new cable route, just below the floor's surface, remained another few years until the decision was made to elevate all cables to metal cable trays well above ground. A second layer of wet concrete was applied over the shallower cable runs; but this would also have trapped a second layer of accumulated contamination. The ultimate removal of concrete flooring from Room 101 had to take this hidden trap into consideration. Even as these sections of concrete laminations were removed in 2002, evidence of contamination at concrete interfaces was found. Topics contained in this book greatly aided a safe containment of this contamination.

Concrete floors in Rooms 101 and 103 (especially) contained residual contamination embedded in the paint. These floors were often contaminated and had been frequently painted. Painting was not done for aesthetic reasons; the purpose was to seal away stubborn contamination. One major leak of the late 1960s passed more than 200 liters of uranyl nitrate solution onto the depressed floor of the tank farm in Room 103. Another leak in the 1960s spread uranyl nitrate solution all over the southwest corner of Room 101.

One specific floor area within Room 101 was watched for possible plutonium contamination. This precaution was a direct result of information revealed in this book. This area of concern was in the north/south center of the room and within the first few meters west of the east wall. Surprisingly, no contamination was ever found there resulting from the major plutonium metal incident of 1983; but the glib assumption that none existed prior to demolition would have been unwise.

The sheet-metal building south of Building 886, itself, often housed heavily contaminated equipment as well

as many items of lesser contamination. The purpose of this building, after all, had been specifically to house contaminated equipment from past experiments that might someday be used a second time. All of these items have properly been disposed of; but their current owners at some nuclear landfill might benefit from knowing their history. (1) A number of small to large machined stainless steel hemishells had been stored in a cabinet in this building. These shells had been in intimate contact with bare plutonium metal and often immersed in hydrogenous liquids. Before being stored, they had been washed in a dilute acid to "pickle" their surface. They were considered "cold" when placed there. The level of contamination suitable for such storage existent in the 1970s may be different from present definitions. (2) A large number (103) of flat stainless steel metal plates alloyed with boron had been used in dozens of experiments where they had been flooded with 450 gU/liter uranyl nitrate solution. Surfaces of these plates were somewhat granular—far from smooth. Plates were cleaned by two men washing both sides at the same time while the sheet hung from a hook in the ceiling. Tools were floor scrubbing brushes and buckets of soapy water. The level of contamination remaining on the plates when boxed and stored was highly suspect. (3) Several concrete reflector components had been cast over the years. These wall panels were such a useful design that many were used a number of times. They were stored in this shed between use. Small amounts of surface contamination had soaked into the porous concrete and had been fixed in place by paint. (4) A few white-painted "oil drums" had been used to store valves and other plumbing hardware removed from various experimental assemblies. This hardware was often saved simply because this author wished to avoid waste. Perhaps he protected taxpayer's dollars too

closely. Nonetheless, this hardware often contained quantities of fissile solution. All these items had to be disposed of properly during the last few years leading up to demolition.

One little-known outside area that might have some very small amount of uranium contamination is the soil a couple meters west of the west wall of the Assembly Room. The problem might exist just to the west of where the entrance to the original filter plenum had been. This possibility obtains from the pool of yellow-cake salt once seen on the floor of that plenum following one of the contamination incidents discussed elsewhere. That layer of salt was disturbed and sent up into the swirling air flow inside the “hot” side of the filter plenum. That all happened while the door to the outside world was open. Even at that moment, however, no contamination was found in the soil, although the depth of that search is not known.

Almost as important as knowing where contamination was or might have been, locations with much lower risk of contamination proved useful. The Storage Vault, Room 102, was never known to be contaminated. The solid fissile fuels it contained were so well packaged as to never result in any known contamination. Another area with low potential is the underground Holding Pit several meters west of Building 886. Records of the waste waters that passed through Tank #440 show that a total of three grams are claimed to have been discarded as waste over decades. Even these areas were given considerable attention prior to demolition.

A final consideration has no connection with fissile material whatsoever. It most likely does not even concern the demolition of Building 886. One experimental program in the 1980s used several neutron-absorbing powders or granular materials. For this project, about 230 kg of fine powdered cadmium oxide had been

purchased. This material is now recognized to be carcinogenic but was not treated as carefully then. The powder was spooned into paper tubes in the open area of the Mechanical Room (Room 111) with the rolling door to the outside fully open because the weather was pleasant that time of year. Workers may have worn rubber gloves and possibly a half-mask respirator; but these details are not recalled for certain. Certainly, others entering the building did not have respiratory protection; and they were only a few meters removed from the site of the filling.

Years later, these hundreds of paper tubes were stored in a white-painted plywood box labeled with their contents. These boxes, in turn, were stored between the Storage Shed south of Building 886 and the Cargo Carrier a few meters to its north. The plan was that someday these paper tubes might be called into use again. Years later, this material was to have been returned to the original supplier. This author vaguely recalls emptying the paper tubes back into a fresh drum for return to the vendor; but this action remains uncertain whether or not it was ever really done. If so, some event delayed immediate shipment from plantsite. Later, when shipment again became a priority, the oxide could not be found. The vendor claims they never received a large drum of cadmium oxide nor does any documentation show it had ever been shipped off plantsite. The cadmium oxide has never ever been found anywhere on plant site in spite of repeated efforts to track down this large amount of possibly hazardous material. It may still exist as a drum of rusty brown powder or in the hundreds of paper tubes. It may still reside somewhere on the Rocky Flats plantsite. Whether or not this material was ever disposed of properly is, sadly, not known. The paper trail proving that point either way has been lost. The status of this material is pure speculation.



## *The Human Side*

The citizens of Building 886 were an eclectic collection of scientists and engineers. Together, they fulfilled every stereotype of that order. They were good researchers knowledgeable about nuclear fission. They were careful and orderly thinkers with a steady eye toward criticality safety. Some were better experimentalists; others, nuclear reactor theorists. Creativity abounded.

Building staff was all of this; but they were human beings too. In that role, they experienced the heights of human joy as well as suffered the utter depths of sadness. Some experiences were humorous; some, tragic. Others were embarrassing. Many moments elicited warmth and compassion while others were spent in nervous tension—occasionally ending in horror. These events are shared here not to bring discomfort to anyone save, on occasion, this author. Instead, they are presented to illustrate how the fabric of the human condition pervades all forms of human occupation.

### *Family Life*

A few marriages took place involving Building 886 employees, although most were already married. The confusion imposed upon this author by Schuske's marital status between his job interview in June 1963, (Schuske was married) and first employment 14 months later (he was not married) has already been mentioned. In the spring of 1965, Schuske, then 44, married Rochelle Hall, 24, amidst a few under-the-breath snickers about the age

differential. One humorous incident stems from this union. This author and Douglas Hunt were selected to purchase a wedding gift for the “boss” and his new bride. Ceramic dishes of a (then) brand-new line called Corell Ware were selected. Though ceramic, this product was noted for its strength. The two scientists opted to buy the product at a well-known and highly-respected—but very old—hardware store in Boulder. Valentine's Hardware had been around since the early 1900s and was noted for its home-like atmosphere and well-worn wooden floors. The sales clerk bragged about the strength of Corell Ware and insisted the buyers drop a large serving dish to the floor. Reluctantly, that was done; and the bowl merely bounced. The softness of the wooden floor, however, was pointed out. The clerk countered with a command to loft the bowl out the open door onto the sidewalk just outside the store. He was sure it would withstand the test. The buyers protested; but the clerk accepted responsibility. Better judgement aside, this author—using his best underarm pitching move—sent the white ceramic object out the door. It smashed into tiny bits and pieces upon impact. The thrower's arm was still in its follow-through posture as a couple of onlookers, innocently walking past the store, paused just long enough to look inside. What they saw included three speechless, wide-eyed, persons (one with right arm extended) as they puzzled silently at the curious sight of dishes flying out the front door of a store.

Other marriages took place too. Secretary Barbara Schneider quit her job to get married. A few years later, her replacement, Carla Norvel became Carla Fisher. This author still has the small, gold-colored ring used to fasten a small pouch of rice hurled upon the happy couple. Deanne Dickenson became Deanne Pecora; and a few others tied the proverbial knot. As decades passed, marriages of children prompted the ubiquitous box of celebratory donuts.

Children were born, always a source of joy and another round of donuts. The precise coincidence of this author's third offspring and the official certification of Building 886 as a Critical Mass Laboratory has been mentioned elsewhere. This date marked the "birth" of the CML as well as his third child. Several building personnel were producing offspring, especially during those early years of the CML when staff was young and so very fertile; but two fathers deserve special comment. Grover Tuck sired a dozen children and Richard (Dick) Egan in the office next door to Tuck's was the proud father of eight. Between the two, they skew the world's population replacement schedule; and Tuck wasn't even Catholic.

Births happen; so do deaths. C. L. Schuske, the founder of criticality safety at Rocky Flats, was tragically killed in a car/bus collision in his home town, Boulder, Colorado, the summer of 1977 (July 12th). His second ex-wife telephoned this author at 1:00 AM with the terse statement: "Bob, Lee's dead!" Schuske had been out to dinner with his three children and was driving home when he veered into a left turn lane and rammed the rear of a bus stopped to make a turn. He was killed instantly and the children injured, one, seriously. No reason for the tragedy has ever been uncovered. The next day,

Building 886 personnel stood around with saddened faces when Norman Gaylord, a fairly new member of the CML staff, arrived late to work. He inquired as to the source of the obvious heavy emotions. When told of the accident, Gaylord flushed red with unknown emotions, turned without a word and left the facility. He remained a recluse in his own apartment for three days. His response was neither expected nor understood. Schuske and he had been known to share a drink or two together on occasion; so they were friends outside the office. They had had a bad falling out over a technical matter a week or two earlier; and the estrangement had never been reconciled. A few months later, Gaylord was also killed in a traffic accident on the Rocky Flats plantsite. He had been jogging during the noon hour on the access road into the plant and, somehow, stepped out into the path of an oncoming car. Whether or not the two deaths are in any way related will never be known; and maybe that's OK.

Both Grover Tuck and Dick Egan lost a son to death under tragic circumstances. Tuck's son had mysteriously left home a few days earlier; and officials found his body following a suicide. Tuck and this author had been performing a critical experiment when word came that "Grover Tuck was needed immediately by the authorities." Experiments were never interrupted for any reason because of safety considerations. Nonetheless, Carla Fisher came to the door that day and told Tuck he was needed on the phone. No words were spoken as the experiment was terminated and Tuck left the room fully fearing the worst had happened.

Egan's son had been returning from a holiday in the mountains to his Boulder, Colorado, home. The 16-year-old was forced off the road by an out-of-control car

driven up the canyon by an inebriated driver. He died at the scene. Egan was a member of this author's carpool and had a reputation for being late. That day was Egan's turn to drive; and he was late as always. Angrily, this author telephoned him to scold him for tardiness. Emotions quickly came into true focus when Egan apologized saying: "I'm sorry, my son was killed yesterday in a car accident. I won't be going to work."

Douglas Payne, a quality electronic assistant to the CML, died of cancer; and this author recalls visiting him on his hospital death bed. Payne mumbled through drugged pain: "I know who you are. Thanks for coming to see me." Douglass Hunt died in a mountain climbing incident a few years after he had left the CML but was still employed at Rocky Flats. He fell about 30 meters to his death. This accident happened a few years after this author fell about 20 meters (1986) but survived serious injury. He had been climbing rocky faces near Lake Powell. More than 8 hours passed before a helicopter transported him to a hospital in Grand Junction, Colorado. Rounding out mountain accidents, Julie Geng tumbled a long distance down a mountain hillside and severely broke her ankle. This happened in 1993.

"Life Is Fragile; Handle With Care!" had been a safety slogan at the Rocky Flats Plant for many years. The preceding tales of birth and death and a multitude of other human emotions between the two support that truth. The rest of this chapter reveals the lighter side of the human situation.

### ***Humor***

Many notes and memos needed to be circulated among building personnel for general interest and public information.

These bore a narrow strip of paper stapled to the upper left corner. This contained the initials of those supposed to read the message. When read, initials were crossed off and the document delivered to another reader. Because of this practice, people became known by their initials. To this day, this author still pictures faces and personalities with CLS, DCH, GT, BBE, HWK, WRS and a long list of others. Some even were called by their initials when the set was almost pronounceable. Thus, Donald R. Ferguson, DRF, was often called "Derf"; and that persists even to this day among older friends. Bruce Ernst, BBE, was called "Buhwee" for some unknown reason. Two came to be known by the first syllable of their last name; and one of these is *not* politically correct. The practice became embarrassing when Donald C. Coonfield was introduced to a black colleague using that familiar shorthand. This author occasionally was called "Dr. Rot" by colleagues. One maintenance worker with whom he became friends (George Coughlin) devised an unusual name. No malice was intended when he addressed this author as "Dr. Stupid." Interestingly, George and his cousin had been, in the 1930s, three-time world champion rock drillers. This was a competition indigenous to the hard-rock miners of the mineral-rich mountain west. The two could drill 22-mm-diameter holes in solid granite almost a meter deep in 15 minutes using muscle-powered hammers and star drills alone.

Many truly humorous events occur during any three-decade-long association with a fairly constant group of colleagues. The maintenance man, Coughlin (above), offered to teach this author how to arc weld. Steps and procedures were explained before the dark-visored welding mask was donned. The "stinger" struck its arc; but the anticipated bluish region of intense light

did not follow. Darkness pervaded the scene; and the welding rod seemed somehow heavy and immobile. Soon, the problem was explained as the welding rod turned into a dull glow which reddened into a bright orange-red line. This inexperienced “welder” had stuck the stinger onto the scrap piece of steel used for instruction as a very high electric current heated up the stinger. This only reinforced the moniker of Dr. Stupid.

Still in the 1960s, Secretary Marilyn Douglas made a public address announcement throughout the building. She called for “all classified material should be returned to the office” because an un-cleared visitor was about to enter the building. She meant, of course, that checked-out classified documents should be returned to designated repositories. Howard King and Bruce Ernst shared an office and had their own two-drawer safe because of their frequent need to access classified documents. Their safe was mounted on castors for some reason. In response to the announcement, the two impish engineers pushed their safe down the hall and into the secretary’s office. It was a harmless joke; but they had forgotten that the back side of the safe—at the front as pushed down the hall—was decorated with a full-color photograph of a lovely woman wearing nothing but a broad smile. She was a refugee from a *Playboy* magazine. Douglas, who might be described as “reserved,” took quick offense at this invasion of her senses.

The Hot Area of Building 886 was firmly secured at night to preclude unauthorized access to fissile materials. Still, safety checks against fires or other disasters were important, too. These were done hourly by members of Plant Protection. They surveyed these rooms via closed-circuit television cameras left on for that

safety purpose. On one occasion, the security forces were “set up” for a humorous shock. The camera had been aimed at a flat wall to which a two-page centerfold pinup from another *Playboy* magazine had been taped. The camera lens was zoomed in until the visiting guards would see only the smiling face of a nude woman kneeling in a chair and looking invitingly at them over her shoulder. This antic preceded sexual harassment cases by a full decade.

Security procedures required lunch boxes be inspected upon entry into the security zone around Building 886. Employees knew that; but wives did not. That fact, combined with Valentine’s Day, parlayed into a humorous event. The event was also a bit embarrassing; so names will be omitted. This male was busy conversing with another as both passed through the Guard Post. Badges were handed to the Guards and lunch boxes routinely opened for inspection. The Guard’s surprised response to a dainty pair of the wife’s panties tucked into the lunch pail along with a romantic Valentine’s Day note brought laughter to all except the husband. Laughter was tempered with hidden envy; and the contents of the note have never been revealed.

D. C. Hunt and this author were working together in Room 103. Each had their attention focused on separate areas of the common problem when Hunt experienced an itch in his ear. He tried to ease the itch with his finger; but that proved too thick. This author recalls seeing, out of peripheral vision, Hunt solve the problem using a yellow, wooden pencil. The eraser end found the itch and nicely placated it according to the look of pleasure in Hunt’s closed eyes. A moment later, Hunt approached this author, a sheepish look on his face, and inquired: “Bob, do you see an

eraser in my ear?” The itch had been so deep that the broken-off eraser was no longer visible. The Rocky Flats medical department is reported to have said: “You have a WHAT stuck in your ear?”

Hunt and this author often worked closely together. Many times opinions as to the outcome of a particular experiment differed. Would it prove critical or not? Countless borderline cases on a wide variety of subjects led one to one opinion and the other to the opposite. These friendly professional differences often led to wagers. The winner would collect the spoils. Whenever such a controversy arose, one could be heard saying to the other: “Betcha a penny . . .” The loser always paid his debt in full. Over about two decades, the two came out about even. Many people have asked this author to explain the very long string of pennies innocently taped to the bookcase just above his desk. Hunt, too, had a similar string of pennies taped in his office. This tale of friendship ends with one anecdote. Hunt did not have a penny one day with which to pay his debt. The hundredth part of a dollar bill—a small triangular corner—was taped into the string of pennies.

The next embarrassing moment brings a blush to this author’s face; so it will be told in first person. Having been to my dentist for an annual checkup and routine cleaning, the hygienist shared with me a rather big word for a person in her profession. I was always interested in learning such trivia and not at all above “showing off” new found knowledge to less-informed colleagues. Later the same day, I shared with several coworkers the fact that I had learned the professional title of the woman who had cleaned my teeth. Their general lack of enthusiasm over this font of information was underwhelming; but, undaunted, I shared with them the word.

As though to seal my victory, I restated the fact: “Yep, the lady who cleans your teeth is called a proctologist!” C. L. Schuske just happened to walk past the doorway during this encore pronouncement and entered the room wide-eyed. Thinking I had a new student, I restated my new-found knowledge. Flustered, Schuske stammered: “No! That’s not right. A Proctologist is a . . ., a . . .” Then, seeing Deanne Dickenson in the room, he modified the end of his sentence: “a . . ., a *fanny* doctor.” Either I had misheard the word or the Hygienist deliberately set up; which was the case will never be known. The assembly present laughed, Schuske’s correction was confirmed by the dictionary, and I blushed as I returned to the security of my own office.

The next day, ready to advance the frontiers of criticality safety, I entered my office only to find a note atop a small boxed item. The note said: “In case you need to brush your teeth today . . .” The package contained a tube of *Preparation H*, a hemorrhoidal relief cream.

A few months later, the annual Christmas gift exchange was to occur in Schuske’s office as we lunched together amidst a festive spirit. Strangely, I had two gifts. One was from the person who had drawn my name; but the other was unexpected. It proved to be a commercial item chanced upon by some mysterious giver. The printed face of the box stated in gay lettering:

*“I wanted to give you an electric toothbrush; but I didn’t know if your mouth was AC or DC. So, I got you a gas-powered one instead!”*

The box contained a familiar plastic toothbrush whose handle fit a length of rubber tubing leading, in turn, to an enema insertion tube. I was the last to make the connection with the earlier incident.

Everyone laughed; but Schuske, the mystery giver, laughed so hard he fell over backward in his chair. He continued laughing still in the “seated” posture. The whole incident was never quite forgotten.

The staff of Building 886 had periodic meetings to discuss what has been accomplished and where each task was headed. Jobs were distributed and progress of existing work reviewed. On one occasion, C. L. Schuske was whimsically reprimanding Sidney J. Altschuler in front of his colleagues for an assignment not completed on time. Altschuler presented his case blaming Schuske for too often impeding progress with other chores. Faithful to typical speech patterns, Altschuler intoned in a musical voice: “Well, Lee, you assign jobs in *fits and starts*,” to employ a somewhat familiar expression. This author quickly added to the good-natured scene saying: “Ya, he has fits; and you start.”

Don Ferguson’s telling of tales about his own true-life adventures created for him a reputation of just narrowly escaping death from an endless array of disasters. For example, his parachute didn’t open properly at first during one of his sky dives. When it did open, he found himself descending faster than expected over a forest. He reports to have been nearly impaled by the top of a tree. Another time, while hiking with his family, a meter-sized rock fell onto the roof of his parked car. One day, he was driving toward a Boulder golf course. Boulder is known for very high winds with strong gusts. He reports that a pickup truck, moving the opposite direction at a good rate of speed, lost a sheet of plywood to one of these gusts. That plywood cartwheeled directly in front of his car narrowly missing it. To believe his tales of near-disaster, Ferguson appears to be related to the man named Joe Bfstplk

from the comic strip, Li'l Abner, who always had a rain cloud just over his head.

Evolution certainly can be seen in three decade’s time. Early papers, reports, memos, and journal articles were typed out on an electrically-driven mechanical typewriter using carbon paper between copies. Youth today may not know the meaning of carbon paper. This autor wrote the original in longhand on every other line to permit editing before turning the much-scribbled text over to a secretary for her painful transcription. Due to an occasional typing error, Carla Fisher has been seen rolling up the platen, erasing the error on each copy, blowing away eraser crumbs, returning the platen to the proper line and location, and hoping the subsequent text aligned satisfactorily. What an amazing improvement when the first typewriter correction fluid came out! Later, the computer changed word-smithing altogether.

Another illustration of evolution concerns the calculation of reciprocal multiplication values. This number is the quotient of two neutron counting rates. One, a 4-digit number; the other, 6 or 7. Prior to the 1960s, the ratio was read from an archaic tool fondly remembered: the slide rule. Electro-mechanical monsters, bearing the name “Frieden,” later provided the desired result until the very early 1970s. Seemingly, lunch could be eaten while electric motors whined and mechanical wheels spun in what appeared to be random fashion before the quotient could be read. Elsewhere, the effects on the data caused by electrical noise generated by making and breaking relays is discussed. Still later, the Rocky Flats CML became one of the very first owners of a brand new kind of calculational device. Manufactured by Singer, also noted for its sewing machines, this electronic wonder had four lines several digits long visible on a tiny

television screen. The lowest two lines could be added, subtracted, multiplied or divided. This last operation yielded the sought for reciprocal multiplication.

One final example of evolution remembers the kindly soul of Grover Tuck, several years older than this author. Recognized in his field through experience, but not adorned with a PhD degree, the older Tuck often counseled younger PhDs on matters derived from his experience. Without pausing the conversation, Tuck would produce a small slip of thin paper in the left hand formed into a U-shape by the fingers. Next he would empty a row of tobacco into it from a cloth pouch, pull the string with his teeth to close the pouch, and roll the cigarette in his left hand—twisting the ends as he spoke. Only a brief pause in the conversation allowed him to lick and seal the paper's edge. Head tilted to one side as though to see around the rising plume of smoke, this wise old man continued his eloquence.

Tuck was the recipient of one of this author's devious manipulations of the English language. A cardboard box had been found with assembly instructions for the box itself printed on the cardboard: "Tuck Flaps Inside." English pupils in grammar school could diagram that imperative sentence easily. The subject, "you" is understood; the verb is "to tuck." The direct object, telling what is tucked, is "Flaps"; and the adverb "inside" tells where the flaps are to be tucked. Applied to Grover Tuck, however, the subject of the sentence becomes the man, himself. The verb, Flaps, has the colloquial meaning to speak randomly or loosely; and "inside" remains an adverb describing where Tuck "flaps." The cardboard sign took on this new meaning when taped to the door to Grover Tuck's office.

On one occasion, a small number of distinguished visiting scientists from England were allowed to visit Building 886. Routine plantwide security measures made such an event quite rare, although exceptions could be made in the late 1960s. Coffee was offered as a means of creating a comfortable atmosphere for some long-ago-forgotten purpose of this international meeting. Most residents of the building drank their coffee black and unsweetened, a condition deemed hardly civilized by the British. Their request for cream and sugar came as somewhat of a start; but the need was quickly assuaged. One person had a container of powered coffee creamer. Its use had to be explained to the visitors because the product was still new on store shelves. This author had a bottle of artificial sweetener which he kept for sweetening his iced tea. It, too, was a recent addition to the nation's food shelves. Naturally, a couple drops of this concentrated sweetener were sufficient for even a large glass of iced tea. The British were visually shaken by the use of *powered* cream and *liquid* sugar; but, muttering under their breath about strange Americans, they attended to their coffee with good nature. Their coffee was creamed to a suitable color. The sweetening process, however, is what earns this vignette a place in recorded history. One British scientist, who admitted to liking four lumps of sugar, proceeded to fill his teaspoon brim full of the concentrate. Horrified Americans watched as he stirred this into his cup. Amazement intensified as a second, then a third, and finally a fourth teaspoon of the syrup found its way into the hot coffee. Evidently, the visitor equated one lump with one teaspoon-full. Schuske's tribe sat transfixed as the guest brought the cup to his lips. Pausing his technical conversation only long enough to take his first swallow,

he interrupted his own train of thought to affirm something like: “Now that’s good coffee!”

Another year into the 1980s, several German scientists were to visit the plant and discuss now-forgotten Rocky Flats business. Plant security measures by then would not allow foreign nationals on plant site; so this author was asked to arrange for the use of other facilities at a scientific institution in Boulder, Colorado. Now, away from plantsite, he worked closely with an international student exchange organization, Youth For Understanding, to bring high school boys and girls from all over the world into schools all over the United States for a year’s study. One of his local charges was a lovely young woman from Göttingen, Germany named Leona Achtenhagen, a student at a nearby high school. Coffee and donuts were announced about mid-morning. Leona entered the room and announced, in German, her name and the fact that she was there to serve them refreshments. The Germans insisted she accompany the entourage to lunch a while later. They enjoyed the twist.

### ***Lunch Time Pursuits***

Rocky Flats has always been a distance from any commercial eating establishment. Traveling to a restaurant for lunch was not a common practice until later years. Most people in Building 886 brought a sack lunch. Games filled the time between fruit and sandwich and the end of the half hour lunch break for many employees. Some of these games might amuse the reader.

“Hearts” is a popular—yet simple—card game wherein players wish *not* to collect hearts nor the queen of spades. Five players is a good number for the game, although three to eight may play a

less-challenging game. The game’s popularity “caught on” and, soon, ten to fourteen players wanted to play. This was far too many people for a single deck of cards. The obvious solution was to play with two decks—twice as many “bad” points to give to somebody else (devilish grin). But, who should take the trick if the highest card happens to be paired? The first one to play it? The second? Scientists and engineers are noted for imagination and creativity; and that naturally extends to a simple card game. The decision was made that paired cards canceled one another; so the next lowest high card would take the trick—with all its hearts and, possibly, paired queens of spades. That card, however, might also be paired; so, then, the next lower high card took the trick. The rule became that the highest *unpaired* card in the led suit would take the trick. Sometimes, the innocuous deuce of some suit might be led and end up taking the trick! Complications continued. Enough players joined the fun that two normal decks of cards were hardly enough. Several jokers from each deck were added to the total; and these cards counted 20 points each against the taker. One final embellishment to the “modified” hearts game was the agreement to play *twice* around the table for one trick. That way, a player dealt paired cards could intentionally cancel himself on the second round. More than 20 playing cards would be taken on a single trick. The game proved quite interesting and was played for several years.

Twelve people around a long table put some players far from the playing center. Most were able to propel their cards onto the pile by imparting sufficient angular momentum to the played card. One player, Lynn A. FitzRandolph, never really mastered this “spin” technique. He more-or-less *threw* the card at the



growing pile. His cards tended to “flutter” toward the pile but never really onto it. One fluttering card ended up in someone else’s coffee cup much to the amusement of all.

At the game’s height, more wanted to play “hearts” than could reasonably be accommodated. The overflow chose to play chess. A half-hour lunch period is insufficient for a normal game of chess; so these clever people modified even this noble game. It became “give away” chess. The winner was the person who *lost* all their pieces first. The rule was made that a player *had* to take a piece if possible; but, if optional captures existed, the choice was his. Obviously the weaker piece would be taken leaving a more powerful one with more capture power. Complications continued. Four wanted to play; so two sets of chessmen were obtained. Both sets were red and white but had different shaped bottoms. The board was embellished by adding a  $2 \times 8$  starting rectangle off each of the four sides, leaving the entire  $8 \times 8$  original board to become the give-away field of play. The game required considerable concentration to play and became really quite sophisticated. One final modification was the agreement to introduce a Monte Carlo sense of chance into whose turn would be next. This seemed appropriate for an organization using the just-introduced Monte Carlo computer code: KENO. Each player was assigned a different colored marble; and a fifth participant drew marbles at random out of a hidden box. The person assigned that marble was obligated to take a turn and to capture someone else’s piece, if possible. Again, if options existed, the least powerful piece of the player having the most pieces remaining was likely chosen. This marble option complicated strategies quite a bit rendering long-range plans almost useless. The game came to be called “Chance Chess.”

Someone in the building discovered somehow and someplace that the plastic lids from either two-pound or three-pound coffee cans are quite aerodynamically stable if thrown with considerable spin imparted by the wrist. With the lip on the rim projecting downward, they behave much like the familiar “Frisbee.” They were, of course, much lighter. Let the games begin!

The main hallway down the north/south portion of the Cold Area was 1.83 m wide by 2.44 m high. The length of the hallway from the T-section with the east/west hallway to the drinking fountain just outside the women’s rest room was about 19 m. With a bit of practice, the coffee can lid could be sailed down that entire length—sometimes without hitting anything. The trajectory was never perfectly straight; so many times the projectile brushed the wall enroute or hit an obstruction and stopped short of the full distance. “Rules” evolved as follows. One player stood at each end of the 19-m-long course. The hurler earned a point if the lid passed the whole distance without touching walls, floor, or ceiling. The other player earned the point if an obstacle stopped the lid short of its goal. Neither earned a point if a surface was grazed yet the entire route was covered. Few obstacles encumbered the course: the waste repository for classified documents to be discarded, the public address speaker in about the center, and doorways leading to five offices. The game, like ping pong, was played to 21 points.

This proved to be another lunchtime pass-time. Many became quite proficient in directing the flight path of this light-weight toy. It provided such amusement that some die-hard advocates occasionally elected to stay late at the end of the day just to play a couple of games of Hallway Frisbee.

Both lunch-time and end-of-day games provide amusing stories. C. L. Schuske wore a bow tie in those early days of Building 886. One day, as the coffee can lid sailed back and forth during the noon break, he exited the main office—his mind intent on some business matter. The plastic lid clipped Schuske's bow tie. The cross section for this event had been considered quite small; but, alas, the players were proven wrong. The noon-time game took a required hiatus for a few weeks. On another occasion, this author had completed a day of working in company-supplied clothing. Radiation surveys revealed no contamination on the clothing; so, according to procedures, he was about to shower before going home for the evening. As the end-of-day sound propagated over the plantsite, he had just removed his white coveralls and was dressed in company T-shirt, white under shorts, and white sox. Chatting with his colleague, Howard W. King suggested a quick game of hallway Frisbee now that the rest of the workers had gone home. This author enjoyed the game and, so, agreed. For shoulder warmth only, he donned a smock but left it unbuttoned. King quickly offered to take the north "goal," leaving the under-dressed author defending the water fountain. About half the game was finished when two events occurred simultaneously. This author balanced on his right foot with his right arm fully extended speeding the Frisbee on its way north. His smock hung open under this posture. The second event was the opening of the door to the women's rest room and the unexpected emergence of Carla Fisher, the secretary. Both froze in their tracks with eyes aghast as King doubled over with laughter at the far end of the hall. He had been fully aware that the building was not completely empty when inviting the game to commence a few moments earlier.

That innocent incident might have consequences in today's work world; but at the time it was recognized for the prank it was. One other oft-repeated scenario involved scientist and Secretary Fisher. Equal innocence is claimed; but the action would not be politically correct today. Fisher's office contained a number of four-drawer safes filled with classified information. She was the constant over-seer of these safes. From time to time throughout the day, Fisher needed to be absent from the office for brief periods of time. Rather than lock up the safes, she asked others in the building to sit at her desk these few minutes. The duty rotated so it was not difficult for anyone to accommodate her. When this author was called upon, his reward was a 30-second-long shoulder massage. In time, Schuske suggested the practice might seem inappropriate; so it ended.

### *Physics*

Raschig rings are amazing things. Modern ones, manufactured since 1970 and subject to an American National Standard, are so strong they can be dropped from considerable height with little chance of breaking. This author had demonstrated that strength quite convincingly time and time again over many settings. Sometimes the glass ring was even thrust upon the floor with considerable force only to bounce around the room. One time, however, the demonstration failed. Out of doors and standing on a concrete surface, this author tossed a ring a meter over his head aimed for a landing on the concrete. As it flew, bragging words were spoken predicting the result of this dramatic exhibition. Troweled concrete, however, sometimes has little hard protrusions in its otherwise smooth surface. This ring found

that hard point and exploded into thousands of fragments. Onlookers laughed while this author sought dust pan and broom.

An interesting physics demonstration involving classical mechanics from first-year graduate study can be obtained from one of these Raschig rings. If the right circular glass cylindrical shell were allowed to lay on its side on the floor, a sharp blow can be imparted to the ring by stomping down hard with the edge of a shoe's heel. This imparts a very large angular momentum to the cylindrical shell sending it spinning and scooting over the floor's surface. The spinning ring will invariably come to rest with its cylindrical axis pointing vertical. The physical explanation behind that unerring phenomenon is that the cylindrical axis has a smaller moment of inertia than either of the other two orthogonal axes. Laws of physics dictate that a spinning object will seek to adopt an orientation yielding the lowest potential energy; and that corresponds to that axis pointing up.

Rocky Flats, as a plantsite, had arranged to shut down completely during the week between Christmas and New Years. This gave all employees (except a few responsible for certain aspects of plant safety) a long break with their families during the festive holiday season. It was a popular arrangement that lasted through more than the 1970s and 1980s. The nation's energy crisis of the earlier decade prompted the plant to adopt a patriotic plan to lower ambient temperatures in working areas plantwide to levels which would prove uncomfortable to human beings. Exceptions were allowed if justified. Building 886 was spared this plight because of the uranyl nitrate solution. No one knew the affect that greatly reduced temperatures would have on the solubility of the uranium salt within dilute nitric acid.

Serious problems could develop if the uranium should precipitate. The worst would be a criticality accident.

On one occasion, the south door to the Assembly Room needed to be opened. This action followed a few years on non-use. The door would not budge in spite of its hefty 3.5 horsepower electric motor. Investigation quickly revealed the cause of the problem. Pigeons found the mechanism under a concrete overhang an excellent place to roost. A metal plate keeping the weather from affecting the mechanism protected the birds from wind and rain, too. The result of residency was a thick pile of bird droppings sufficient to bind up the motor drive.

### *An Award Ceremony*

During the years Rockwell International managed the plant, Rocky Flats employees had an opportunity to be nominated for and earn the coveted title "Engineer of the Year." This prestigious award was given out annually to the best scientists and engineers within the company's world-wide corporation. Typically, about a dozen recipients were named each year with no ranking within that illustrious group. The award was considered a rich plum and was highly respected.

One year about the mid-1980s, a Formal Luncheon was held in honor of the present year's winner as well as past recipients. The guest speaker was introduced as a high-ranking member of the Russian government's involvement in the nuclear industry. The speaker's last name has long since been forgotten; but it was something close to "Petrovich." He was a stout figure, tall on a large frame; and he sported a close-cropped style of shimmering white hair. He was quite an imposing, yet handsome, figure.

Petrovich spoke with a fairly thick Russian accent; but his English was quite good. His speech began with the usual pleasantries with an overview of the entire speech. He seemed to strangely emphasize the fact that it would be divided into three parts; but this was quickly dismissed as a quirk of his speaking style. Part one began along anticipated lines; but his remarks slowly grew abrasive. One of his earliest troubling remarks was when he readily acknowledged the attractiveness of the Rocky Mountains (which wall the plant to the west) but quickly tempered that shallow compliment with a comparison with Russia's Ural Mountains. Clearly, from his glowing comparison, the Urals were far superior. The audience fidgeted a little but reluctantly accepted this as a biased opinion.

Next, he thanked Rocky Flats management for their courteous reception but quickly chastised the same management in the next breath. He claimed to be disappointed that he had not been offered a tour through some of Rocky Flat's more secure buildings. "On the other hand," he assured the audience "a visiting American scientist would surely have been give access to even the innermost operations of Soviet nuclear installations." The audience squirmed noticeably in disbelief but more in resentment of his crude accusation. Still, he was our guest; and his manners, though rude, were to be overlooked. Nonetheless, the verbal barbs persisted and even became more pointed. He became more and more hostile toward the United States, the government, and Rocky Flats in general. Many in the audience considered walking out on him but proper protocol prevented that. This politeness was tested, however, when Petrovich looked at a woman in the

audience, a past winner of the coveted award. He openly accosted her verbally stating that, "In Russia, women knew their place. They were to remain at home, take care of the house, bear children, and leave the serious and intelligent work in the hands of the more-competent male." Even this author's knuckles turned white as he gripped his chair wondering how much more verbal abuse should be absorbed in the name of diplomacy.

Part two of Petrovich's speech began unnoticed. It took several minutes to unfold. He had slipped into it so smoothly that no one recognized the transition. The thesis of this second part was that "seldom are things exactly as they seem." Without the audience realizing it, his thick Russian accent began to weaken. It faded more and more with each passing moment. The process was so slow that different people realized at different times that the speaker's accent was altogether gone. He was speaking in a clear English, totally devoid of *any* accent!

Part three revealed that Petrovich was not his real name. Nor was he even Russian! He was, in fact, a speaker from the United States government, possibly even the Central Intelligence Agency. Part three contained the explanation of his ruse. His goal had been to illustrate the ease with which international spies could fool a careless public. This fake Russian diplomat received a well-earned ovation at the end of his object lesson.

### ***Not Associated With Rocky Flats***

This last snip-it from history does not involve the CML or the Rocky Flats Plant at all. It is a humorous event drawn from the archives of the nuclear industry as a whole. It is too funny to omit from this chapter merely because it does not involve Rocky Flats.

The tale was regaled by Dr. Herbert Kouts, once the head of Brookhaven National Laboratory's (BNL) Critical Mass Laboratory. The story was contained in a Keynote Address to some long-forgotten professional meeting. According to him, one of the earlier nuclear reactors built in the USA, possibly at BNL itself, required a considerable amount of steel in its design. This steel was needed as forms for pouring concrete for radiation shielding somewhere in the periphery of the reactor. World War II had recently ended; so a large number of naval vessels were available for scrap. Armor plate from some out-of-service battleship was obtained for the required shielding construction. These scrap plates had many holes and odd shapes in them to accommodate their original purpose. Engineering drawings for the reactor design specified that the odd shapes were to be cut away to leave the required final geometry, possibly rectangles; and drawings instructed that holes were to be filled in. Presumably, solid slabs of steel were needed for this purpose.

Some years later, another reactor was to be built using the same overall design. It would be quite similar to the first. Use of existing drawings would save considerable engineering expense; and this shortcut seemed prudent because the same massive amount of steel was needed. No more moth-balled battleships resided in the warehouse; so new rectangular slabs of steel plate were purchased. Drawings for

the new reactor contained quite specific instructions. The new steel plate was first cut to the shape of the scrap material from the retired battleship; and "necessary" holes were cut into the metal. Next, the holes were filled in by welding them shut; and the plates were cut to smaller sized rectangles. The drawings *really* had been specific. A considerable amount of paper and engineering time had been saved by reusing an earlier design; but that certainly was overwhelmingly offset by the amount of discarded steel plate. This author's notes about this humorous episode bear the date May 10, 1994; but the meaning of this date is not recalled.

### ***In Perspective***

Only four events in American history during the entire life-span of the nuclear fission industry (1938 to present) are woven together with the following unique common thread. That commonality is that every American old enough to have any adult recollection of the event will know where he/she was when that particular event took place. These four are:

The bombing of Pearl Harbor  
December 7, 1941

The assassination of President Kennedy  
November 22, 1963

The explosion of the Challenger  
January 28, 1986

Terrorist attacks on the World Trade Center  
September 11, 2001

This author barely remembers "The day that will live in infamy" because he was only six years old. He does carry cloudy images of concerned parents listening intently to the radio and speaking in unfamiliar tones as he innocently inquired why things seemed different that day. For the second of these, he was a graduate student at the University of Wisconsin.

He was sweat-soldering many pieces of large-diameter copper tubing together to make a high-vacuum system for the Tandem Van de Graaf accelerator later used for his PhD thesis data when the news horrified a nation. The proudly completed task lay on the floor of the accelerator room and seemed less important somehow.

For the third, he recalls sitting in silence in the Electronics Support Room to the CML as the tragedy unfolded. Douglas Payne had rigged up a makeshift antenna to a spare television set (destined for the Control Console eventually) in order to receive television channels. Most building personnel sat in awed silence watching replay after replay on the tragic accident. Each was absorbed in their own thoughts. Some cried. No critical mass physics research happened that day. The last just happened to coincide with this author's professional presentation on "Aspects of the History of the Rocky Flats Critical Mass Laboratory" to a collection of professional scientists and engineers associated with the nuclear industry. These persons were to have traveled from nearby states in some cases for this talk. His notes lay scattered on the kitchen table during breakfast when this author's daughter called to inform us of the attack on the twin towers. The talk was cancelled,<sup>88</sup> the plant was closed due to high security alert, and the author's drive to give this paper understandably vanished.

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<sup>88</sup>The talk was eventually rescheduled for the spring on 2002 and successfully delivered.

## ***Acknowledgments***

Patricia Buffer, then with the Rocky Flats Communications Department, was a ready and willing source of information, especially in facts related to the entire Rocky Flats site. She graciously confirmed events and dates recalled by this author but in need of that confirmation. Another significant help in recalling the correct sequence of even unrelated events at the plant was found in a history paper authored by D. Jayne Aaron and Judith Berryman. This effort was completed in September, 1998. The document is called an HISTORIC AMERICAN ENGINEERING RECORD (HAER No. CO-83). The title of this 88-page document is simply "ROCKY FLATS PLANT." The document fulfills a legal requirement because the Rocky Flats plant, a location on the National Park Service's National Registry of Historic Places, will be demolished in future years. The document can be found in the Library of Congress. This author had been given a copy by Ms. Aaron because he had contributed certain portions of the paper to her in the first place.

Kathy Abeyta of the Rocky Flats photography department was most gracious in supplying working copies of dozens of photographs most of which were incorporated into this document. Originals of these photographs existed in this author's personal collection; but he was not willing to part with them for fear of breaking up the complete set. That large collection of original photographs will be donated to the LANL Archives about the year 2004.

This author's secretary for almost three decades, Carla L. Fisher, was kind enough to print out one full copy of the nearly-completed text for an important near-final proof reading by the author. Thanks to her for that and for being a close friend all those decades. She also served as a ready resource for checking out hazily-remembered details on a number of occasions.

Rock Neveau, a Radiological Engineer currently assigned to Building 886, has been most generous with his help. He provided many details about the building concerning events since this author left plantsite as well as a number of photographs which are now figures in the present document. These pictures included the removal of the uranium solution storage tanks and the equipment used to transfer the solution out of Building 886 in the mid-1990s as well as modern respiratory apparel. Paul D. Felsher, Jerry E. Hicks, Robert (Bob) W. Wilson, and a few others still employed at Rocky Flats and associated with Building 886 long after this author's departure also graciously provided needed assistance whenever asked. Gilbert ("Gil") Garcia, also now retired, reviewed a portion of the text for accuracy with respect to certain radiological safety measures.

This author is grateful that retirement did not end his close association with Rocky Flats, its people, the plant's mission, or the nuclear industry itself. Several of the above-named persons and others contacted this author on a number of occasions asking questions about a wide variety of issues relating to Building 886.

Answers helped them in their day-to-day tasks but made this author feel continually useful. In response to this help, Rock Neveau was kind enough to host a luncheon in this author's honor in the summer of 2001. Two sentimental souvenirs of the building were presented at that time and accepted with grateful emotion. One, a cylindrical core-drilled section of the concrete foundation of the Assembly Room, now proudly decorates this author's flower garden at his home to his wife's feigned exasperation. Bob Wilson arranged a formal presentation of a concluding paper on the author's work at the Rocky Flats CML on September 11<sup>th</sup> of 2001. Persons associated with the nuclear industry from all over Colorado and nearby states were invited to this nostalgic visit to the memory of a once-glorious laboratory. That talk was delayed by about a year due to the tragic events surrounding the World Trade Center.



## *Author's Biography*

One could make a point that the life of Dr. Robert E. (Bob) Rothe is boring because of his long-term stability; but, he views his career and his life as a whole differently. True, he has had only one professional employment in his entire career: Rocky Flats. He has only worked in one building: Building 886. He has only and always been a Critical Mass Physicist. Outside of work, he has been married to only one woman; and they have owned but one home. Humorously, this stability is the opposite of his company. The company for which he worked and which served as a prime contractor to the US government bore four different names; and the governmental agency to which that company reported has rotated through three titles during this same span of decades.

Childhood on the northwest side of Chicago was relatively uneventful, although the imaginative youngster was once expelled from kindergarden!<sup>89</sup> Like most pubescent boys, he would sneak clandestine reading material when left alone at home. Unlike others, however, that secretive document was the family's encyclopedia. Absorbing all the physics and chemistry those pages could offer, this 12-year-old boy memorized densities of elements and half-lives of isotopes as well as the structure of the Periodic Chart of the elements. He strained to understand the

meaning of "electronic configurations"; after all, the meaning of "4f electrons" is not immediately obvious. He decided to become a nuclear physicist at the early age of 12.

Childhood led to Knox College in Galesburg, Illinois, about 160 miles west of Chicago. There, he met his life-long partner, Judy, and graduated with a Bachelor of Arts degree—being the first ever to graduate with Honors in *two* departments: physics and mathematics. A year of graduate study at the California Institute of Technology, however, burst his self-imagined ego—a fantasy wherein one day he would win one more Nobel Prize than any other person ever has won.

Summer jobs at the Navel Research Laboratory two years in a row guided him further in his career selection. One year was spent doing experimental work on dynamic metallurgical properties of ship-plate steel. His mentor, Dr Joseph Krafft, was instrumental in directing this author's future career choice. The other summer found him on a theoretical research project. In spite of being under the direction of a world-renowned physicist (Dr. Robert Jastrow), those two years forever cemented his love of experimental work.

Subsequent employment, while still in pursuit of a degree, further clarified his interest in experimentation. He participated in the development of the accelerating cavity for the Zero Gradient Proton Synchrotron at the Argonne National Laboratory. This machine served as the forerunner to the synchrotron accelerator

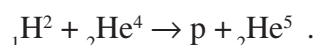
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<sup>89</sup>He had so enjoyed playing with his toy PT boat (with the school room floor the ocean's surface) that he shot his teacher in the leg with a "torpedo" rather than put away the toy at the end of show-and-tell time. He was only expelled from school on two other occasions.

built at Weston, Illinois. Dr. John Martin was mentor and often offered this young man, often lacking in confidence, wonderful advice. Dr. Martin, too, is acknowledged for his patient guidance.

The University of Wisconsin seemed to be a happy location for this author's continued progress toward a PhD degree. Some questioned how a young man with a wife and two children could possibly focus on an advanced degree. This author, however, readily admits he could *not* have waded through requirements *without* the support of a family.

Again, accelerators entered into the picture. At first, he assisted older graduate students on the Tandem Van de Graaf accelerator built by High Voltage Engineering, a Boston firm. This device was capable of achieving 7,500,000 volts on its polished dome and, thus, produced 15 MeV charged particles for experimental research. His group, under the able leadership of Dr. Hugh Richards, was involved in the study of nuclear energy levels of light nuclei. This was accomplished through the interaction of various light charged particles (protons, deuterons, and alpha particles) with light nuclei from hydrogen to oxygen. In time, his turn came; and his PhD thesis, in particular, involved the search for the possible non-conservation of isotopic spin, T. In particular, he studied the reaction between deuterons and helium nuclei. Both of these are T = 0 particles. Three energy levels in the compound nucleus ( ${}^6_3\text{Li}$ ) exhibit T = 1 characteristics and should not be excited through this interaction. His thesis study, then, was:



This author readily acknowledges Dr. Richard's patient guidance resulting in his PhD degree in the summer of 1964.

Judy and he were married in 1957 while still enrolled at Caltech and well before the University of Wisconsin era. They had four children in two sets of two. The first two were born during the Wisconsin years and 14 months apart. The last two were born in Colorado, also 14 months apart.

His search for a employment led to a trip to Colorado in 1963, a full year before the thesis was finished. He was interviewed by Clarence Lee Schuske for some not-quite-understood-at-the-time group called "Nuclear Safety." Although he liked the experimental nature of the work proposed and had about decided to accept the position offered, he did not truly know the overall mission of the plantsite. That was a well-kept secret. He was not told more than he absolutely needed to know; and even that fell within limited governmental guidelines. He still remembers discussing, weeks later, the potential job with another professor at Wisconsin and was openly surprised when Dr. Heinz Barshall said in an advisory tone, "Oh, that's the new nuclear weapons manufacturing plant!"

He took the job and bid farewell to Madison, Wisconsin. His parting promise to Dr. Richards was that he would get his PhD thesis published in the open literature within one year. Professor Richard's wry smile gave away skepticism. He had been promised that by other students; but they never delivered. The excitement of a new career, the challenge of new frontiers, and a dedication to a new—and larger—source of income always caused the promise to slide to next month ...then, next year. Now, about half a century later, this author is considering finally being faithful to that promise to a knowing Professor. The publication, by now, would be little more than a Technical Note or Letter to the Editor.

Construction on Building 86 had just been started and was several months away from completion when he began his professional career. The date was August 10, 1964. A few weeks later, Schuske assigned him the responsibility for managing the yet-to-be-delivered uranyl nitrate solution and for designing and performing critical experiments using that fissile liquid. He was to participate in other critical experiments, too, of course; but his primary assignment dealt with the fissile solution.

Silently, this somewhat frightened novice in the field of nuclear criticality nervously questioned his apparent major change in arenas of expertise. Graduate school had involved charged particle interactions with the lightest of nuclei. Now, the professional world wanted him to investigate neutral particle fissioning of the heaviest of nuclei. Could he deal with this transition? What were the properties of uranyl nitrate solution? What on earth is a Raschig Ring? Does one die if you ingest a nuclear poison? Shouldn't he have at least taken one course in Reactor Physics? What was he getting into? Far more questions than answers!

In retrospect, his first year was ignominious. In fact, it was really not at all successful. The solution arrived at the building in a number of drums in the summer of 1965; and three major problems emerged almost immediately. Why he did not receive a criticality infraction for admitting 540 gU/l uranyl nitrate solution into a tank clearly limited to 450 gU/l will never be known. The first ten drums *averaged* that; and it was only an accident of fate that he unintentionally chose the highest concentration to be the first solution into the tank farm. Second, the amount of uranium sent by the shipping building (Building 81) did not agree with the amount received at the CML by some

50 kg. In his defense, this latter shipper/receiver difference was not at all his fault. Still, he did not ask the right questions nor understand the procedures being employed as the transfer was under way. Finally, in this year of tribulations, the first summer produced three annoying contamination incidents; and these *were* altogether his fault. Moreover, some of them appear downright stupid. C. L. Schuske showed remarkable patience with this fledgling scientist.

Things improved with time. Experiments became better designed. Problems with the solution handling became less and less.<sup>90</sup> His ability to design good experiments grew; and he felt more confident as years progressed. By the end of three decades, he had led or participated in some 1700 critical and critical-approach experiments. These involved uranium at two enrichments as well as plutonium. Experiments involved metal, solution, and powder; and they were bare as well as reflected. Some involved neutron absorbers; others did not. Single units and arrays were studied. Geometries ranged from simple to complicated. Careful precision in experimental research became the watchword of the entire CML.

Apart from critical experiments, state-of-the-art solution handling and inventory techniques were creatively implemented such that consecutive triennial inventories often agreed with one another to within a few hundred grams (an amazing 0.15%!). He became involved in the American Nuclear Society and served as the Secretary for the writing of an American National Standard: ANS 8.5-1996. He became recognized as an expert on the subject of borosilicate glass Raschig rings—

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<sup>90</sup>One serious breach of this statement, in 1969, is discussed in another chapter.

those same glass cylinders that had befuddled him so in 1964.

He remains grateful for the recognition given him during these decades. He, along with a few others, had been selected for Rockwell International's coveted world-wide "Engineer Of The Year" award in 1981—this from a field of candidates that spanned Rockwell's world-wide facilities. A couple years later, he received Rockwell's "Good Citizen" award. Apart from work-related areas, he and his wife were Foster Parents to 90 children in the 1970s. In the next two decades, they hosted over seven dozen young adults from other countries through three different international programs. They have been recognized for these efforts through several awards.

His hobbies include model railroading, white water river rafting, teaching history classes, and singing in operas. He is the world's 281<sup>st</sup> "Master Model Railroader," has rafted over two hundred trips on dozens of rivers, and sung in 13 operas.

Life is wonderful. This author is grateful to an industry that has given him so many challenges, recognized his successes, and overlooked his weaknesses. He is pleased to be able to leave that same industry with this "Technically Useful History of the Rocky Flats Critical Mass Laboratory." He considers its completion a successful and happy conclusion to a rewarding career.

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The more than 100 references contained in this section are almost completely associated with one chapter of the book. That is the chapter titled “A Chronology of Experimental Programs.” That unusual situation arose from one goal of that chapter which was to document those publications stemming from each different program ever conducted at the CML. Other chapters are devoid of references because

almost all of them are eventually contained in this one chapter. The very few documents which might have been referenced—but were not—in other chapters were not done so simply because those references were lost or unknown to this author. In a few cases, the reader is directed in other chapters to the LANL Archives where some of these documents may still exist.

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