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AN EMPIRICAL MODEL FOR SAFE PIPE INTERSECTIONS CONTAINING FISSILE SOLUTION

CHEMICAL PROCESSING

DEANNE DICKINSON and C. L. SCHUSKE *The Dow Chemical Company*
Rocky Flats Division, P.O. Box 888, Golden, Colorado 80401

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An empirical model is presented for calculating safe nuclear criticality parameters for systems of intersecting pipes containing enriched uranyl nitrate solution. The model, which applies to systems consisting of a main pipe (the central column) from which smaller pipes (arms) branch off, uses as a criticality parameter the area of intersection of the arms with the column. Maximum safe values for both the central column diameter and the area of intersection of the arms with the column are provided for conditions of minimal, nominal, or full reflection.

The current model, an extension of an earlier one, is based on Monte Carlo calculations as well as on experimental data. A review of the experimental and calculational data is included.

INTRODUCTION

One problem arising in the design of plants that handle fissile materials concerns the criticality safety of piping systems for fissile solution. This paper describes an empirical model, derived from experimental and calculational data,^{1,2} for calculating subcritical pipe diameters and spacings for systems of intersecting pipes containing highly enriched, concentrated uranyl nitrate solution. The model uses as a critical parameter the area of intersection of the arms (pipes) with the central column. The model hereafter will be referred to as the GAI (Generalized Area of Intersection) model.

The original Area of Intersection (AI) model¹ was designed to predict subcritical dimensions and spacings for complex pipe systems with an

appropriate margin of safety. However, when applied to simple intersections such as T's or crosses, the AI model is overly conservative. The GAI model, on the other hand, calculates both simple and complex intersections with adequate but not over conservatism. The AI model limits the area of intersection *per quadrant* of arms with the central column, regardless of whether or not the other quadrants in the sector actually contain arms. The GAI model provides different limits on the intersection area and column size depending on the number of quadrants that contain arms. (For explanation of terms used in text see following section.)

DEFINITIONS

Diameter — Always the inner diameter of a pipe.

(Central) Column — The main column or pipe from which branching of arms occurs; the largest diameter pipe.

Arm — Any pipe or cylinder intersecting the central column.

Intersection Area — The area of intersection of an arm with the tangent plane of the column at the point where the axis of the arm intersects the column. [See Fig. 1, where D = diameter, θ = angle between arm axis and column axis, and A = area of intersection.]

Sector — Any 18-in. length of the central column. (See Fig. 2.)

Quadrant — One-fourth of a sector; the sector is divided into four quadrants by two perpendicular planes intersecting along the axis of the sector. (See Fig. 2.)

Minimal Reflection — The reflection from the $\sim\frac{1}{8}$ -in.-thick steel walls of the pipes only.

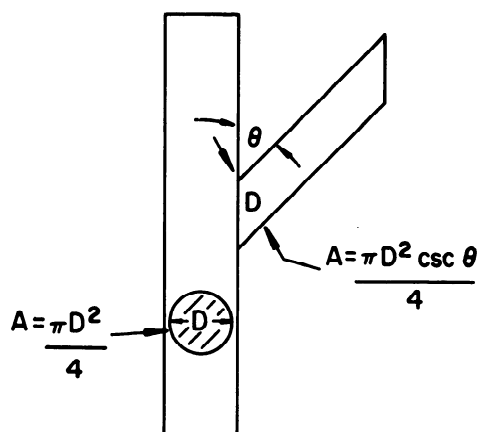


Fig. 1. Surface area in contact with central column.

Nominal Reflection — Reflection from $\frac{1}{8}$ -in.-thick steel walls of the pipe plus $\frac{1}{2}$ -in. of water reflector (or an equivalent amount of reflection) around the pipes.

Full Reflection — Reflection due to full water flooding of a pipe system (pipes have $\frac{1}{8}$ -in.-thick steel walls); safe dimensions are calculated by reducing all diameters in the minimal cases by a factor of 0.635.¹

Area of Intersection (AI) Model — An empirical model for designing safe pipe systems for uranyl nitrate solution.¹

Generalized Area of Intersection (GAI) Model — A less restrictive version of the AI model; the GAI model is described in the present article.

Generalized Equivalent Cylinder (GEC) Model — An empirical model for assessing the safety of pipe intersections containing fissile solution by considering an "equivalent cylinder" whose height and diameter are defined in terms of the parameters of the intersection.²

DERIVATION OF THE GAI MODEL

Summary of Past Work

The data upon which the Area of Intersection (AI) model is based, together with a brief description of the derivation of that model, are included here for reference since the GAI model depends strongly on this earlier work. Some of the relevant experimental results from RFP-1197 are summarized in Table I.

The derivation of the AI model from the experimental data proceeded as follows. Critical edge-to-edge spacings for layers of four 6.4-in. arms

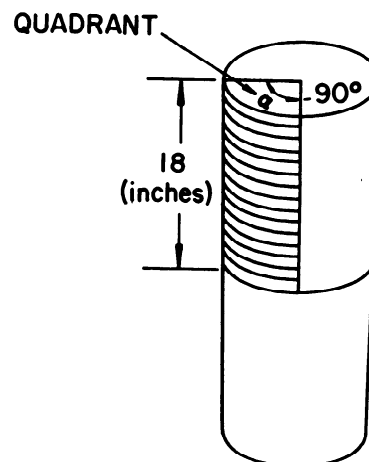


Fig. 2. Sector and quadrant definitions.

on a 7-in. square column were determined experimentally using concentrated, enriched (93.1%) uranyl nitrate as the fissile solution. This information was extrapolated to the case of an infinitely repeating system consisting of layers of four 6.4-in. arms on a 7-in. square column with a critical surface-to-surface spacing of 7.8 in. Conservative corrections were made to these critical dimensions to account for uncertainties in the experimental data and in the long extrapolation. The buckling equation was used to replace the square central column by a circular one, and the arm diameters were reduced to account for steel at the arm-column interface in the experiments. Computational checks of these corrections are reported in Ref. 2. Finally, the resulting diameters were decreased by $\sim 10\%$ and the spacing increased by $\sim 10\%$ to obtain the dimensions of a safely subcritical infinitely repeating system.

To generalize to other systems (e.g., arms at an angle other than 90 deg or several small arms rather than a single large one), the hypothesis was made that the total area of intersection of the arms with the column was closely related to the criticality of the pipe system. This relationship was first inferred from a study of the experimental critical data and has been further supported by Monte Carlo calculations.² For example, for a subcritical intersection consisting of a single arm on a column, k_{eff} varied by less than one standard error ($\sim 2\%$ in k_{eff}) as the angle between the arm and the column varied from 10 to 90 deg (the arm diameter was varied to keep the area of intersection constant).

If the same total area of intersection is divided among several smaller arms, the intersection becomes less reactive than the intersection of a single large arm, since the leakage of the system increases. To examine this effect, at least for

TABLE I

Summary of Experimental Critical Data for Pipe Systems Containing Concentrated, Enriched (~93.1%) Uranyl Nitrate Solution in Steel Pipes

Description of System ^a	Arm Diameter (in.)	Edge-to-Edge Spacing of Layers (in.)	Angle Between Arm and Column (deg)	$k_{eff} \pm \sigma^b$
Eight arms (2 layers, 4 arms per layer)	6.4	5.19	90	0.994 ± 0.018
Twelve arms (3 layers, 4 arms per layer)	6.4	6.63	90	1.015 ± 0.013
Eight arms (2 layers, 4 arms per layer)	5.35	0.25	90	0.995 ± 0.017
Twelve arms (3 layers, 4 arms per layer)	5.35	1.75	90	---
Sixteen arms (4 layers, 4 arms per layer)	5.35	2.75	90	---
Two square arms at 90 deg to each other, 4.82 in. of solution above top of arms	7.0 (square)	--	45	0.984 ± 0.018
Eight arms (2 layers, 4 arms per layer)	5.35	6.16	45	---
Six arms (3 layers, 2 arms per layer, arms in layer at 90 deg to each other)	6.4	0.0	90	0.991 ± 0.016

NOTE: The arms used in the experiments were closed on both ends and were placed against the column, not actually intersecting it. This resulted in a double layer of steel (from the arm end and the column wall) at the arm-column interface. These systems would be supercritical if the extra steel were not present. The arm diameters should be reduced by ~0.28 in. to compensate for the removal of the steel.^{1,2}

^aIn all cases, the central column had a square cross section 7 in. on a side and had $\frac{1}{8}$ -in.-thick steel (Type 304 stainless) walls. The cylindrical steel arms had walls 0.116 in. thick. Unless otherwise mentioned, there was at least 40 in. of solution in the column above the top layer of arms.

^bAll k_{eff} values were calculated using the O5R Monte Carlo code.³ Averages are based on 3000 to 4600 neutron histories.

TABLE II

Monte Carlo Calculations to Investigate the Effect of Redistributing the Same Area of Intersection Among Several Arms

Column Diameter (in.)	Arm Diameter (in.)	Number of Arms	Reflection	$k_{eff} \pm \sigma^a$	Ratio of Thermal Flux to Total Flux ^a
7.25	7.25	1	Minimal ^b	0.837 ± 0.016	0.025
7.25	5.13	2	Minimal	0.805 ± 0.012	0.025
7.25	3.625	4 ^c	Minimal	0.802 ± 0.013	0.025
6.25	6.25	1	Nominal ^d	0.806 ± 0.014	0.037
6.25	4.42	2	Nominal	0.792 ± 0.014	0.039
6.25	3.125	4 ^c	Nominal	0.789 ± 0.012	0.040

^aResults from O5R Monte Carlo calculations³ based on 5000 neutron histories.

^bReflection from $\frac{1}{8}$ -in. steel pipe walls only.

^cFour arms arranged in diamond pattern.

^dReflection from $\frac{1}{8}$ -in. steel pipe walls plus a $\frac{1}{2}$ -in.-thick layer of water around each pipe.

one simple configuration, an O5R calculation was done for a T-intersection consisting of one 7.25-in. arm on a 7.25 in. column. Then calculations were done for the same column with two and with four arms, keeping the total cross-sectional area of the arms constant. The sequence of three calculations was repeated for an intersection with

nominal reflection, to see if the change in the spectrum due to moderation by water affected the results. These calculations are summarized in Table II. For minimal reflection, the two- or four-arm geometry is less reactive than the single arm on a column. For nominal reflection, all three cases have essentially the same k_{eff} .

In the AI model¹ and in the model to be described in this paper, there is a limit of four arms per quadrant for nominally or fully reflected intersections. This limit was imposed to prevent a large shift in the spectrum due to moderation that would occur if a very large number of small arms were used. No experimental data were available to indicate how many arms were required to produce a significant shift in the spectrum, and the limit of four arms per quadrant was chosen somewhat arbitrarily. As shown in Table II, the systems with nominal reflection all have approximately the same k_{eff} , but the ratio of thermal-to-total flux increases as the number of arms increases.

Hence, it is impossible to create by any reapportionment of the intersection area an intersection which is significantly more reactive than the intersection of a single arm with area equal to the maximum allowable intersection area per quadrant.

One of the basic simplifying assumptions of the GAI model (and others) is that an evaluation of the safety of a complex pipe system can be broken down into the study of a number of smaller parts. If each of these parts satisfies the safety criteria, the entire system is also safe. This "decoupling" is achieved by limiting arm diameters and spacings so severely that an infinite repetition along the central column of any allowable intersection is safe.

Generalization of the AI Model

The AI model¹ was based on a configuration consisting of a repeating system of four arms in a planar layer around the central column, one arm in each quadrant. If, for example, each layer contained only two arms (i.e., only two quadrants

contained arms), larger arm diameters would be required to maintain criticality. To extend the AI model, it was necessary to have data on critical arrays with only one or two quadrants containing arms. Since there was insufficient experimental information and since the O5R code³ had shown acceptable accuracy in reproducing experimental results, the code was used to generate the necessary critical data. Later, calculations were performed to verify that the safe dimension pipe systems actually were far subcritical ($k_{eff} + 4\sigma < 0.95$).

The procedure used to derive the safe dimensions of the GAI model was first to select arbitrarily a reasonable central column diameter and then to calculate critical arm diameters for the case of minimal reflection for the following configurations: (a) the simple repeating T (one quadrant per sector), and (b) two quadrants per sector. The cases for 3 and 4 quadrants per sector are combined and are handled as previously presented in RFP-1197. Safe dimensions were obtained from these critical cases by reducing the central column diameter and the arm diameters by 10 to 15%. The safe dimensions for nominally and fully reflected systems were obtained, as in RFP-1197, by applying a reflector savings correction to the data for minimally reflected systems. (See Definitions section for description of reflection conditions.) The calculational data used in arriving at the safe dimensions are given in Table III.

Effect of Additional Columns

All previous models have been limited to the case of a single central column, leaving it up to the user to decide when a second column is sufficiently far away to be considered isolated. No

TABLE III
Calculations for GAI Model for Uranyl Nitrate Solution*

Number of Quadrants Containing Arms	Figure Reference	Near Critical Dimensions ^a			Safe Dimensions ^a		
		Column Diameter (in.)	Arm Diameter (in.)	$k_{eff} \pm \sigma^b$	Column Diameter (in.)	Arm Diameter (in.)	$k_{eff} \pm \sigma^b$
1	3	8.5	8.5	0.982 ± 0.014	7.25	7.25	0.864 ± 0.019
2	4a	7.8	7.0	0.968 ± 0.019	7.0	6.15	0.829 ± 0.011
2	4b	---	---	---	7.0	6.15	0.815 ± 0.013
4	5	7.6 ^c	6.12 ^c	---	6.5	5.5	0.852 ± 0.015

*Solution is 451 g/liter uranyl nitrate; the uranium is enriched to 93.1% by weight ²³⁵U. The concentration used is in the minimum critical volume region.

^aIn all cases, the intersection was repeated six times. All pipe walls are 1/8-in. thick steel.

^bAll k_{eff} calculations were performed by the O5R Monte Carlo code.³

^cFrom experimental data.¹

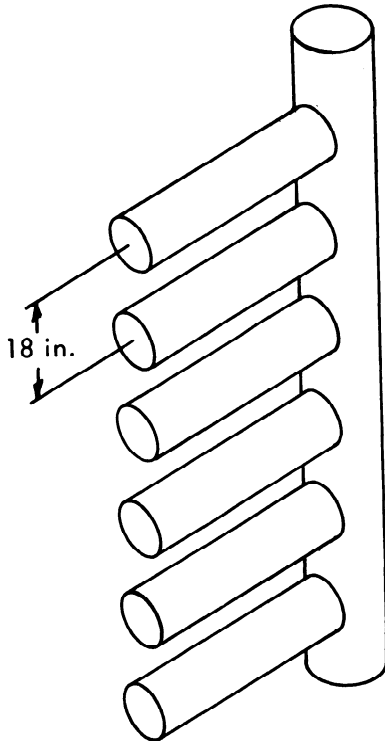
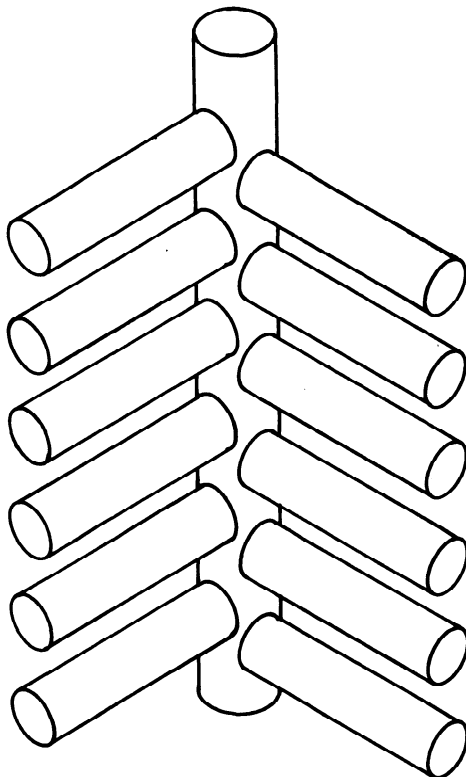


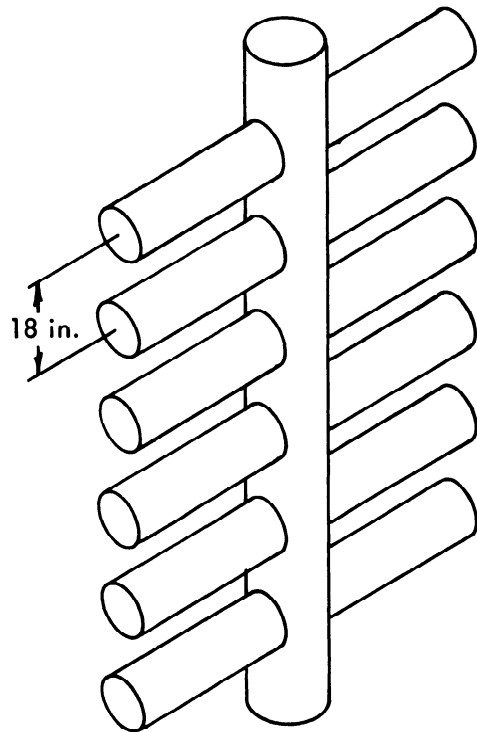
Fig. 3. Six layer T-intersection (one quadrant containing arms).

experimental results exist for the case of interconnected pipe systems, each consisting of a central column with attached arms. However, data on the interaction of cylinders (i.e., columns) indicate that interaction decreases rapidly with distance. For example, for a pair of infinitely tall cylinders in water at a surface to surface separation of 12 in., the critical diameter of each cylinder is >99% of the critical diameter for a single infinite cylinder.⁴ Three unreflected 8-in.-diam cylinders containing enriched uranyl fluoride solution (which is more reactive than uranyl nitrate solution) and arranged in an equilateral triangle pattern are subcritical at any solution height for and edge-to-edge spacing of 9 in.⁵

Monte Carlo calculations were performed to determine the effect of adding a second column to each of two intersections, one near critical, the second safe. For the first case, a second column was added to a near-critical cross intersection (see Fig. 6). The variation of k_{eff} with the center-to-center distance between the columns is shown in Table IV. The goal of these calculations was to find the separation at which the second column had a negligible effect on the k_{eff} of a critical system. Since the increase in k_{eff} due to a second column at a separation of 2 ft was less than one standard error, the 2-ft distance was



(a) Arms at 90 deg to each other.



(b) Arms at 180 deg to each other.

Fig. 4. Six layer intersection with two quadrants containing arms.

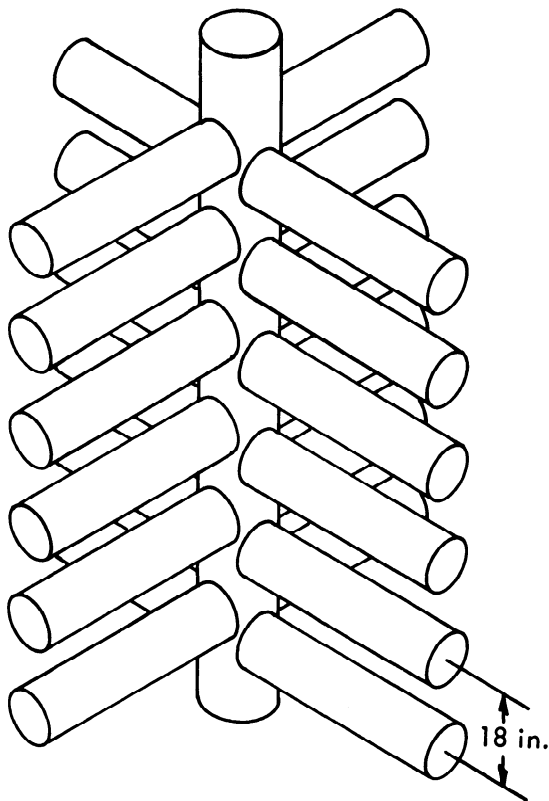


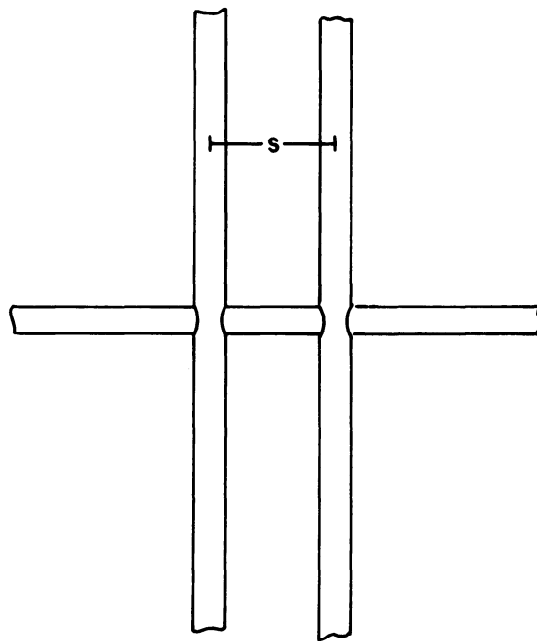
Fig. 5. Six layer intersection with four quadrants containing arms.

TABLE IV
Change in k_{eff} Due to a Second Column for a Near-Critical Cross Intersection (See Fig. 6)

Number of Columns	Center-to-Center Separation of Columns (in.)	$k_{eff} \pm \sigma$
1	--	0.989 ± 0.010
2	24	0.993 ± 0.015
2	18	1.010 ± 0.014

NOTE: All pipe diameters are 8.25 in., and all pipes have $\frac{1}{8}$ -in.-thick steel walls.

selected as the minimum separation permitted by the GAI model. Then a calculation was performed on a safe six-layer cross intersection to determine the change in k_{eff} produced on a far sub-critical intersection by a second column; the resulting increase in k_{eff} was only 0.002 (from 0.815 ± 0.013 to 0.817 ± 0.016), which is insignificant when compared to the standard errors involved. Because of the smallness of the change produced by adding a second column, it is inferred



s = CENTER-TO-CENTER SEPARATION OF COLUMNS

Fig. 6. Cross intersection with second column added.

that a third column would also produce an acceptably small change in k_{eff} , although no calculations were done to study the effect of a third column. An example (see Example 2) is presented of a system containing three interconnected columns, and an O5R calculation verified that the diameters and separations calculated by the GAI model are safe.

RULES DEFINING THE GAI MODEL

1. The area of intersection of the arms with the column must be calculated for all quadrants containing arms, and the calculated area must not exceed the maximum value given in Table V for the appropriate number of quadrants used and reflection condition. The intersection area must be distributed in such a way that it is impossible to find *any* quadrant which contains more area than that permitted by Table V.

2. The central column diameter must not be greater than the appropriate limiting value given in Table V.

3. A maximum of *three* columns is permitted, and the center-to-center distance between any pair of columns must be *at least* 2 ft.

4. For the case of *nominal* or *full* reflection, a maximum of *four arms per quadrant* is per-

TABLE V

Maximum Intersection Areas and Column Diameters Permitted by the GAI 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 (sq. in.)	Maximum Central Column Diameter (in.)	Maximum Intersection Area per Quadrant (sq. in.)	Maximum Central Column Diameter (in.)	Maximum Intersection Area per Quadrant (sq. in.)
1	7.25	41.28	6.25	30.68	4.60	16.62
2	7.00	29.70	6.00	20.83	4.44	11.98
3 or 4	6.50	23.75	5.50	16.00	4.12	9.60

mitted. There is no limitation on the number of arms per quadrant in the case of minimal reflection.

EXAMPLES

The following examples illustrate the application of the GAI model. In each case, the goal is to maximize pipe diameters and minimize spacings. All pipes are assumed to be filled with enriched (93.1% by weight ^{235}U) uranyl nitrate solution at a concentration of 450 g/liter of uranium, and minimal reflection is assumed.

Example 1 (See Fig. 7)

Note that arms 1-6, all of diameter d_2 , must be placed in the same sector. Assume that the separation, S , is large enough to put arms 7-10, all of diameter d_3 , in a separate sector. For the first sector (arms 1-6), only two quadrants contain arms, and hence each quadrant is permitted 29.7 sq. in. of intersection area, giving

$$d_2 = \sqrt{\frac{4}{\pi} \left(\frac{29.7}{3} \right)} = 3.55 \text{ in.}$$

For the sector containing arms 7-10, the four quadrants are used, and hence d_1 , the column diameter, is 6.5 in., and $d_3 = 5.5$ in.

Finally, the separation, S , must be chosen large enough so that no quadrant contains more intersection area than permitted by Table V. This is accomplished by setting $S = 18 \text{ in.} - 3.55 \text{ in.} = 14.45 \text{ in.}$

By comparison, the maximum arm diameters permitted by the GEC model for a 6.5-in. column are $d_2 = 3.72 \text{ in.}$ and $d_3 = 5.02 \text{ in.}$

Example 2 (See Fig. 8)

Consider first the spacing of the columns, since that is independent of arm or column diam-

eters. The distances S_1 and S_2 must each be 24 in.; then the distance between columns 1 and 3 is $24\sqrt{2}$ in.

For column 1, there is only one sector to consider, and it has two quadrants containing arms. Therefore, column 1 may have a diameter of 7.0 in., and each quadrant may contain 29.7 sq. in. of intersection area; thus, arm 2 may have a diameter of 6.15 in. and arm 1, which is at 45 deg, a diameter of 5.17 in. Note that the diameter of arm 2, which also intersects column 2, may have to be reduced to make column 2 safe.

Regarding column 2, assume that the distance S_3 will be chosen so that arms 3 and 4 are in different sectors. Then the sector containing arm 4 uses only one quadrant. However, the sector containing arms 2 and 3 has two quadrants containing arms, and hence column 2 is limited to a diam-

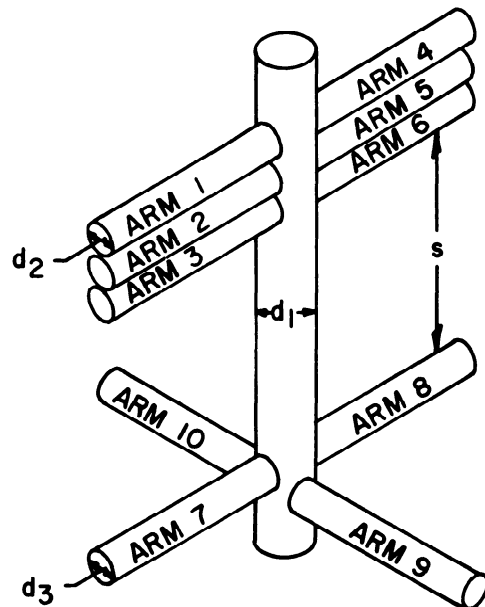


Fig. 7. Geometry for Example 1.

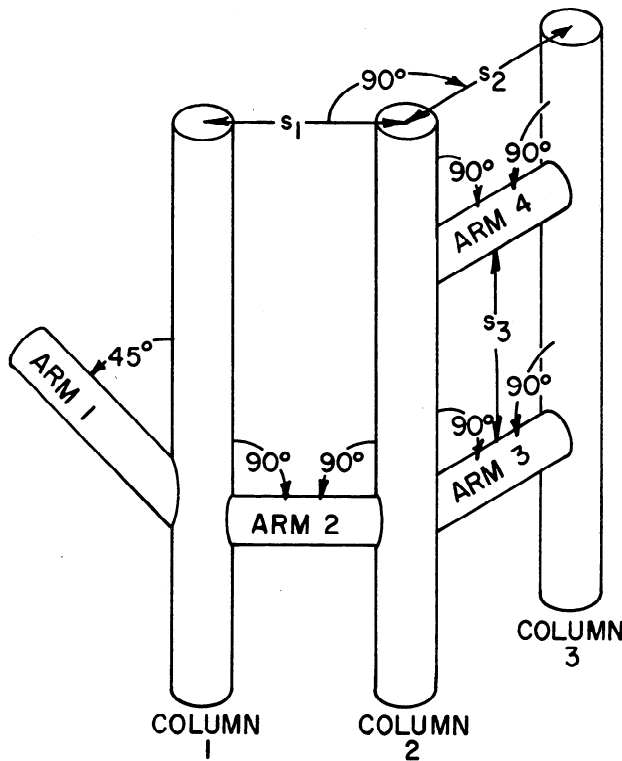


Fig. 8. Intersecting system with three columns. Permissible pipe diameters are calculated in Example 2.

eter of 7 in. Arms 2 and 3 may each be 6.15 in. in diameter (so the previously assigned diameter for arm 2, relative to column 1, is allowed to stand). Arm 4, which is permitted 41.28 sq. in. of intersection area (corresponding to a diameter of 7.25 in.), can be only 7 in. in diameter, since the arm diameter cannot be larger than the column diameter.

Finally, column 3 has two sectors to consider, each of which contains only one arm. Hence, column 3 may have a diameter of 7.25 in. Arms 3 and 4 are also permitted 7.25-in. diam, so the smaller diameters already assigned also satisfy the safety criteria for column 3.

Setting $S_3 = 11.85$ in. puts arms 3 and 4 in separate sectors.

The calculated k_{eff} for this system, using the diameters previously assigned, is $k_{eff} = 0.852 \pm 0.018$.

Example 3 (See Fig. 9)

For this example, the column diameter is allowed to vary. Consider first the sector containing arm 1. Only one quadrant is used, so $d_1 = d_2 = 7.25$ in.

Next, the sector containing arms 2 and 3 uses two quadrants, and the maximum column diameter is $d_3 = 7.0$ in. For the arms, $d_4 = 6.15$ in. and $d_5 = 5.17$ in. (by the same calculations used for arms 1 and 2 of Example 2).

The distance S_2 must be chosen so that the 7.25-in. part of the column cannot be placed in the same sector with arms 2 and 3. This is prevented by setting $S_2 = 18$ in. There is no restriction on S_1 , since the choice of S_2 is sufficient to put arm 1 in a separate sector from the one containing arms 2 and 3.

To check the conservatism of the GAI model, two O5R calculations were done for this example. With all diameters and spacings as calculated, and with $S_1 \cong 0.2$ in., $k_{eff} = 0.833 \pm 0.017$. For $S_1 \cong 18$ in., $k_{eff} = 0.821 \pm 0.016$.

COMPARISON OF GEC AND GAI MODELS

A different model for evaluating the safety of pipe intersections for fissile solution was described in RFP-1499.² That model, called the Generalized Equivalent Cylinder (GEC) model, was based on the idea of replacing an intersection by an equivalent cylinder, whose height and diameter are calculated from the parameters of the intersection. The intersection is deemed safe if the equivalent cylinder is subcritical.

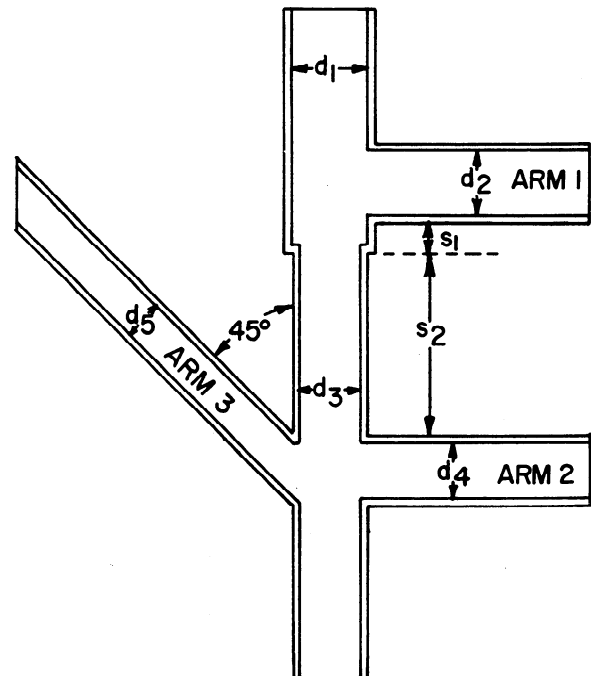


Fig. 9. Pipe system with central column of variable diameter. See Example 3 for calculation of safe dimensions.

When applied to uranyl nitrate solution, the GAI model generally allows much larger diameters than the GEC model. Exceptions may occur in the case of a quadrant containing several arms, since the GAI model makes the overconservative rule that the total allowable area is to be divided among the various arms (see Example 1, results for arms 1-6).

SUGGESTIONS FOR USE OF THE MODEL

The derivation of the GAI model required only properties common to all fissile solutions, such as the reflector savings correction or the fact that k_{eff} is decreased by replacing one pipe by several smaller ones with the same total area of intersection. Hence, the concept of the GAI model can be applied to other fissile solutions (e.g., plutonium, ^{233}U , or low-enrichment uranium) if calculations or experiments are performed to provide the appropriate numerical values for column diameter and intersection area as given in Table V for uranyl nitrate. The rules of the model are exactly as given here.

Recent French experiments⁶ indicate that the GAI model, using the data given in Table V for uranyl nitrate, would be even more conservative when applied to certain bare plutonium solution systems. In particular, plutonium nitrate solution (3.13% ^{240}Pu , acidity about 2N, concentration >82 g/liter of ^{239}Pu) is found to be less reactive than uranyl nitrate (90% ^{235}U , acidity about 2N) for the same concentration of the fissile isotope (Ref. 6, p. 19).

A second possible variation of the GAI model concerns the particular column diameters and corresponding intersection areas given in Table V. If, for example, one did not need column diameters as large as those given in Table V but needed instead larger intersection areas, one could make such modifications if appropriate calculations or experiments were performed to support these changes, but the basic assumptions of the GAI model would still apply.

The authors suggest that, whenever possible, proposed pipe systems for fissile solution be evaluated using both the GEC² and the GAI models. Since both models are adequately conservative, one can choose the model that gives the better result in each particular case.

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