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NOMINALLY REFLECTED PIPE INTERSECTIONS CONTAINING FISSILE SOLUTION

CHEMICAL PROCESSING

KEYWORDS: *uranyl nitrates, Monte Carlo method, criticality, pipes, aluminum, Plexiglas, steels, plutonium-240, solutions, concretes, stainless steels, geometry, plutonium nitrates*

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Monte Carlo calculations for pipe intersections containing highly enriched, concentrated uranyl nitrate solution and reflected by a concrete room provide safe pipe diameters for a range of room sizes. The pipe-wall material (steel, aluminum, or Plexiglas) has a small effect on k_{eff} for 0.125-in.-thick pipes. Replacing the uranyl nitrate solution by uranyl fluoride results in a large increase in k_{eff}, and using plutonium nitrate (3% ^{240}Pu) lowers k_{eff}. Reflector savings curves for water and for concrete around an infinite cylinder of uranyl nitrate solution show that thick concrete is a much better reflector than an equal thickness of water. The calculational data are summarized in the form of a table and a set of rules for the use of the table in the calculation of safe dimensions for a system of intersecting pipes. This method is also applicable to plutonium systems if the plutonium contains at least 3 wt% ^{240}Pu and no ^{241}Pu.

I. INTRODUCTION

A model for determining critically safe dimensions for pipe intersections containing fissile solution was described in Ref. 1 and extended in Ref. 2. Safe parameters were given for highly enriched uranyl nitrate solution for three reflection conditions: minimal, nominal, and full. The purpose of this paper is to redefine the condition of nominal reflection (originally defined as reflection equivalent to a $\frac{1}{2}$-in. water jacket around the pipe intersection) as well as to report additional computational results concerning pipe intersection geometries.

For most plant applications, the condition of nominal reflection actually refers to a concrete room rather than to a water jacket. The differences between the reflecting properties of water and concrete and the geometric difference between a large cuboidal shell and a close-fitting reflector make it desirable to evaluate the effect of a concrete shell reflector directly. One problem that arises when studying the effect of a concrete room reflector is the addition of several other parameters, e.g., the distance from the pipe intersection to the reflector, the size and shape of the room, and the thickness and composition of the concrete. The distance parameter has been accounted for by defining two cases: (a) pipes that are at least 1 ft from a concrete wall, and (b) pipes that are <1 ft from a wall. For the first case, calculations were done with the pipes at 1 ft from the nearest walls and, for the second case, the intersection is in contact with the nearest walls. Several room sizes were used in the calculations and the dimensions of the pipe system were varied to fit the room. These results are discussed in Sec. IV.B.

Section II contains definitions of terms, Sec. III discusses calculational methods, and Sec. IV contains the results of numerous Monte Carlo calculations on concrete-reflected pipe intersections. Section V presents an updated version of the pipe intersection model of Ref. 2, modified to include the data of Sec. IV.

II. DEFINITIONS

The following terms are used in the description of pipe intersections. Note that the definition of nominal reflection differs from that of Ref. 2.

Central Column. The largest diameter pipe in a system. All other pipes in the system intersect the central column.

Arm. Any pipe intersecting the central column.

Area of Intersection. The area of the intersection of an arm with the tangent plane of the central column at the point where the axis of the arm intersects the central column.

Sector. Any 18-in. length of the central column.

Quadrant. One-fourth of a sector; the sector is divided into four quadrants by two perpendicular planes intersecting along the axis of the sector.

Minimal Reflection. The reflection from $\frac{1}{8}$-in.-thick stainless-steel pipe walls only.

Nominal Reflection. The reflection from $\frac{1}{8}$-in.-thick stainless-steel pipe walls plus a concrete room with 12-in.-thick walls, floor, and ceiling. The dimensions of the side of the room perpendicular to the central column are at least 10×10 ft, the dimension parallel to the central column is at least 9 ft, and all pipes are at least 1 ft from any concrete surface.

Full Reflection. The reflection from $\frac{1}{8}$-in.-thick stainless-steel pipe walls plus full water flooding.

Diameter. The inside diameter (i.d.) of a pipe.

Two arms are in the same sector if the distance between the points where their axes intersect the central column, measured parallel to the axis of the central column, is <18 in. Two arms are in the same quadrant if they are in the same sector and if the angle between the projections of their axes on a plane perpendicular to the axis of the central column is <90 deg. See Ref. 2 for further explanation of these terms.

The definitions of minimal, nominal, and full reflection include a $\frac{1}{8}$-in.-thick stainless-steel pipe wall. It is shown in Table VI that $\frac{1}{4}$-in.-thick steel walls are also acceptable for nominally reflected systems.

III. CALCULATIONAL METHODS AND DATA

III.A. Computer Codes and Cross-Section Data

The calculations in Ref. 2 were performed using the O5R Monte Carlo code.[3] The calculations in the present paper were done with the KENO-II code,[4,5] since it is simpler to use and requires less computer time than the O5R code. The Hansen-Roach sixteen-group cross-section set[6] was used. The material compositions used in these calculations are given in Table I.

Previous experience[11,12] indicates that Hansen-Roach data may give nonconservative results for concentrated, highly enriched uranyl nitrate solution under conditions of minimal or nominal reflection. To estimate the magnitude of this bias, KENO-II calculations were performed on some of the experimentally critical pipe intersections described in Ref. 1. The k_{eff}'s for these critical systems, presented in Table II, have an average value of 0.978 with a standard deviation of 0.015. (This agrees with an average k_{eff} of 0.9776 ± 0.0027 reported in Ref. 13). There is some indication of source convergence problems on several of the calculations, even after 60 batches of 300 neutrons each. To allow for the cross-section bias and lack of source convergence, any system with a k_{eff} greater than 0.96 is said to be critical.

No experimental data are available for pipe intersections containing plutonium nitrate solution, but validation calculations for other geometries have been reported in Ref. 11. There is essentially no bias in these calculations.

III.B. Interpretation of Results

The quoted values of k_{eff} have not been corrected for the calculational bias discussed in the previous section, and the error associated with k_{eff} represents only the statistical error resulting from the use of the Monte Carlo method. No allowance has been made for other factors that can increase k_{eff} such as an increase in reflection from adjacent equipment or personnel or the presence of other fissile material such as a slab of solution on the floor as the result of a spill.

III.C. Standard Calculational Assumptions

The facts and conditions listed below apply to all calculations reported, unless an explicit statement to the contrary is made. Uranyl nitrate solution, plutonium nitrate solution, and stainless steel have the compositions given in Table I. Pipe walls are $\frac{1}{8}$-in.-thick stainless steel, concrete is Type 02-a as described in Table I, and all concrete reflectors are 12 in. thick. Pipe intersections are in a corner of the concrete room with the arms 12 in. from the nearest wall, and the intersection is repeated at 18-in. (center-to-center) intervals along the central column.

The KENO-II calculations consisted of 60 batches with 300 neutrons per batch, and the first 10 batches were excluded from the computation of average values. The source for batch one was usually a combination of a cosine source over the length of the column and a uniform distribution over the arms. Running times varied from 45 to 75 min of IBM 360/65 CPU time.

All dimensions are given in English units, since these are the units used in engineering drawings and standard pipe (see Ex. 1).

TABLE I

Number Densities of Materials Used in Pipe Intersection Calculations

Element[a]	Uranyl Nitrate Solution[b]	Plutonium Nitrate Solution[c]	Type 304 Stainless Steel[d]	Type 02-a Concrete[e]	Oak Ridge Concrete[d]
H[f]	0.0550057	0.061935		0.013740	0.0085
C			3.17 E-4	1.15 E-4	0.0202
N	0.0027429	0.0020160			
O	0.0378239	0.037016		0.045930	0.0355
Na				9.64 E-4	1.63 E-5
Mg[f,g]				1.24 E-4	0.00186
Al				0.001740	1.56 E-4
Si[f,g]			0.001694	0.016620	0.0017
K				4.61 E-4	4.03 E-5
Ca[h]				0.001500	0.0111
Cr[i]			0.016471		
Mn[f,g]			0.001732		
Fe			0.060360	3.45 E-4	1.93 E-4
Ni			0.006483		
^{235}U	0.00107686				
^{238}U	7.769 E-5				
^{239}Pu		4.8895 E-4			
^{240}Pu		1.5059 E-5			
Density (g/cm^3)	1.611	1.33	7.9	2.2	2.3

[a]Cross-section data is from Hansen and Roach[6] and scattering is isotropic unless otherwise noted.
[b]The uranium is enriched to 93.19% ^{235}U, the concentration is 450.8-g U/liter, and the nitric acid normality is 0.72.
[c]The plutonium is 97% ^{239}Pu and 3% ^{240}Pu, the concentration is 200-g Pu/liter, and there is no excess nitric acid.
[d]Data from Ref. 7.
[e]Data from Ref. 8.
[f]Linear anisotropic scattering.
[g]XSDRN cross-section data (Ref. 9).
[h]GAM-II cross-section data (Ref. 10).
[i]Aerojet cross-section data.

The reader should note that some of the pipe intersections presented in various tables and examples are not permissible according to the model of Sec. V. Of those not permitted, some are nevertheless safe (e.g., C of Table IV) and some are unsafe (e.g., D of Table IV). The designer may use these safe but not permitted cases if applicable.

III.D. Note on Geometry of Pipe Intersections

When several pipes intersect a cylindrical central column in a planar layer, there are geometrical limitations on either the pipe sizes or the angles between the arms, since the arms must not intersect each other. These restrictions are discussed in Ref. 14. Two useful results are quoted here.

Let R_1 and R_2 be the outer radii of two arms that intersect a central column of outer radius R_c at right angles to the column. If the axes of R_1 and R_2 are to lie in the same plane, the minimum angle between the axes is

$$\phi_{min} = \sin^{-1}\left(\frac{R_1}{R_c}\right) + \sin^{-1}\left(\frac{R_2}{R_c}\right) \quad . \tag{1}$$

If two arms are to intersect the central column at 90 deg to the column and to each other, the

TABLE II

KENO-II k_{eff} Calculations for Experimentally Critical Pipe Intersections

Arm Diameter (in.)	From Ref. 1		Number of Arms	Angle Between Arms and Central Column (deg)	Edge-to-Edge Spacing (in.)	Critical Height[a] (in.)	Source for Batch 1	$k_{eff} \pm \sigma$
	Figure	Table						
6.4	3	I	8	90	5.19	45.94	75 neutrons with cosine distribution in boxes around each intersection; 150 neutrons uniform over box containing intersections.	0.995 ± 0.007
6.4	3	I	12	90	6.63	Column full	50 neutrons with cosine distribution in boxes around each intersection; 150 neutrons uniform over box containing intersections.	0.982 ± 0.007
5.35	3	I	8	90	0.0	4.37	Cosine distribution over box containing intersection.	0.970 ± 0.009
7.0[b]	6	II	2	45	--	4.82	Cosine over entire system.	0.970 ± 0.009
7.0[b]	6	II	2	45	--	4.82	Uniform over entire system.	0.949 ± 0.008
6.4	7	II	6	45	9.46	Column full	Cosine over system.	0.991 ± 0.009
6.4	7	II	6	45	9.46	Column full	100 neutrons uniform over core; 200 uniform over box around intersections.	0.972 ± 0.009
6.4	7	II	6	45	9.46	Column full	Uniform in box around intersections.	0.968 ± 0.010
6.4	11	III	6	90	0.0	Column full	Cosine source in box around intersection.	0.986 ± 0.010
6.4	11	III	6	90	0.0	Column full	Uniform source in box around intersection.	0.996 ± 0.011

[a]Critical height along column from top of top arm in array.
[b]Square arms.

minimum distance between the planes normal to the central column containing the axes of R_1 and R_2 is

$$h_{min} = [2\,(R_1^2 + R_2^2 - R_c^2)]^{1/2} \quad . \qquad (2)$$

If $R_1^2 + R_2^2 \leq R_c^2$, the arms can lie in the same plane.

It is shown later that under certain conditions it is safe to have two 4.8-in.-i.d. arms intersecting a 5.75-in.-i.d. column. If the pipes have $\frac{1}{8}$-in.-thick walls, then R_c = 3 in., $R_1 = R_2$ = 2.525 in., and the minimum distance between the planes containing the axes of the arms is 2.74 in.

IV. RESULTS

IV.A. Relation of Results to Previous Work

Previous work[1,2,14] has shown that safe dimensions for a few simple pipe intersections (see Figs. 3, 4, and 5 of Ref. 2) can be applied conservatively to a variety of more complicated systems, using as a critical parameter the area of intersection of the arms with the central column. These simple intersections consist of a central column together with one, two, or four arms at 90 deg to the central column and to each other (i.e., there is at most one arm per quadrant). Safe arm and column diameters are calculated for each set of values of the system parameters. These parameters are composition of fissile solution (at minimum critical volume concentration), thickness and composition of reflector, and number of arms (at most one per quadrant). The intersection is repeated at 18-in. intervals along the central column.

For example, consider the case of highly enriched uranyl nitrate solution reflected only by $\frac{1}{8}$-in.-thick steel pipe walls. For a T intersection (one arm intersecting the central column at a 90-deg angle), safe arm and column diameters are 7.25 in. each.[2] The area of intersection of the arm with the column is $\pi(7.25/2)^2$ = 41.28 in.^{2} Now suppose one wants to calculate the safe diameter for each arm in a row of three edge-to-edge at an angle of 45 deg to the central column. The safe diameter, D, must satisfy

$$3(\pi D^2/4)(1/\sin 45) \leq 41.28 \text{ in.}^2 \quad ,$$

and one finds $D \cong 3.5$ in.

IV.B. Results for Nominal Reflection

This subsection presents results for intersections in a concrete room and at least 1 ft from any concrete surface, a condition defined as nominal reflection. First, a series of exploratory calculations to choose safe pipe diameters was done using a 9.5- × 9.5- × 15-ft^3 concrete room, since a small room was expected to be more reactive than a large one. Calculations were done for the three simple intersections described in Sec. IV.A. The pipe diameters and associated k_{eff}'s for safe and near-critical repeated intersections in this room are shown in Table III. [A critical k_{eff} is $\cong$0.96, and a safe k_{eff} is $\lesssim$0.84; i.e., for a safe geometry, k_{eff} + 0.04 (bias) + $4\sigma \lesssim 0.92$.] In all of the safe cases, the column and arm diameters are 20 to 22% less than the corresponding diameters for the near-critical intersections.

Calculational results for different room sizes are shown in Table IV. In all cases, the length of the column and arms and the number of times an intersection is repeated are adjusted to fit the room. There are two competing trends as room size varies:

1. As the room gets wider, the arms get longer, and as the room is made taller, there is space for more layers of arms on the column, so k_{eff} tends to increase.

2. However, as the room gets larger, the concrete reflector is farther away from some of the pipes, and k_{eff} tends to decrease.

The intersections with two or four quadrants with arms are most reactive in the 10- × 10- × 21-ft^3 room and are safely subcritical in all of the rooms considered in Table IV. However, the single-quadrant intersection (a repeating T-intersection) with arm and column diameters of 5.75 in. is not safe in the long, narrow 60- × 10- × 21-ft^3 room, although it is safe in some other cases. Since reducing the maximum length of the room to 30 ft or the maximum height to 15 ft did not reduce k_{eff} to a safe value, it was necessary to reduce the maximum arm diameter to 5.25 in. Thus, 5.25 in. is the maximum diameter permitted by the model of Sec. V, even though, as Table IV shows, a 5.75-in.-diam arm is safe under most conditions.

The safe arm diameters of 5.25, 4.80, and 4.50 in. for the three basic intersections correspond to the safe intersection areas of 21.65, 18.10, and 15.90 in.^{2} in column 5 of Table VIII.

Values of k_{eff} lower than those in Table IV will result for intersections that are more than 1 ft from the wall. Calculation H of Table IV was redone with the central column in the center of the room, and k_{eff} decreased by 0.034 ± 0.013.

IV.C. Intersections Less Than One Foot from the Wall

Calculations were done for intersections similar to those in Table IV, except that the column was tangent to one or two walls of the room, and the arm and column diameters were all reduced by 0.25 in. The results of these calculations are shown in Table V. None of the k_{eff}'s in Table V are significantly higher than the corresponding value in Table IV, and several are lower.

IV.D. Different Material Compositions

All of the calculational results presented thus far have been for $\frac{1}{8}$-in.-thick Type 304 stainless steel and Type 02-a concrete, as described in Table I. Other common piping materials are mild

TABLE III

Calculated Values of k_{eff} for Safe and Near-Critical Pipe Intersections* in a 9.5- × 9.5- × 15-ft^3 Concrete Room

Number of Arms per Intersection	Near-Critical Intersection			Safe Intersection		
	Column Diameter (in.)	Arm Diameter (in.)	$k_{eff} \pm \sigma$	Column Diameter (in.)	Arm Diameter (in.)	$k_{eff} \pm \sigma$
1	7.0	7.0	0.971 ± 0.008	5.75	5.75	0.821 ± 0.008
2	6.9	5.8	0.970 ± 0.008	5.75	4.8	0.825 ± 0.008
4	6.6	5.5	0.965 ± 0.008	5.5	4.5	0.823 ± 0.009

*See Figs. 3, 4a, and 5 of Ref. 2 for the geometry of these intersections.

TABLE IV

Variation of k_{eff} with Room Size and Shape for Uranyl-Nitrate-Filled Pipe Intersections in a Concrete Room

Number of Arms per Intersection	Column Diameter (in.)	Arm Diameter (in.)	$k_{eff} \pm \sigma$				
			9.5- × 9.5- × 15-ft³ Room	10- × 10- × 9-ft³ Room	10- × 10- × 21-ft³ Room	60- × 10- × 21-ft³ Room	60- × 60- × 21-ft³ Room
1	5.75	5.25	---	---	0.7590 ± 0.0073	0.8220 ± 0.0076[A][a]	0.7314 ± 0.0061
1	5.75	5.75	0.8212 ± 0.0081[B]	0.7921 ± 0.0082	0.8384 ± 0.0089[C]	0.8856 ± 0.0075[D]	0.8059 ± 0.0074
2	5.75	4.80	0.8254 ± 0.0079[E]	0.7721 ± 0.0085	0.8427 ± 0.0080[F]	0.8029 ± 0.0082[G]	0.7639 ± 0.0089
4	5.50	4.50	0.8234 ± 0.0090[H]	0.7894 ± 0.0050	0.8239 ± 0.0090[I]	0.8012 ± 0.0062	0.7739 ± 0.0071[J]

[a]Calculations noted with a capital-letter superscript are discussed in the text or referenced in other tables.

steel, aluminum, and various plastics. Different types of steel have similar densities and nuclear properties, and no significant change in k_{eff} would be expected if stainless steel were replaced by mild steel. Aluminum and Plexiglas have nuclear properties very different from those of steel. However, as Table VI shows, for thin ($\frac{1}{8}$-in.) pipe walls, changes in pipe composition do not produce significant changes in k_{eff}. Several calculations using $\frac{1}{4}$-in.-thick steel pipes also showed little change in k_{eff}. Note that the effect of replacing steel with other materials can be quite significant under some conditions, e.g., full water reflection rather than nominal reflection. See Ex. 3 of Sec. V for an example of this.

Concrete compositions vary greatly, change with time, and are generally not known accurately for a particular facility. A few calculations were done using Oak Ridge National Laboratory concrete (Table I), which has a lower water content than the Type 02-a mixture. The k_{eff}'s for these cases are shown in Table VI; only one is significantly higher than the corresponding value shown in Table IV.

Combinations of the various factors considered in Table VI have not been investigated.

IV.E. Other Fissile Solutions

As mentioned in Ref. 2, the data in Table IV can be used conservatively for plutonium nitrate solution containing at least 3 wt% ^{240}Pu, no excess nitric acid, and no other fissile isotopes (e.g., ^{241}Pu). This statement was based on experimental data reported in Ref. 15. Calculations providing additional support for this conclusion are shown in Table VI. The k_{eff}'s for plutonium in Table VI are lower than the corresponding values for uranium in Table IV, even without taking into account the k_{eff} bias of 0.04 for uranium; this means that the model in Sec. V is even more conservative for plutonium than for uranium.

Calculations for uranyl nitrate cannot be applied to uranyl fluoride solution, since it is considerably more reactive than the nitrate solution. A few uranyl fluoride calculations, reported in Table VI, show increases in k_{eff} of ~0.07 to ~0.08. Similarly, these data do not apply to ^{233}U solutions or to metal-water mixtures.

IV.F. Reflector Savings Calculations

Pipes in process plants are often reflected by water or other materials, and this additional reflection must be taken into account in criticality calculations. The DTF-IV transport code[16] has been used to calculate reflector savings for water or concrete reflecting an infinite critical cylinder

TABLE V

Calculations of k_{eff} for Uranyl-Nitrate-Filled Pipe Intersections Tangent to a Concrete Surface

Number of Arms per Intersection	Column Diameter (in.)	Arm Diameter (in.)	Corresponding Calculation in Table IV	$k_{eff} \pm \sigma$
1	5.5	5.5	B	0.8370 ± 0.0070
1	5.5	5.5	C	0.8521 ± 0.0079
1	5.5	5.0	A	0.8085 ± 0.0071
1	5.5	5.0	A	0.7860 ± 0.0083[a]
2	5.5	4.55	E	0.8405 ± 0.0074
2	5.5	4.55	F	0.8427 ± 0.0076
2	5.5	4.55	F	0.8157 ± 0.0071[a]
4	5.25	4.25	I	0.7771 ± 0.0063
4	5.25	4.25	-	0.7582 ± 0.0077[b]

[a] The lowest layer of arms is resting on the floor.
[b] The column is centered along one of the 60-ft walls of a 60- × 10- × 21-ft^3 room.

of uranyl nitrate solution. The reflector savings on the radius, defined as the bare critical radius minus the reflected critical radius, is shown in Fig. 1. Note that in all cases the solution is contained in a $\frac{1}{8}$-in.-thick stainless-steel pipe.

Two differences between concrete and water reflectors can be noted:

1. for thin ($\lesssim$3.0-in.) reflectors, water is more effective than concrete, but asymptotically concrete is better

2. 5.7 in. of water or 12.3 in. of concrete is effectively infinite (i.e., the reflector savings is 99% of the value for an infinite reflector).

One consequence of item 1 is that the model described in Sec. V for fully water-reflected systems is not applicable to thick concrete reflectors.

IV.G. Comparison Between a Water Jacket Reflector and a Concrete Room Reflector

The values of k_{eff} for water jacket and concrete room reflectors are given in Table VII. For the cases of 1 or 2 quadrants with arms, the concrete room is approximately equivalent to a 1-in. water jacket, while, for 4 quadrants with arms, the 1-in. water jacket is a better reflector than the concrete room. According to Fig. 1, a 1-in. water jacket is equivalent to 0.72 in. (use 0.75 in.) of reflector savings on the radius. Hence, safe diameters for an unreflected or minimally reflected intersection must all be reduced by 1.5 in. to give safe dimensions for an intersection in a concrete room and at least 1 ft from all reflecting surfaces (i.e., for nominal reflection). If the intersection is <1 ft from a reflector, an additional 0.25 in. must be deducted from the safe diameters for nominal reflection (i.e., a reduction of all safe dimensions for minimal reflection by 1.75 in.).

Hence, the use of a reflector savings correction is an alternative way to calculate safe dimensions for a nominally reflected pipe intersection, if safe dimensions for the same intersection under conditions of minimal reflection are known. (Since computer codes such as KENO-II require far less time to calculate minimally reflected systems than nominally reflected ones, the use of a reflector savings correction may save considerable computer time.)

V. A MODEL FOR CRITICALLY SAFE PIPE INTERSECTIONS FOR HIGHLY ENRICHED URANYL NITRATE SOLUTION

V.A. Introduction

The model presented here is an updated version of the one given in Ref. 2, taking into account

TABLE VI

Changes in k_{eff} Due to Changes in Fissile Solution, Pipe Wall Material or Thickness, and Concrete Composition

Reference Calculation in Table IV	Modification	$k_{eff} \pm \sigma$	$\Delta k_{eff} \pm \sigma^a$
A	Stainless steel replaced by iron[b]	0.8267 ± 0.0080	0.0047 ± 0.0110
F		0.8367 ± 0.0082	-0.0060 ± 0.0115
I		0.8329 ± 0.0075	0.0090 ± 0.0117
A	Stainless steel replaced by aluminum[c]	0.8278 ± 0.0076	0.0058 ± 0.0107
F		0.8442 ± 0.0070	0.0015 ± 0.0106
H		0.8327 ± 0.0074	0.0093 ± 0.0117
I		0.8502 ± 0.0079	0.0263 ± 0.0120
A	Stainless steel replaced by Plexiglas[d]	0.8297 ± 0.0075	0.0077 ± 0.0107
F		0.8386 ± 0.0070	-0.0041 ± 0.0106
I		0.8394 ± 0.0081	0.0155 ± 0.0121
A	0.25-in.-thick stainless-steel pipes	0.8133 ± 0.0065	-0.0087 ± 0.0100
F		0.8098 ± 0.0080	-0.0329 ± 0.0113
I		0.8325 ± 0.0077	0.0086 ± 0.0118
J		0.7873 ± 0.0066	0.0134 ± 0.0097
A	Type 02-a concrete replaced by Oak Ridge National Laboratory concrete	0.8411 ± 0.0065	0.0191 ± 0.0100
F		0.8541 ± 0.0074	0.0114 ± 0.0109
G		0.8333 ± 0.0101	0.0304 ± 0.0130
I		0.8410 ± 0.0081	0.0171 ± 0.0121
A	Uranyl nitrate solution replaced by plutonium nitrate solution	0.8109 ± 0.0068	-0.0111 ± 0.0102
F		0.8172 ± 0.0070	-0.0255 ± 0.0106
I		0.8012 ± 0.0055	-0.0227 ± 0.0105
J		0.7428 ± 0.0076	-0.0311 ± 0.0104
A	Uranyl nitrate solution replaced by uranyl fluoride solution[e]	0.8891 ± 0.0060	0.0671 ± 0.0097
F		0.9222 ± 0.0067	0.0795 ± 0.0104
I		0.8997 ± 0.0071	0.0758 ± 0.0115

[a] $\Delta k_{eff} = k_{eff}$ (Table VI) - k_{eff} (Table IV) and $\sigma = [\sigma^2$ (Table IV) + σ^2 (Table VI)$]^{1/2}$.
[b] Density 7.77 g/cm^3; number density 0.083855 nuclei/(b cm).
[c] Density 2.7 g/cm^3; number density 0.060295 nuclei/(b cm).
[d] Density 1.182 g/cm^3; H, C, and O number densities are 0.056884, 0.035552, and 0.014221 nuclei/(b cm), respectively.
[e] Solution contains 576.8-g U/liter and the uranium is enriched to 93.2 wt% ^{235}U.

TABLE VII

Comparison of k_{eff}'s for Pipe Intersections Reflected by a Water Jacket or a 9.5- × 9.5- × 15-ft^3 Concrete Room

Number of Arms per Intersection	Column Diameter (in.)	Arm Diameter (in.)	Description of Reflector	$k_{eff} \pm \sigma$
1	6.0	6.0	None	0.673 ± 0.007
1	6.0	6.0	½-in. water jacket	0.777 ± 0.009
1	6.0	6.0	1-in. water jacket	0.842 ± 0.006
1	6.0	6.0	concrete room	0.834 ± 0.008
2	5.75	4.8	1-in. water jacket	0.829 ± 0.010
2	5.75	4.8	concrete room	0.825 ± 0.008
4	5.25	4.25	1-in. water jacket	0.813 ± 0.009
4	5.25	4.25	concrete room	0.758 ± 0.009

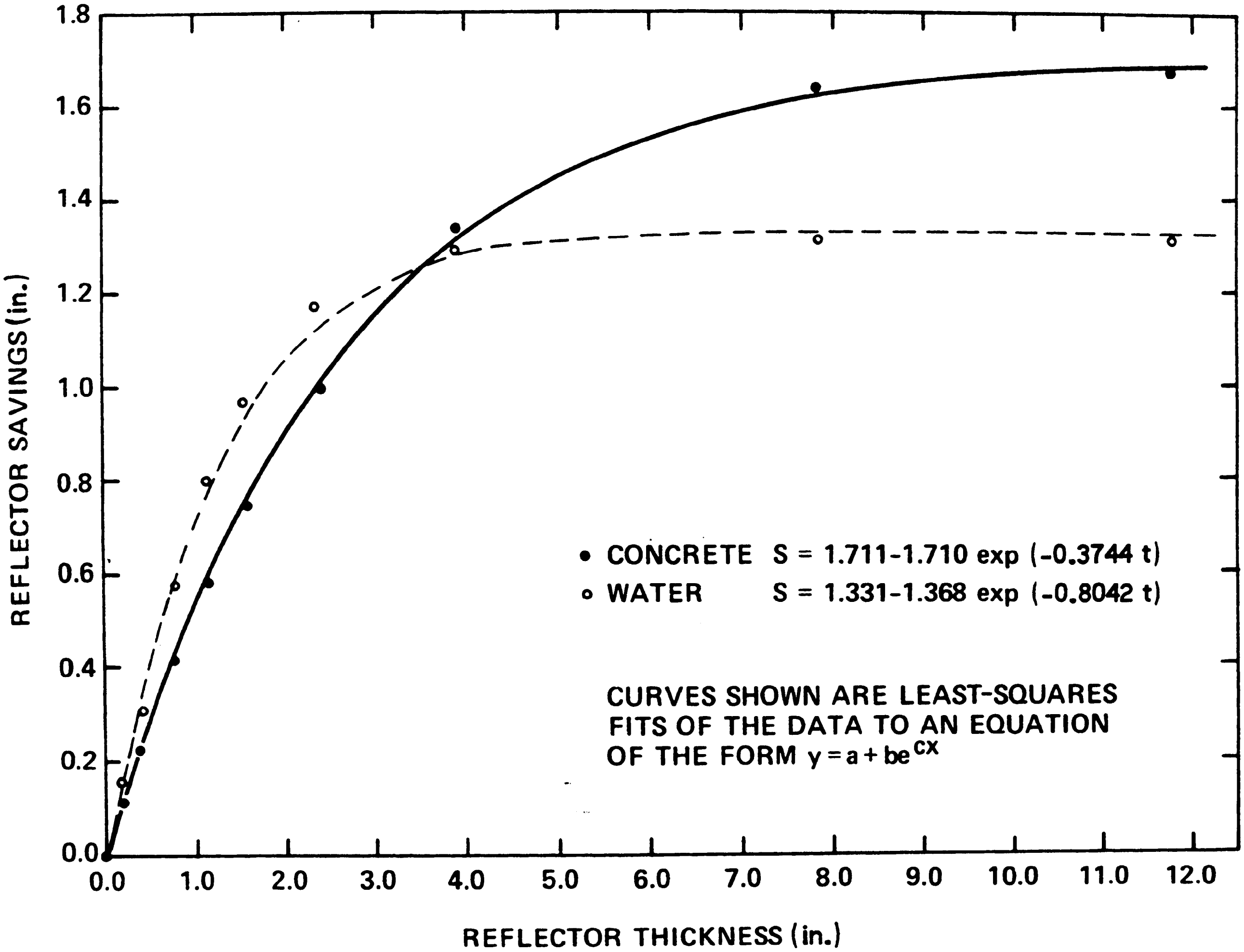

Fig. 1. Reflector savings versus reflector thickness for an infinite cylinder of 450.8 g/liter $U(93)O_2(NO_3)_2$ solution reflected by $\frac{1}{8}$ in. of stainless steel and either water or concrete.

the new work on nominal reflection. The model uses the area of intersection of the arms with the central column as a critical parameter. Safe dimensions predicted by the model permit the intersection to be repeated at 18-in. intervals along the central column, and the model will predict very conservative dimensions for a single intersection. The model does not take into account abnormal or accident conditions, nor does it allow for the presence of other fissile material in the same room.

As shown in Table VI and Secs. IV.D. and IV.E., some of the conditions of the model may be relaxed slightly (e.g., pipe walls of 0.25-in.-thick steel are acceptable). Since these modifications have not been studied in detail and in combination with other changes, they have not been incorporated into the model.

V.B. Model

Rule 1. The fissile material shall be an aqueous solution of uranyl nitrate. The uranium isotopic content shall be at most 93.5 wt% ^{235}U, with the only other isotopes present being ^{234}U, ^{236}U, and ^{238}U.

Rule 2. The central column diameter shall be less than or equal to the appropriate maximum value given in Table VIII.

Rule 3. The area of intersection of the arms with the column shall be calculated for all quadrants containing arms, and the calculated area shall not exceed the appropriate value in Table VIII. The intersection area shall be distributed in such a way that it is impossible to find any

TABLE VIII

Maximum Central Column Diameters and Areas of Intersection Permitted by the Model

Number of Quadrants Containing Arms in a Sector	Minimal Reflection		Nominal Reflection		Full Reflection	
	Maximum Central Column Diameter (in.)	Maximum Intersection Area per Quadrant (in.^{2})	Maximum Central Column Diameter (in.)	Maximum Intersection Area per Quadrant (in.^{2})	Maximum Central Column Diameter (in.)	Maximum Intersection Area per Quadrant (in.^{2})
1	7.25	41.28	5.75	21.65	4.60	16.62
2	7.00	29.70	5.75	18.10	4.44	11.98
3 or 4	6.50	23.75	5.50	15.90	4.12	9.60

quadrant that contains an area of intersection greater than that permitted by Table VIII.

Rule 4. There shall be a maximum of four arms per quadrant for any intersection which has moderating material among the pipes. This rule always applies to fully reflected systems.

Rule 5. If a pipe in a concrete room is <1 ft from a concrete surface, its diameter shall be reduced by 0.25 in. from the value calculated assuming nominal reflection.

Rule 6. For the case of nominal reflection, the maximum number of sectors containing arms is 14, and the maximum dimensions of the pipe system perpendicular to the central column are 60 × 60 ft.

V.C. Comments on Rules

Rules 2 and 3 and the data in Table VIII contain the essentials of the model. The application of Rule 3 usually involves considering a pipe as belonging to more than one sector, as shown in Ex. 4.

Rule 4 is necessary to disallow a situation with many small pipes and interspersed moderator, creating in effect a large volume of lower concentration solution. The limit of four pipes is somewhat arbitrary, but probably adequate for most practical applications. Example 3 shows the necessity for some limit on the number of pipes.

Note that Rule 5 does not apply to pipes embedded in concrete; e.g., a pipe that passes through a wall. Also, as shown in Sec. IV.F., the data for full reflection do not apply to full concrete reflection.

The maximum system size and number of sectors permitted by Rule 6 are simply the largest values checked in the derivation of the model. Recall that the definition of nominal reflection requires a minimum room size of 10 × 10 × 9 ft^3.

V.D. Examples

Example 1. The pipe intersection geometry is described in Fig. 2 and Table IX. The intersection is in a 40- × 20- × 21-ft^3 concrete room, and the fissile solution is uranyl nitrate. According to Table VIII, the maximum central column diameter is 5.5 in., the maximum area of intersection is 15.90 in.^{2}, and the model predicts that the intersection is safe. A KENO-II calculation for this intersection repeated 14 times gives k_{eff} = 0.7179 ± 0.0089. This low value of k_{eff} is the result of two factors: First, the intersection areas are smaller than the model permits and, second, dividing the area of intersection between pipes C and D increases the leakage compared to a system with a single larger pipe.

Example 2. The geometry is the same as in Ex. 1, except that pipes C and D are 3 in.,

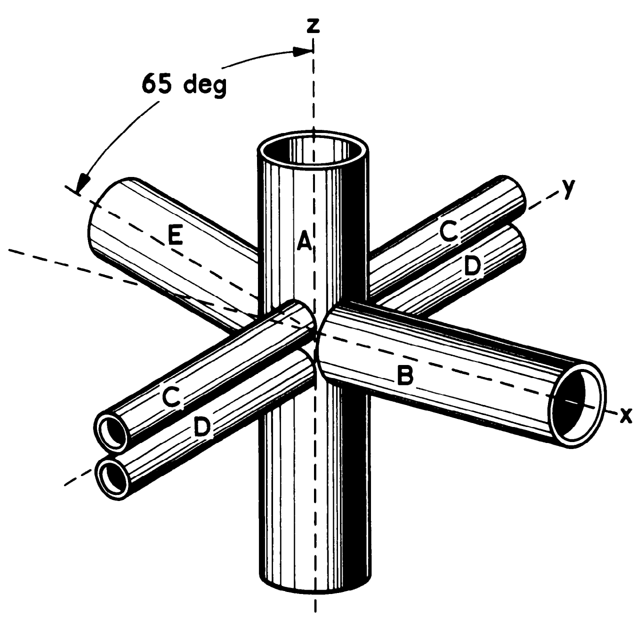

Fig. 2. Pipe intersection geometry for Exs. 1 and 2.

TABLE IX

Data for Ex. 1

Pipe Identification in Fig. 2	Nominal Pipe Size (in.)	Schedule	Inner Diameter (in.)	Wall Thickness (in.)	Area of Intersection (in.^{2})
A	5	10S	5.295	0.134	---
B	4	10S	4.26	0.12	14.25
C	2.5	10S	2.635	0.12	5.45
D	2.5	10S	2.635	0.12	5.45
E	4	10S	4.26	0.12	15.73

schedule 10 pipe (diameter 3.26 in., wall thickness 0.12 in., area of intersection 8.35 in.^{2}). Now the area of intersection for the quadrant containing pipes C and D is 16.7 in.^{2}, >15.9 in.^{2} as permitted by the model. The k_{eff} for this intersection is 0.7425 ± 0.0084. (Note that, according to Ex. 2, the axes of arms C and D must be spaced vertically 0.88 in. above and below the axes of arms B and E. The actual spacing is 1.75 in., the outer radius of arms C and D.) This example shows that a system that is not permitted by the model may still have a very low value of k_{eff}.

Example 3. Rule 4 of the model limits the number of arms per quadrant for systems containing a moderator interspersed among the arms. Figure 3a shows an intersection with four arms in one quadrant, total area of intersection 16.62 in.^{2}, as permitted by the model. The intersection is completely reflected by water, and it is repeated infinitely many times at 18-in. intervals. The k_{eff} for this system is 0.813 ± 0.010.

Figure 3b shows part of an intersection with 84 arms in one quadrant, a system that is not permitted by the model. The total area of intersection is $84 \times \pi/4 \times 0.5^2 = 16.49$ in.^{2}. There is an 0.25-in. surface-to-surface separation between the layers of arms (there was no attempt to find the separation that gave the highest k_{eff}). The intersection shown has a k_{eff} of 0.77 ± 0.01 if all pipes have $\frac{1}{8}$-in.-thick stainless-steel walls. Note that because of the small arm diameter, there is actually a larger volume of steel than solution in the arms. If the steel is replaced by $\frac{1}{8}$-in.-thick aluminum, k_{eff} increases to 0.89 ± 0.01 so that, unlike the situation for nominal reflection, a change in pipe wall material produces a large change in k_{eff}. If the pipe walls are removed, k_{eff} = 0.96 ± 0.02.

Example 4. The geometry for this intersection is shown in Fig. 4. The problem is to find the maximum diameters for all pipes. The system is in a concrete room, and all pipes except D are tangent to a concrete surface. There are two

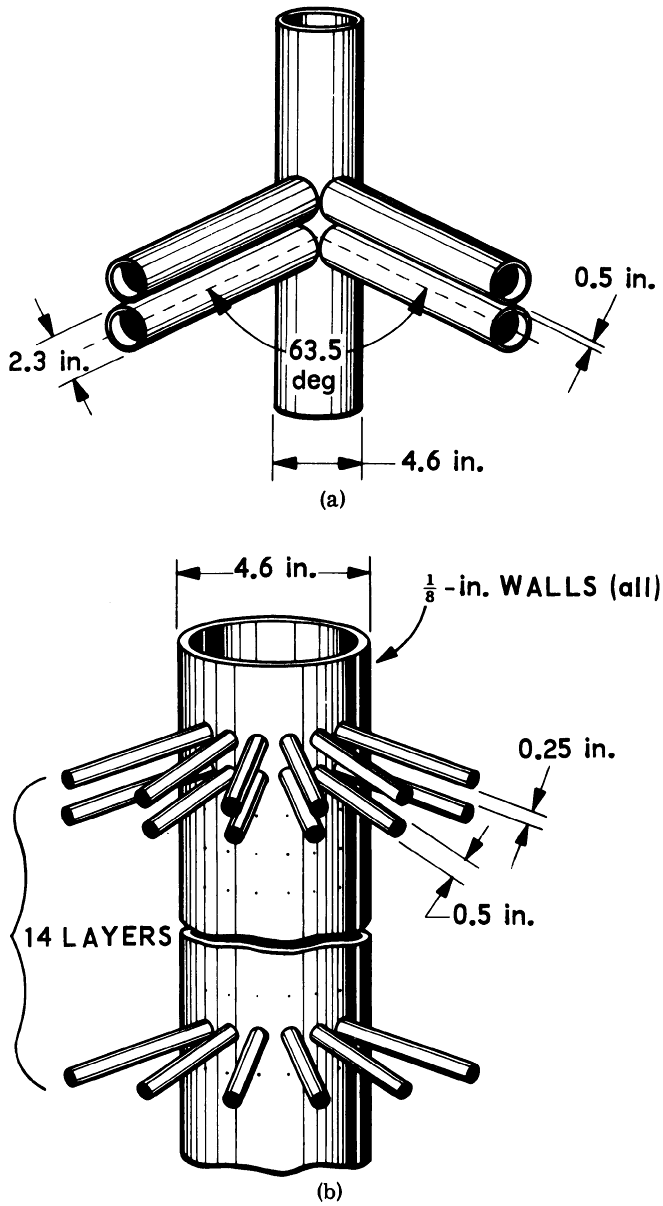

Fig. 3. Pipe intersection geometry for Ex. 3. (a) Intersection with four arms in one quadrant, as permitted by model. (b) Intersection with 84 arms (14 layers, 6 arms per layer) in one quadrant, not permitted by model.

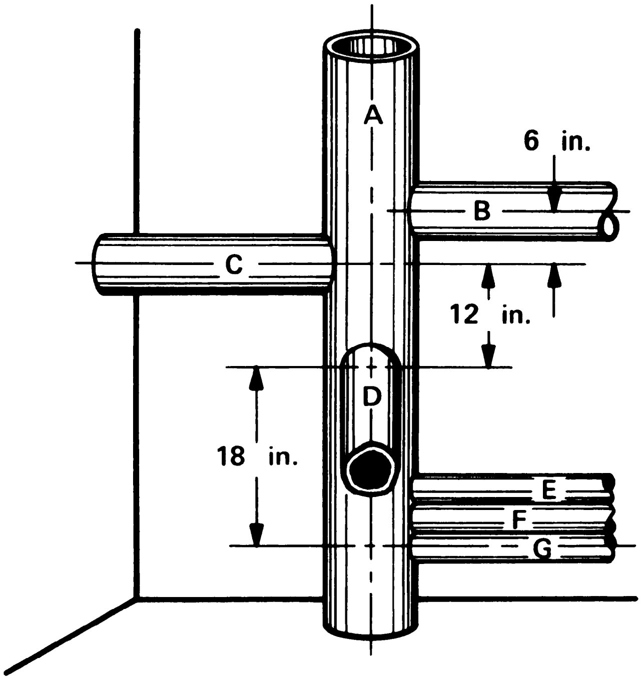

Fig. 4. Geometry for Ex. 4

sectors to consider, one containing arms B, C, and D and another with D, E, F, and G. There are three quadrants with arms in the first sector and two in the second. The calculations for this example are shown in Table X. Pipes A and D belong to both sectors, and the smaller diameter is chosen in each case.

A KENO-II calculation was done for this intersection (not repeated) in a 60- × 10- × 9-ft^3 concrete room with arms B, C, E, F, and G along the 60-ft wall and with arm C 3 ft long. The resulting value of k_{eff} was 0.655 ± 0.006.

TABLE X

Calculation of Pipe Dimensions for Ex. 4

Pipe	Diameter for Nominal Reflection (in.)		Correction for <1 ft from Wall (in.)	Diameter Permitted by Model (in.)
	Sector 1	Sector 2		
A	5.5	5.75	0.25	5.25
B	4.5	---	0.25	4.25
C	4.5	---	0.25	4.25
D	4.5	4.8	0.0	4.50
E,F,G	---	2.77	0.25	2.52

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