HEALTH PHYSICS FOLLOWING A NUCLEAR EXCURSION:
THE LRL INCIDENT OF 26 MARCH 1963

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RONALD L. KATHREN, WALTER C. DAY,
DALE H. DENHAM, and JACK L. BROWN

Lawrence Radiation Laboratory, University of California
Livermore, California
June 3, 1963

Abstract—On 26 March 1963 at 0000 hours a nuclear excursion occurred in a
shielded vault designed for critical assembly experiments. The excursion
was estimated at $4 \times 10^{17}$ fissions, and was followed by oxidation of the en-
riched uranium metal in the assembly. The fire was observed via closed
circuit TV; later entry established that burning was limited to the assembly.
Nearby combustibles did not burn or scorch.

Disaster plans were immediately implemented to determine: (1) radia-
tion exposures to personnel directly involved, (2) the possibility of recurring
criticality, and (3) the extent of release of radioactive materials to the Labo-
rary and to the off-site environment.

Air and surface contamination levels were determined in the building
housing the vault and at other points within the Laboratory perimeter. Air,
vegetation, and soil samples, obtained within hours following the excursion,
were analyzed for fission product and alpha activity fallout. Results indicated
the release of small amounts of short-lived, high-yield gaseous fission prod-
ucts and their daughters. No detectable alpha activity was released to the
environment.
The maximum exposure to any of the four persons in the building at the time was 120 mrem penetrating gamma radiation. All neutron exposures were less than detectable limits, i.e., 50 mrem fast neutrons and 1 mrem thermal neutrons. Urinalyses, nasal swipes, and thyroid scans were all negative, indicating no internal exposure.

An air sample taken from within the vault 57 hours after the excursion showed levels of $\sim 2 \times 10^{-6} \mu\text{c/cc}$ of short-lived fission products. Radioactive decay and changing the vault air reduced these levels to below MPC values. The air exhausted from the vault was filtered and scrubbed with caustic before release to the atmosphere.

The initial vault entry was made to size up and — if necessary — to eliminate the possibility of a further excursion. The gross amounts of all fissile material were removed before decontamination operations were begun. The building, exclusive of the vault, was reoccupied six days after the incident.

This incident reaffirms for us the value of carefully designed vault facilities for critical assembly work.

INTRODUCTION

On 26 March 1963 at 0000 hours, a nuclear excursion occurred in a shielded vault at the Lawrence Radiation Laboratory, Livermore. The experiment in progress was the stepwise measurement of neutron multiplication in a critical assembly.

The vault, designed for critical assembly experiments, is part of a building housing office spaces, a machine shop, and other experimental areas.
Two of the vault walls are poured concrete and two are made of large concrete blocks set in mortar; all walls are 5 feet thick. The insides of the walls were painted with two coats of polyvinyl paint. The roof is made from interlocking concrete beams 30 inches thick with all cracks taped to form a complete seal. A 6 foot water window and a closed-circuit television permit direct observation from the control room into the vault. A slight negative pressure (~0.015 inch water) can be maintained in the vault by an exhaust ventilation system independent of the rest of the building. Air withdrawn from the vault is assed through a double bank of filters before being released to the environment.

THE INCIDENT

The experimental critical assembly consisted of concentric cylinders of enriched uranium, surrounded by a beryllium reflector. When fitted together, the uranium formed a single hollow right cylinder. The approach to criticality was to be achieved by moving an enriched uranium ram up into the open portion of the cylinder. This was to be accomplished in a stepwise fashion to determine neutron multiplication at several levels of the ram. A maximum neutron multiplication of 100 was set for this experiment. The total quantity of uranium in the assembly was 47 kilograms.

On the eve of the excursion, two safety check assemblies had been tested satisfactorily; the experiment was then begun with the actual assembly. Neutron multiplication measurements were made at the first seven stepwise positions of the ram (Fig. 2). After each measurement, the ram was lowered away from the rest of the assembly and a polyethylene safety ring removed. Removal of the ring permitted the ram to be raised to the next higher step. The ram was raised to the eighth stepwise position and a measurement begun. Neutron multiplication rose to the expected level for a few seconds, and then without warning the assembly went prompt critical (Fig. 2).
This sudden rise in reactivity was accompanied by an explosive sound heard in the control room over the intercom system to the vault. Scram and criticality alarms were actuated, the vault vent valve automatically closed, and the ventilation system shut down. For a few seconds, the television monitor was blank, then the observers in the control room could see flames and what apparently were portions of the assembly melting and breaking apart. The emergency call was sounded and the four occupants of the building quickly left.

The prompt gamma radiation from the burst was detected by continuous air monitors located in the building (Figs. 3, 4), and by continuous air monitors in each of two other buildings about 350 meters distant (Fig. 5). Hand and foot counters in these buildings alarmed. The burst was not detectable elsewhere on the Laboratory site.

Fire and monitoring units responded to the emergency call independently and arrived on the scene about three minutes after the burst. Radiation levels outside the building were less than 1 mr/hour. An entry was made into the building approximately nine minutes after the criticality by emergency personnel wearing full protective clothing and air-supplied respirators. Radiation levels were low, varying from 10 mr/hour in the control room to a maximum of 90 mr/hour near the vault door. No entry was made into the vault, but gamma radiation was about 10 r/hour as indicated by three remote area monitors on different interior walls of the vault (Fig. 1). Later readings showed that these levels closely followed the \( t^{-1.2} \) decay estimate for fission products.
CAUSE AND MAGNITUDE OF THE EXCursion

The cause of the excursion is believed to be directly attributable to mechanical failure. The ram may have been slightly off center with respect to the remainder of the assembly (Fig. 6A), and, as it was raised, the ram carried the innermost cylinder upwards (Fig. 6B). A small disturbance re-aligned the cylinder, and it slipped down over the ram, changing the geometry sufficiently to allow a prompt criticality to occur. The excursion was halted by a change in geometry caused by the melting uranium, and by the activated scram system. The explosive noise probably resulted from portions of the assembly being forced against the top plate of the assembly carriage.

The magnitude of the excursion was estimated by radiochemical analysis for Mo$^{99}$ at $8 \times 10^{12}$ fissions/gram. For a 47-kg assembly this results in $3.76 \times 10^{17}$ fissions. Table 1 presents some comparative data on the energy release of the criticality.

Table 1. Comparative energy release data.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of fissions</td>
<td>$3.76 \times 10^{17}$</td>
</tr>
<tr>
<td>Heat generated</td>
<td>$3.07 \times 10^{6}$ calories</td>
</tr>
<tr>
<td>Power produced</td>
<td>$1.28 \times 10^{7}$ Watt-seconds</td>
</tr>
<tr>
<td>Quantity of U$^{235}$ fissioned</td>
<td>$2.0 \times 10^{-4}$ gram</td>
</tr>
<tr>
<td>Radioactivity produced</td>
<td>$3.84 \times 10^{7}$ curies</td>
</tr>
<tr>
<td>I$^{131}$ produced</td>
<td>0.280 curie</td>
</tr>
<tr>
<td>Sr$^{90}$ produced</td>
<td>0.590 curie</td>
</tr>
<tr>
<td>Yield (TNT equivalent)</td>
<td>5.76 pounds</td>
</tr>
</tbody>
</table>
The $\text{Mo}^{99}$ estimate of the extent of the excursion is not inconsistent with those made by other means, including a nuclear accident dosimeter located in the vault. A similar dosimeter in the control room indicated no detectable thermal or fast neutron exposure, based on gold and sulfur activation analysis (limits of detection: thermal neutrons, 1 mrad; fast neutrons, 1 rad).

Exposure to personnel in or near the building at the time of the excursion was low, in no case more than 120 mrem. These data were obtained from film badges and are presented in Table 2.

<table>
<thead>
<tr>
<th>Location (Fig. 1)</th>
<th>Gamma (mrem)</th>
<th>Fast Neutrons (mrem)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AR Control Room</td>
<td>120</td>
<td>0</td>
</tr>
<tr>
<td>HB Washroom (opposite control room)</td>
<td>100</td>
<td>-</td>
</tr>
<tr>
<td>HR Kiosk (outside NE corner of bldg.)</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>MR Hallway</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>RR Control Room</td>
<td>70</td>
<td>0</td>
</tr>
</tbody>
</table>

In all cases, the films had been worn by the individuals for several days prior to the excursion; hence, some or all of the gamma exposure may have actually occurred before the excursion. Nasal wipes, thyroid scans, and urinalyses on the individuals in the building were negative, indicating no internal exposure. Theoretical internal dose estimates can be made using the equations derived in the Appendix.
Physical damage was confined to the assembly and associated equipment (Figs. 7 through 9). About 15 kg of uranium and some polyethylene were burned. Other combustibles in the vault were not consumed. The vault floor was highly contaminated with gross quantities of melted and oxidized uranium (Fig. 10); the walls, overhead, and other apparatus in the vault were contaminated to a lesser degree. About 10 kg of uranium had melted and was spread over the floor.

RELEASE OF RADIOACTIVITY

Shortly after the incident, efforts were begun to determine the amount of radioactive material released from the vault, and to determine if any had escaped off-site. It had already been determined by the emergency response team that a direct radiation hazard did not exist outside the vault. However, the possibility of air contamination and recurrence of criticality suggested the evacuation of the emergency crew to a control point away from the building. From this point entries were made to the building to collect air samples and wipes and to view conditions in the vault via the television monitor in the control room. Estimates of possible excursion cloud movements were made and a perimeter survey team dispatched to make radiation surveys and to collect air samples. Vegetation and soil samples were collected a few hours later. A summary of the data from both on- and off-site contamination is shown in Table 3.

The overpressure generated by the excursion released a small fraction of the radioactivity from the vault; most of this was confined to the building. Contamination was found along the cracks between shielding blocks on top of the vault and about $1.2 \times 10^{-8}$ μcuries/cc of particulate beta activity was
### Table 3. Summary of post-incident contamination.

<table>
<thead>
<tr>
<th>Location</th>
<th>Time – date sample taken</th>
<th>Beta-gamma activity</th>
<th>Alpha activity</th>
<th>Isotope (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vault stack (downstream from filters)</td>
<td>0000-0500, 3/26</td>
<td>$1.2 \times 10^{-8}$ μcuries/cc</td>
<td>$4 \times 10^{-10}$ μcuries/cc</td>
<td>MFP$^a$ and U$^{235}$</td>
</tr>
<tr>
<td>Ambient air in building</td>
<td>0000-0100, 3/26</td>
<td>$2.8 \times 10^{-7}$ μcuries/cc</td>
<td>-----</td>
<td>Short-lived fission gases and daughters</td>
</tr>
<tr>
<td>Work area just outside vault</td>
<td>0045-0305, 3/26</td>
<td>$\approx 8 \times 10^{-7}$ μcuries/cc</td>
<td>$7 \times 10^{-10}$ μcuries/cc</td>
<td>MFP and U$^{235}$</td>
</tr>
<tr>
<td>On-site, 350 meters north of building</td>
<td>0100, 3/26</td>
<td>$1.3 \times 10^{-9}$ μcuries/cc</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>On-site, 1000 meters southwest of building</td>
<td>0200, 3/26</td>
<td>$1.6 \times 10^{-8}$ μcuries/cc (by pulse-height analysis and total gamma counting)</td>
<td>-----</td>
<td>$^{135}$I</td>
</tr>
<tr>
<td>Site perimeter</td>
<td>0200, 3/26</td>
<td>$\leq 3.7 \times 10^{-8}$ μcuries/cc (by pulse-height analysis and total gamma counting)</td>
<td>-----</td>
<td>$^{135}$I</td>
</tr>
<tr>
<td>Vault</td>
<td>0500-0504, 3/26</td>
<td>25 rad/hour (direct reading on filter with open window Juno) estimated to be $\approx 10^{-3}$ μcurie/cc</td>
<td>-----</td>
<td>MFP and uranium</td>
</tr>
<tr>
<td>Vault</td>
<td>0900, 3/28</td>
<td>$2.0 \times 10^{-6}$ μcuries/cc</td>
<td>-----</td>
<td>MFP and uranium</td>
</tr>
</tbody>
</table>
Table 3. (Continued)

<table>
<thead>
<tr>
<th>Location</th>
<th>Time – date sample taken</th>
<th>Beta activity (d/m/100 cm²)</th>
<th>Alpha activity (d/m/100 cm²)</th>
<th>Time – date counted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Work area just outside vault</td>
<td>0800, 3/26</td>
<td>93,000</td>
<td>6</td>
<td>1400, 3/26</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1,000</td>
<td>6</td>
<td>1345, 4/10</td>
</tr>
<tr>
<td>Downtown Livermore</td>
<td>0900, 3/26</td>
<td>NDA b</td>
<td>NDA</td>
<td>1600, 4/2</td>
</tr>
<tr>
<td>Work area mezzanine</td>
<td>1200, 3/27</td>
<td>57,000</td>
<td>5</td>
<td>1701, 3/27</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8,800</td>
<td>5</td>
<td>1135, 4/10</td>
</tr>
<tr>
<td>Floors and desk tops in building offices</td>
<td>Morning, 3/29</td>
<td>≤ 800</td>
<td>≤ 5</td>
<td>Afternoon 3/29</td>
</tr>
<tr>
<td>Vault floor</td>
<td>1500, 3/29</td>
<td>15 mrad/hour (by open window Juno)</td>
<td>---</td>
<td>1500, 3/29</td>
</tr>
<tr>
<td></td>
<td></td>
<td>500,000</td>
<td>42,000</td>
<td>5/17</td>
</tr>
</tbody>
</table>

**Vegetation**

<table>
<thead>
<tr>
<th>Sampling Location</th>
<th>Date taken</th>
<th>Sample preparation</th>
<th>Results (µcuries/gram of sample)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Samples taken from the Livermore-Pleasanton area</td>
<td>3/26</td>
<td>Total digestion</td>
<td>High: 1.1 × 10⁻⁴, Average: 6.9 × 10⁻⁵</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Iodine extraction</td>
<td>High: 7.4 ± 1 × 10⁻⁷, Average: 2.7 ± 1 × 10⁻⁷</td>
</tr>
</tbody>
</table>
Table 3. (Continued)

<table>
<thead>
<tr>
<th>Sampling location</th>
<th>Date taken</th>
<th>Sample preparation</th>
<th>Results (μcuries/gram of sample)</th>
<th>High</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Livermore Valley</td>
<td>4/2</td>
<td>Soil dissolved and plated</td>
<td>12.9 $\times 10^{-5}$</td>
<td>4.3 $\times 10^{-5}$</td>
<td></td>
</tr>
<tr>
<td>Livermore Valley</td>
<td>1962</td>
<td>Soil dissolved and plated</td>
<td>25 $\times 10^{-5}$</td>
<td>4.2 $\times 10^{-5}$</td>
<td></td>
</tr>
</tbody>
</table>

*aMFP – mixed fission products

bNDA – no detectable activity.
\textit{In the air that had passed through the vault stack filter bank. Particulate radioactivity in the cloud was observed to have a short half-life Fig. 4). A peak concentration of }2.8 \times 10^{-7}\text{ \textmu curies/cc was recorded on an air monitor used to sample ambient air in another part of the building.}

A few hundred meters to the north of the building the particulate beta radioactivity was }1.3 \times 10^{-9}\text{ \textmu curies/cc. These levels did not indicate any serious problems, since the activity was due mostly to daughters of the high-field, short-lived gaseous fission products. Furthermore, cloud movement and dilution tended to reduce the average concentration in the cloud rapidly. Actually no visible "cloud" existed; this word is used merely for convenience.}

During early entries to the building, an effort was made to determine whether significant amounts of uranium had escaped from the vault. Air samples (Table 3) recovered from the building did indicate that some alpha activity had escaped. Wipes taken throughout the building showed slight alpha contamination (Table 3) when counted in the laboratory. However, no detectable alpha surface contamination was found at the same locations with portable survey instruments, underscoring the need for laboratory counting techniques. Portable survey instruments were useful for finding "hot spots" (\(\leq 20,000\text{ dpm/100 cm}^2\)) along the cracks between the vault-roof shielding blocks. No alpha activity — other than that of natural radon and thoron daughters — was found in any air samples or wipes taken outside the building or in the off-site environment.

A PoBe neutron source was included in the experiment at the time of the excursion. Because of the radiotoxicity of }\text{Po}^{210}\text{, alpha pulse-height analyses were made of samples showing alpha activity with a solid state detector. A typical energy spectrum is shown in Fig. 11, indicating no alpha activity from }\text{Po}^{210}\text{.}
A few hours after the incident, an air sample (Table 3) was pulled from the vault through an existing sampling line designed for routine vault air monitoring. This and subsequent air samples obtained during the week were taken using Whatman ACG-B charcoal filter paper. By using these filters in series with HV-70 or Whatman 41 filter paper, a collection efficiency of greater than 90% was obtained for iodines and particulate mixed fission products.

Gamma pulse-height analysis substantiated earlier assumption that most of the airborne radioactivity collected was from radioiodines. To provide ultraconservative health physics estimates, all activity collected on the charcoal filters was assumed to be $^{131}$I, the most hazardous of the radioiodines. Airborne radioactivity, as determined by this method, was for the most part at or below the 80-hour MPC for $^{131}$I in work areas adjacent to the vault.

The extent of release of radioactive materials to the off-site environment was difficult to determine since the quantities were small enough to be masked by background. External beta-gamma levels were nominally background. No removable alpha or beta activity was found on wipes taken at several locations in the Livermore area. Vegetation samples may have contained small amounts of beta contamination, but lack of previous data from similar samples prevented accurate evaluation of such low levels. Since the most hazardous probable nuclides were the radioiodines, iodine extraction was performed on vegetation samples. Results of these analyses are presented in Table 3 and confirm that the off-site environment had not been compromised as a result of the incident.

Soil samples, collected a week after the incident, showed no significant rise in activity (Table 3) when compared with samples collected at the same locations during the past year. Milk samples, obtained from local dairies
over the two-week period following the burst, were analyzed by the California State Department of Public Health for radioiodine. Iodine was not detected in any of the samples.

VAULT RE-ENTRY AND CLEANUP

During the first several hours following the excursion, attempts were made to establish what might have caused the burst and to determine what configuration the material took after the excursion. It was decided that this information could best be determined by entry into the vault.

In the afternoon, the vault ventilation system was sealed and operated on "recirculate" in an attempt to reduce airborne radioactivity by passing the vault air through the filter bank. The vault pressure increased to about 0.015 inch of water positive, forcing airborne radioactivity from the vault. The recirculating attempt was halted after about two minutes of operation.

A caustic scrubber (Fig. 12) was installed on the afternoon of 28 March as a further attempt to reduce air concentrations in the vault. The scrubber system effectively maintained the vault at a negative pressure, ≈0.01 inch of water. Several changes of the vault air were accomplished during the 1-day scrubber operation. The unit pulled about 400 cfm from the vault through three absolute filters and a caustic scrubbing solution, and then released this air directly into the building work area adjacent to the vault. This air contained about $10^{-8}$ microcuries/cc (Table 4), essentially radioiodines as indicated by gamma pulse-height analysis (Fig. 13).

The first vault re-entry was accomplished on the morning of 29 March to size up the situation and, if necessary, to eliminate the possibility of a further criticality. The entry party noted levels of 10 rad/hour $\beta - \gamma$ near
the assembly and 2 rad/hour $\beta - \gamma$ at 1 meter. General levels in the vault were 50 mrad/hour $\beta - \gamma$. Based on information gathered at this time, plans were made to remove the large pieces of fissile material from the assembly and surrounding floor (Figs. 7-10).

Table 4. Air concentrations from vault scrubber exhaust.

<table>
<thead>
<tr>
<th>Date</th>
<th>Sampling Time (on-off)</th>
<th>Total beta $\mu$curies/cc</th>
<th>Estimated $^{131}I$ $\mu$curies/cc</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/28</td>
<td>1645-1710</td>
<td>$3 \times 10^{-8}$</td>
<td>$6 \times 10^{-9}$</td>
</tr>
<tr>
<td></td>
<td>1710-1755</td>
<td>$2.1 \times 10^{-8}$</td>
<td>$4.2 \times 10^{-9}$</td>
</tr>
<tr>
<td></td>
<td>1755-2005</td>
<td>$6 \times 10^{-9}$</td>
<td>$1.2 \times 10^{-9}$</td>
</tr>
<tr>
<td></td>
<td>2005-2237</td>
<td>$9.8 \times 10^{-9}$</td>
<td>$2 \times 10^{-9}$</td>
</tr>
<tr>
<td></td>
<td>2237-2316</td>
<td>$1.2 \times 10^{-8}$</td>
<td>$2.4 \times 10^{-9}$</td>
</tr>
<tr>
<td>3/29</td>
<td>0852-0957</td>
<td>$6.5 \times 10^{-9}$</td>
<td>$1.3 \times 10^{-9}$</td>
</tr>
</tbody>
</table>

No further vault entries were attempted until Monday morning, 1 April, at which time the PoBe neutron source was located and removed. On the following afternoon, approximately 15 kg of uranium were recovered from the structural members of the assembly machine.

A lifting device was built to facilitate remote removal of the upper portion of the assembly, which still contained a large amount of fissible material surrounded by a beryllium reflector. Figures 14 and 15 show the device used to raise this large chunk of beryllium and uranium from the floor. A holding tray with a boral bottom plate was used to support the beryllium and uranium chunk while loose oxidized material was removed. By the afternoon of 4 April, approximately 90% of the fissible material had been
lytically removed from the vault. This reduced the general background radiation in the vault to 10 mr/hour and about 25 mr/hour near the partially dismantled assembly. The balance of operations was reduced to routine, but difficult, decontamination of the vault. The large chunk of beryllium and uranium was still a potential criticality hazard and plans were made to disassemble it remotely.

Although levels of contamination throughout the building were very low, wet wiping was done as an additional precautionary measure. The office areas were reoccupied one week after the excursion.

CONCLUSIONS

The data presented in this report lead to the following conclusions:

1. No uncontrolled external radiation hazard was present on- or off-site at any time.

2. Although some gaseous fission products were released to the environment, no internal hazard resulted. This was due to the small total volume of the cloud, the short potential exposure time, and the short half-life of most of the radionuclides, as well as the small total quantity released.

3. No measurable alpha activity was released to the outside environment. Very small amounts of surface and air alpha contamination were noted inside the building in the immediate vicinity of the vault.

4. Scrubbing with caustic proved to be effective in cleaning the vault air and permitted early re-entry into the vault.

5. Well-designed vault facilities for critical assembly experiments are valuable for containment and personnel safety.

6. The off-site environment was in no way compromised by the excursion.
ACKNOWLEDGMENTS

Many people participated in securing the information presented; to these individuals the authors are grateful. In particular, the efforts of J. J. Balanda, W. P. Bennett, H. B. Keller, and the entire Hazards Control staff are acknowledged.

This work was performed under the auspices of the U. S. Atomic Energy Commission.
APPENDIX

THEORETICAL ESTIMATES OF INTERNAL RADIATION EXPOSURE

Many attempts have been made to characterize the internal exposure of an individual located downwind from a single instantaneous release of radioactivity. Most of these are either quite similar to, or based on, Sutton's well-known solution of the Fickian diffusion equation for a "puff" case.

Fitzgerald, Hurwitz, and Tonks\(^{(1)}\) have developed an expression that is well suited for describing the amount of activity deposited in a critical organ of a downwind observer. Their equation takes into account the variation of cloud size as a function of distance from the point of origin as well as atmospheric stability and diffusion parameters. This expression, adapted to the release of U\(^{235}\), is given by Eq. (1):

\[
q = \frac{k f J Q}{s \pi d^2}
\]

where

- \(q\) is the activity retained in the critical organ, in \(\mu\)curies,
- \(k\) is a constant numerically equal to \(1.17 \times 10^{-6}\) curie minutes/g-sec,
- \(f\) is the fraction of inhaled activity retained in the critical organ, and is numerically equal to 0.083 (Ref. 2),
- \(J\) is the breathing rate, taken as 17 liters per minute,
- \(Q\) is the quantity of U\(^{235}\) released, in grams,
- \(s\) is the wind velocity, in meters/sec,
- \(d\) is the distance from the point of release to the observer.

Substituting the constants, Eq. (1) becomes:

\[
q = \frac{1.6 \times 10^{-5} Q}{s \pi d^2}
\]
Since \( \pi d^2 = \frac{V}{2/3} \) where \( V \) is the cloud volume, Eq. (2) becomes:

\[
q = \frac{1.6 \times 10^{-5} Q}{s\sqrt[3]{V}}.
\]  

(3)

The cloud volume, \( V \), can be conveniently obtained from the nomographs of Fitzgerald and Chappell\(^{(3)}\) if the distance from the point of release to the observer, the stability parameter, and the diffusion coefficient are known.

In our case, the distance selected was 3200 meters, about the distance from the point of release to the city of Livermore. At the time of release, an inversion was present and the stability parameter was taken as 0.5, a conservative estimate. The wind velocity was approximately 1 meter per second, and the diffusion coefficient was taken as 0.08, based on measurements made by Holland\(^{(4)}\) at Oak Ridge. Hence, \( V \) was found to be \( 5 \times 10^4 \) cubic meters. If a 1% release of activity (470 g) is assumed, then the amount of \( U^{235} \) retained in the critical organ of the hypothetical observer in the city of Livermore would be

\[
\frac{1.6 \times 10^{-5} \times 470}{1 \times (5 \times 10^4)^{2/3}} = 5.7 \times 10^{-6} \mu\text{curies}.
\]

This quantity, based on extremely conservative assumptions, is several orders of magnitude less than the maximum permissible body burden.\(^{(5)}\)

The dose rate, \( \frac{dR}{dt} \), to the critical organ, can be obtained from Eq. (4), which is based on the body burden equations put forth by the International Committee on Radiation Protection\(^{(2)}\):

\[
\frac{dR}{dt} = \frac{k_1 k_2 q E}{k_3 m} e^{-\lambda t}
\]

(4)

where
\(k_1\) is a constant equal to \(1.32 \times 10^8\) disintegrations per hour per \(\mu\)curie
\(k_2\) is a constant equal to \(1.6 \times 10^{-6}\) ergs/MeV
\(q\) is the quantity retained in the critical organ, in \(\mu\)curie
\(E\) is the effective absorbed energy per disintegration in MeV
\(m\) is the mass of the critical organ, in grams
\(k_3\) is a constant equal to 100 ergs/gram
\(\lambda\) is the effective decay constant, in reciprocal hours
\(t\) is the time, in hours, after deposition.

Since \(\lambda \ll 1\), \(e^{-\lambda t} \rightarrow 1\), and, by putting in the constants, Eq. (4) becomes

\[
\frac{dR}{dt} = \frac{2.1 \cdot qE}{m} \cdot (5)
\]

Substituting in Eq. (5) \(q\) from Eq. (3), and \(E = 230\) MeV and \(m = 7 \times 10^{-3}\) g, the dose rate to the critical organ is

\[
\frac{2.1 \times 5.7 \times 10^{-6} \times 230}{7 \times 10^3} = 4 \times 10^{-7} \text{ rad/hour}
\]

or about 3.5 millirad per year.

Internal exposures from other nuclides can be computed in an analogous fashion. For nuclides with relatively large \(\lambda\) (i.e., coming to equilibrium in the body within 50 years), the total exposure to the critical organ, \(R\), at any time \(t\) after deposition, can be obtained by integration of Eq. (4):

\[
R = \int_0^t \frac{k_1 k_2 qE}{k_3 m} e^{-\lambda t} \, dt,
\]

\[
R = \frac{k_1 k_2 qE}{k_3 m} (1 - e^{-\lambda t})
\]

or, as \(t \to \infty\),
which reduces to
\[ R = \frac{2.1 qE}{m\lambda} \]  
when the numerical values of the constants are substituted.

For example, Eq. (6) can be used to obtain the infinite exposure to the thyroid from $^{131}$I released by the incident. If the release of $^{131}$I is assumed to be 2.75 millicuries, $q$ for the observer 3200 meters from the point of release is $5.8 \times 10^{-5}$ microcuries and the infinite exposure to the thyroid is
\[ R = \frac{2.1 \times 5.8 \times 10^{-5} \times 0.23}{20 \times 3.8 \times 10^{-3}} = 3.7 \times 10^{-4} \text{ rad.} \]

REFERENCES

Change of sea

Step 7

Ion chamber - ammeter chart record
chart speed 0.2 in./min - 10 in. = 300 sec

Scale
one in.

Fig. 2. Neutron levels during experiment.
Fig. 3. Constant air monitor chart record from unit located outside of vault near wall and sampling vault stack effluent.
Fig. 4. Constant air monitor chart record from units located 35 meters from assembly and sampling building air.
Fig. 5. Constant air monitor chart record from another building located 350 meters north.
Fig. 6. Schematic representation of criticality mechanism. (a) Ram positioned slightly off center below the uranium cylinders. (b) Ram off center in raised position forcing innermost uranium cylinder upward.
Fig 7. Overall view of assembly after excursion showing extent of damage.
Area of assembly following excursion. Note oxidized uranium.
FIG. 2. Group of assembly following excursion. Note oxidized uranium.
Fig. 10. Floor contamination near assembly.
Fig. 11. Alpha pulse-height spectrum of vault floor contamination showing absence of Po\textsubscript{210}.
SCHEMATIC OF VAULT AIR CLEANING SYSTEM

Fig. 12. Scrubber flow diagram.
Fig. 13. Gamma pulse-height analysis of scrubber effluent air.
Fig. 14. Lifting device for raising large chunk of uranium and beryllium (remains of upper portion of assembly).
Fig. 15. Closeup of lifting device for raising large chunk of uranium and beryllium.