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AEC RESEARCH AND DEVELOPMENT REPORT

SELF-CONSISTENT CRITERIA FOR EVALUATION OF NEUTRON INTERACTION

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OAK RIDGE GASEOUS DIFFUSION PLANT

Operated by

UNION CARBIDE NUCLEAR COMPANY
A DIVISION OF UNION CARBIDE AND CARBON CORPORATION

for the Atomic Energy Commission

Acting Under U. S. Government Contract W7405 eng 26

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SELF-CONSISTENT CRITERIA FOR EVALUATION OF NEUTRON INTERACTION

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Oak Ridge Gaseous Diffusion Plant
Oak Ridge, Tennessee

Report Number: K-1317

Title: SELF-CONSISTENT CRITERIA FOR EVALUATION OF NEUTRON INTERACTION

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ABSTRACT

New safe interaction criteria for containers of fissionable materials handled at the Oak Ridge Gaseous Diffusion Plant have been developed on the basis of an interaction theory using the basic concepts of a safe solid angle subtended by interacting containers, and the multiplication factor as determined by two-group theory for an individually safe container. The calculated results agree satisfactorily with experimental data obtained with identical interacting units involving both cylinders and slabs containing highly enriched uranium, the core compositions of which were varied between H/U-235 atomic ratios of 44.3 and 337.

The application of the derived interaction criteria to items containing material with low moderation or low U-235 assay, and to containers for which nuclear safety is dependent upon control of the U-235 mass or U-235 concentration is discussed.

SELF-CONSISTENT CRITERIA FOR EVALUATION OF NEUTRON INTERACTION

Introduction

At the Oak Ridge Gaseous Diffusion Plant, the concept that containers of fissionable materials should be spaced in accord with a geometrical solid angle criterion has been used as a basic operational premise due to the facts that it appears to have some theoretical justification and that it is easily applicable to any system of containers or vessels of varying dimensions and materials. These factors, plus ease of administration of systematic separation rules developed from the basic criteria, are considered highly desirable in a large production plant where fissionable materials of varying assays, densities, and concentrations are regularly used or stored in a wide variety of containers. In general, the ORGDP philosophy has been that only 3 principal conditions must be satisfied for a system of containers to be so spaced as to be considered nuclearly safe:[1]

1. All containers must be safe* when completely surrounded by water.
2. The container separation may never be less than 12 inches.
3. Containers must always be so separated from each other that the maximum solid angle subtended by the most central unit in the group does not exceed some safe value.

Of these 3 criteria, the first 2 have been considered necessary to provide protection against criticality in the event of accidental or purposeful flooding of a system of interacting containers and are involved only slightly in neutron exchange considerations. The third criterion, however, is connected with the possible effects of neutron exchange between containers in the absence of such flooding and is therefore the principal subject of interest in this report.

The safe solid angle may be considered roughly as the permissible fraction of the total surface area of a container which can "see" other containers. This was originally established at the ORGDP as 3% of 4π (0.38 steradian), but in January, 1953, the specification was increased to 8% of 4π (1.0 steradian),[2] primarily as a result of theoretical work by Henry and Edlund[3] as well as some experimental work[4] indicating that "ring-tamping" was not a significant factor. Although the specifications themselves were considered sufficiently conservative to compensate for the uncertainties in the nuclear data at that time, it was recognized that there were large gaps in the fundamental knowledge of neutron interaction and the need for additional experimental information was stressed. Some of these gaps have been filled recently, and the new

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* The term "safe", when applied to individual containers, will refer to units meeting "limited-safe" criteria as defined in report K-1019.

experimental data, primarily with highly enriched and well-moderated uranium, and their theoretical interpretation have been tabulated in a previous report.[5] In essence, the theory relates the multiplication factor, k, of an isolated bare container to the fractional solid angle, Ω, between an interacting pair of such containers by the simple relation

$$K = k\left[1 + \ell\Omega(1 - U_f)\right]$$

where K is the multiplication factor of each container considered as a part of the system, as well as that of the system itself, and is thus unity at criticality; $(1 - U_f)$ is the probability that a neutron above thermal energy will escape the container in which it was born; and $\ell\Omega$ is the probability that an escaping neutron will intercept the adjacent container, ℓ being a correction factor for end leakage in the case of cylindrical or slab containers. This simple relation has also been extended to multi-body systems and verified by comparison with experimental data, with the parameters k, ℓ, and $(1 - U_f)$ being determined by simple 2-group theory.*

The purpose of the present report is to review the available data,[5,6,7,8] not only to determine the adequacy of present interaction criteria at the ORGDP but also to provide a firmer basis for the establishment of such new criteria as may be justified in view of the present knowledge. It is, of course, recognized that any criteria must be such as to prevent the possibility of criticality inadvertently occurring because of the neutron exchange, or "interaction", between several individually subcritical containers.

Summary of the Basic Interaction Criteria

It has been determined[5] that, for a critical system, the total fractional solid angle, Ω_t, subtended by the most central container of a system of identical and individually subcritical units is a function of the multiplication factor, k, of that single bare container. Hence, the basic criteria, as developed from the new interaction data, specify safe solid angle limits based on the multiplication factor of the individually safe units considered. These criteria, which are considered to be conservative for any of the conditions anticipated at the ORGDP, are summarized below:

1. All containers must be safe when completely reflected by water.

2. The container separation may never be less than 12 inches.

3. The solid angle may be 48% of 4π (6.0 steradians) for $k < 0.30$.

4. The solid angle may be determined by a straight line interpolation between 48% of 4π and 8% of 4π (6.0 steradians and 1.0 steradian) for $0.30 < k < 0.80$.

---

* Although a 2-group theory was chosen[5] for convenience in calculation, obviously other computing methods may be employed to determine the basic parameters used in the simple interaction relation. It may be further noted that the extrapolation length, e, used in the theory, was considered a function of Ω by the simple empirical relation, $e = 2.5 + 4.5\Omega$, where e is in cm., and that k is identified in the previous report[5] as k_1.

5. For values of $k > 0.80$, separation should be based on experimental data.

6. A solid angle of 0.04% of 4π (0.005 steradian) may be neglected in considering interaction between individually safe units.

Determination of the Basic Interaction Criteria

Since any criterion developed must be appropriate to prevent criticality in systems of containers which may be unreflected, completely reflected by water,* or partially reflected, the adequacy of the single set of criteria proposed are reviewed for each of these conditions. Considerations of partial reflection are interpreted for a container fully reflected over 50% of the surface since this is taken as the most reactive condition where partial reflection only is considered, and which will be subsequently referred to as half-reflection. Further, since geometry is the principal nuclear safety control factor at the ORGDP, and since much of the data available are for geometry-controlled experiments with identical slabs or cylinders of well-moderated uranium at U-235 assays of about 90%, the basic analyses are made for these cases. However, some comments are made on the applicability of the criteria developed to those units where the moderation, U-235 assay, U-235 mass, and the U-235 concentration may be control parameters.**

As noted in the previous report,[5] the method used in determining k is applicable only to unreflected containers although it is perhaps obvious that k, or K, is actually unity for any container or system which is critical. Thus, in this report, all values of k given are those for the bare and isolated units in question and, accordingly, the change in this value of k caused by some change in conditions external to the container is considered a measure of that effect upon the reactivity of the unit container. The symbol Δk is generally used to denote this effect. For example, with a critical assembly of interacting containers, $\Delta k = K - k$, may be considered a measure of the effect of interaction upon the reactivity of the system, or, in the case of a reflected container, the difference between unity and the k calculated from the dimensions of the bare container, which is critical when reflected, may be considered as a measure of the reflector savings.

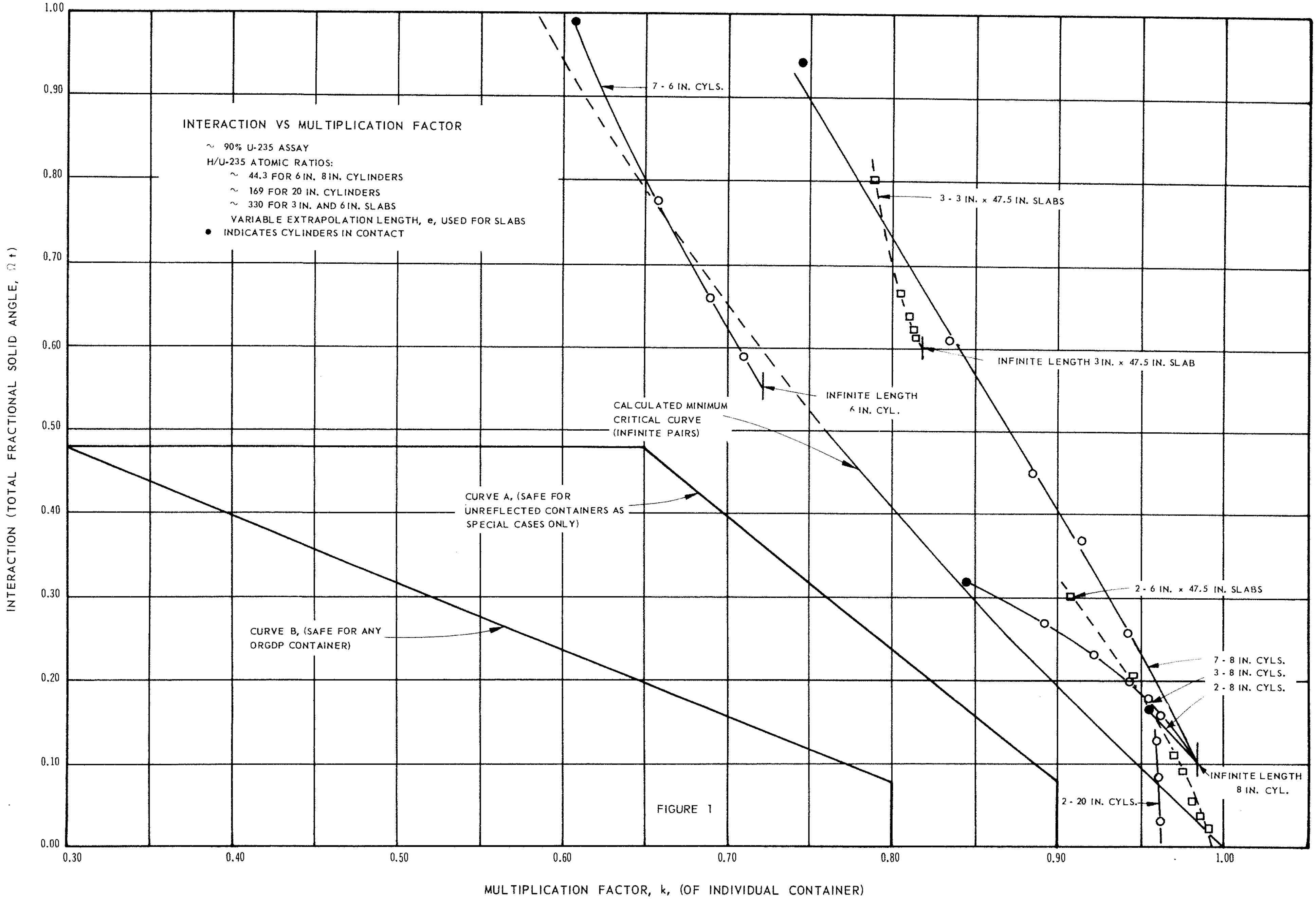
1. The Unreflected Case

The data which were obtained from experimental and theoretical interaction studies are plotted in figure 1 to show the total fractional solid angle, Ω_t, subtended by the most central container of a system, as a function of the multiplication factor, k, of that single bare container when criticality is obtained for

---

* Where reference is made to water reflection, this includes other materials either with a hydrogen density equal to that of water or with comparable neutron reflection properties.

** The interaction criteria as developed herein were based primarily upon experimental considerations of homogeneous systems of identical containers. The application of these criteria to non-homogeneous systems will be discussed in a forthcoming report.


INTERACTION VS MULTIPLICATION FACTOR
~ 90% U-235 ASSAY
H/U-235 ATOMIC RATIOS:
~ 44.3 FOR 6 IN. 8 IN. CYLINDERS
~ 169 FOR 20 IN. CYLINDERS
~ 330 FOR 3 IN. AND 6 IN. SLABS
VARIABLE EXTRAPOLATION LENGTH, e, USED FOR SLABS
● INDICATES CYLINDERS IN CONTACT
7 - 6 IN. CYLS.
3 - 3 IN. x 47.5 IN. SLABS
INFINITE LENGTH 3 IN. x 47.5 IN. SLAB
INFINITE LENGTH 6 IN. CYL.
CALCULATED MINIMUM CRITICAL CURVE (INFINITE PAIRS)
CURVE A, (SAFE FOR UNREFLECTED CONTAINERS AS SPECIAL CASES ONLY)
CURVE B, (SAFE FOR ANY ORGDP CONTAINER)
2 - 6 IN. x 47.5 IN. SLABS
7 - 8 IN. CYLS.
3 - 8 IN. CYLS.
2 - 8 IN. CYLS.
INFINITE LENGTH 8 IN. CYL.
2 - 20 IN. CYLS.
INTERACTION (TOTAL FRACTIONAL SOLID ANGLE, Ωt)
MULTIPLICATION FACTOR, k, (OF INDIVIDUAL CONTAINER)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
FIGURE 1

the system.* From these data, it appears that:

a. For units of different geometrical shapes but identical multiplication factors, interaction is more effective between slab geometries than between non-slab geometries.**

b. For criticality to be attained, a "larger" solid angle of interaction is apparently necessary for a multi-body system than for a 2-body system. This difference is due primarily to the ORGDP calculation method of assuming solid angles from several containers to be additive, whereas theoretical considerations[5] indicate that the effective solid angle for several containers is less than the sum of these solid angles. Thus, a practical separation for multi-body systems which is based on a solid angle considered safe for a 2-body system should be highly conservative.

c. The values of k obtained for cylinders of large radii and small critical heights may be essentially non-conservative; that is, the calculated K for a system which was experimentally determined to be critical is less than unity.

Also plotted in figure 1 is a minimum critical curve which was determined for 2-body systems using the 2-group interpretation of the interaction relationship described above. Essentially, the method involved taking pairs of infinite cylinders with diameters so chosen that $k < 1$ when filled with the most reactive high assay uranium solution, considered as that with an H/U-235 atomic ratio of 44.3. The fractional solid angle, Ω, was then determined such that $K = 1$ for the system. Similar determinations for pairs of infinite slabs gave results which were not appreciably different than those for pairs of cylinders; hence, only one curve is shown. It may be noted that the maximum solid angle for 2 cylinders in contact is about 20% of 4π and that for 2 slabs in contact is about 50% of 4π. Thus, while the minimum critical curve obviously has no physical significance for 2-body systems at solid angles greater than 20% and 50% of 4π for cylinders and slabs, respectively, these portions of the curve may be taken as conservative theoretical limits for multi-body systems.

It may be noted that another curve in figure 1, identified as curve A, is well below both the estimated minimum critical curve for 2-body systems and the experimental curves and is thus in a subcritical region. Since it includes an appropriate allowance for experimental or theoretical uncertainties, it may be considered a "safety curve", which appears to be sufficiently conservative for use under any conditions where significant neutron reflection of system components

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* The k values shown in figure 1 are also tabulated in report K-1309.

** A slab geometry is defined as any geometry where the area of any 2 parallel plane surfaces is greater than 50% of the total surface area.

is virtually impossible. Thus, it may be concluded that individually safe units will also be safe if separated in accord with curve **A** of figure 1 which specifies as limits:

a. A solid angle of 48% of 4π (6.0 steradians) for $k < 0.65$.

b. A straight line interpolation between 48% of 4π and 8% of 4π (6.0 steradians and 1.0 steradian) for $0.65 < k < 0.90$.

However, for cases where the calculated $k > 0.90$, it is suggested that interaction specifications depend upon direct experimental data.

2. The Half-Reflected Case

Since it is possible in many instances for 2 containers to be partially reflected and yet have no neutron absorbing material between them, a system of 2 components, each "half-reflected" as previously defined, has been evaluated in order to determine the maximum effect of such partial reflection on an interacting system. From the experimental critical heights of interacting as well as isolated units given in tables I and II, respectively, it is obvious that not only is a single container more reactive if half-reflected than if bare, but also that the half-reflected system is more highly reactive than an identical one but with the units unreflected.

Also given in table I are Δk values of the reactivity change of a single 10 in. I.D. cylinder due to the interaction between 2 such containers, both for the bare and half-reflected cases; in each case, Δk is determined by the method outlined above. From the curves shown in figure 2, where these Δk values are plotted as a function of the fractional solid angle, Ω, it may be noted that for a given solid angle, the interaction effect, as measured by Δk values, is somewhat greater for bare than for half-reflected units. Thus, it appears that use of a solid angle criterion for the determination of container separation should give highly conservative* results for the half-reflected case where the criterion used is based upon safety requirements for data with bare containers.

From the above, it is apparent that the interaction relation considered may be applicable to the half-reflected case provided suitable values of the multiplication factor, $k_{\frac{1}{2}R}$, for a half-reflected container can be obtained. From both the limited experimental data available and semitheoretical considerations, it appears that a conservative value of $k_{\frac{1}{2}R}$ for a half-reflected container is one midway between the corresponding factors for the same container if

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* From the standpoint of nuclear safety, a conservative result is one where the factors concerned are so chosen that criticality is predicted for an experimentally subcritical assembly and, correspondingly, a critical assembly is predicted to be supercritical. Thus, the calculations are conservative if the actual multiplication factor of a container or system is lower, and thus less reactive, than is indicated by the 2-group analysis of the data given.

TABLE I

EFFECT OF HALF-REFLECTION ON CRITICAL HEIGHTS OF TWO 10 IN. I.D. INTERACTING CYLINDERS

(H/U-235) $\cong$ 330

Separation (Inches)	Critical Ht. (Inches)	Fractional Solid Angle Ω	BARE k	BARE K	BARE Δ k of Interaction (K - k)	HALF-REFLECTION k	HALF-REFLECTION $k_{\frac{1}{2}R}$*	HALF-REFLECTION $K_{\frac{1}{2}R}$	HALF-REFLECTION Δ k of Interaction ($K_{\frac{1}{2}R}$ - $k_{\frac{1}{2}R}$)
0.12	16.06	0.1720	0.9317	0.9938	0.0621				
0.87	17.67	0.1466	0.9472	1.0013	0.0541				
1.00	11.67	0.1310	-	-	-	0.8731	0.9520	0.9981	0.0461
2.00	19.68	0.1220	0.9574	1.0034	0.0460				
3.26	21.57	0.1033	0.9648	1.0044	0.0396				
6.65	25.47	0.0724	0.9826	1.0111	0.0285				
12.00	14.17	0.0310	-	-	-	0.9119	0.9908	1.0025	0.0117
12.44	29.29	0.0455	0.9891	1.0073	0.0182				
17.16	31.50	0.0337	0.9923	1.0058	0.0135				
27.00	14.94	0.0107	-	-	-	0.9209	0.9998	1.0039	0.0041
∞	58.20	-	1.0106	-	-				
∞	14.97	-	-	-	-	0.9211	1.0000	-	-

* The Δ k due to half-reflection is taken in all cases as the difference between unity, the multiplication factor of the isolated half-reflected unit, and 0.9211, the k for this unit if unreflected. Thus, $k_{\frac{1}{2}R} = k + 0.0789$.

TABLE II

EFFECT OF HALF-REFLECTION AND COMPLETE REFLECTION ON CRITICAL HEIGHTS

OF BARE CYLINDRICAL AND SLAB CONTAINERS

Container Dimensions (Inches)	H/U-235 Atomic Ratio	BARE Critical Ht. (Inches)	BARE k	Δk 1st. Half-Ref.	HALF-REFLECTION Critical Ht. (Inches)	HALF-REFLECTION k	Δk 2nd. Half-Ref.	COMPLETE REFLECTION Critical Ht. (Inches)	COMPLETE REFLECTION k
8μ	51.5	(Not Critical at ∞)	0.9795	0.0585	18.15	0.9210	0.1623	7.68	0.7587
10μ	330	58.20	1.0106	0.0900	14.97	0.9206	0.1210	8.80	0.7996
30μ	71.5	5.28*	1.0229	0.2122	3.98	0.8107	0.3169	2.44	0.4938
20x20λ	71.5	5.47	0.9950	0.1273	4.46	0.8677	0.3331	2.71	0.5346
30x60λ	51.5	4.86**	1.0000	0.2535	3.50***	0.7465	0.3124	2.09	0.4341
6x47.5λ	337	47.80	0.9862	0.1247	11.99	0.8615	0.1323	7.26****	0.7292

μ Diameter.

λ Edge Lengths.

* Estimated from subcritical height of 4.80 inches.

** Estimated by 2-group theory.

*** (H/U-235) atomic ratio 56.9.

**** Estimated by pile theory transformation of experimental data.

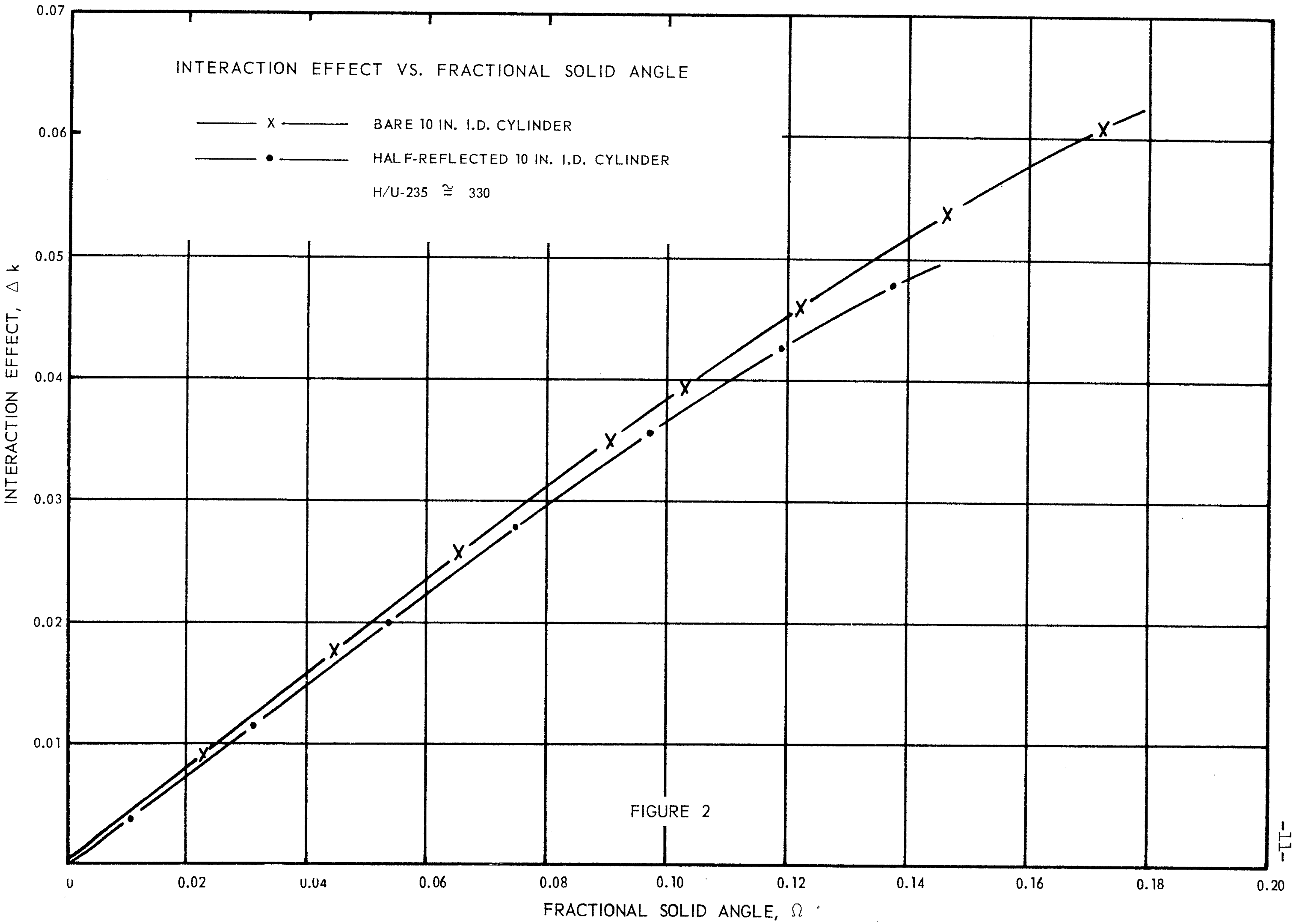
INTERACTION EFFECT VS. FRACTIONAL SOLID ANGLE
X BARE 10 IN. I.D. CYLINDER
• HALF-REFLECTED 10 IN. I.D. CYLINDER
H/U-235 ≅ 330
INTERACTION EFFECT, Δ k
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0.20
FRACTIONAL SOLID ANGLE, Ω

FIGURE 2

totally reflected and if unreflected; the resultant simple expression is:

$$k_{\frac{1}{2}R} = 0.5\ (k_R + k)$$

where k is the value of the multiplication factor for an unreflected container and k_R that for a reflected container having the same dimensions and contents. For the special case where the reflected container is just critical and k_R is thus unity, this expression reduces to:

$$k_{\frac{1}{2}R} = 0.5\ (1 + k).$$

The basic conservatism in the practical use of this relation is indicated in table II where the reactivity change, Δk, due to the reflector savings is shown for containers which were experimentally critical or near thereto, both when half-reflected and when completely reflected; this table includes all data known to be available experimentally on half-reflected individual units. By comparing the Δk values, it may be noted that, in all cases, the change in reactivity due to the addition of half-reflection of a bare container is less than the corresponding change produced by completely reflecting a half-reflected container; this consideration also appears to have some intuitive theoretical justification. Thus, it is apparent that the actual value of $k_{\frac{1}{2}R}$ will be somewhat less than is indicated by the simple expression. This is a conservative factor.

Applied to interaction, this infers that the actual effect of interaction upon the container will need to be greater than is indicated from the multiplication factor determined by the simple relation noted. Further, since the empirical relationship was derived for containers which are critical when reflected, its use for containers which are subcritical when completely reflected, as is the case for any container actually used at the ORGDP,* is a conservative factor. Thus, since the effect of interaction between half-reflected units appears to be less than that for bare units, and since the simple relation developed gives conservative values of the multiplication factors of half-reflected units, the use of the solid angle criterion for containers where half-reflection is possible appears to be basically sound from the standpoint of nuclear safety with the values of k chosen as described.

Based on the above considerations, it appears that the "safety curve" proposed for the unreflected case may also be conservatively applicable to the half-reflected case provided the value of the multiplication factor used is defined by the relation, $k_{\frac{1}{2}R} = 0.5(1 + k)$. Hence, curve B of figure 1 represents a "safety curve" as derived

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* It is obvious, of course, that the derived relation should not be used where $k_R > 1$ as is the case of a container which is critical when only half-reflected.

from curve A for values of k where "half-reflection" is considered possible. Thus, units which are individually safe will also be safe when half-reflected, if separated in accord with this "safety curve" which specifies as limits:

a. A solid angle of 48% of 4π (6.0 steradians) for $k < 0.30$.

b. A straight line interpolation between 48% of 4π and 8% of 4π (6.0 steradians and 1.0 steradian) for $0.30 < k < 0.80$.

These criteria are considered adequate to provide nuclear safety for any conditions normally encountered at the ORGDP. However, for values of $k > 0.80$, separation should be based on experimental data where half-reflection is considered possible; this should insure adequate safety of individual units.

3. The Totally-Reflected Case

Since neutron interaction between containers in close-packed arrays decreases* with container separation due to the attenuation of neutrons in water, it was considered necessary to determine if there is a minimum separation at which the safety factor for a completely reflected container is more important, reactivity-wise, than the effect of residual neutron exchange; previously, a minimum separation of 1 ft. had been chosen on the basis of the high neutron absorption of water[3] to satisfy this condition.

The interaction effect of residual neutron exchange may be noted in figure 3, where the multiplication factor, k, of an individual container,** in a reflected array, is plotted as a function of the container separation; Δk_1, which is the difference between the k of an isolated container and that of a container in an array, is thus considered as an indication of the effect of residual neutron interaction. It may be noted that, for all cases where experimental data are available, Δk_1 becomes < 0.008 at separations of 1 ft.

Figure 4 gives a plot of the multiplication factor, k, for bare containers which are critical when reflected, together with the corresponding safe values of k as determined for containers which are "safe" when totally reflected; Δk_2, the difference between these values of k, is obviously a measure of the container safety. Comparison of values of Δk_1 and of Δk_2 for cylindrical containers indicates that the safety factors of individually "safe" containers are more than adequate to compensate for any residual neutron exchange which may occur through 1 ft. of water.

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* For short separations, up to a maximum of about 6.0 in., the moderation effect may increase the reactivity in some cases. See references 4 and 8.

** Values of the multiplication factor, k, given in figures 3 and 4, are determined from the dimensions of the unreflected containers which are critical when reflected.

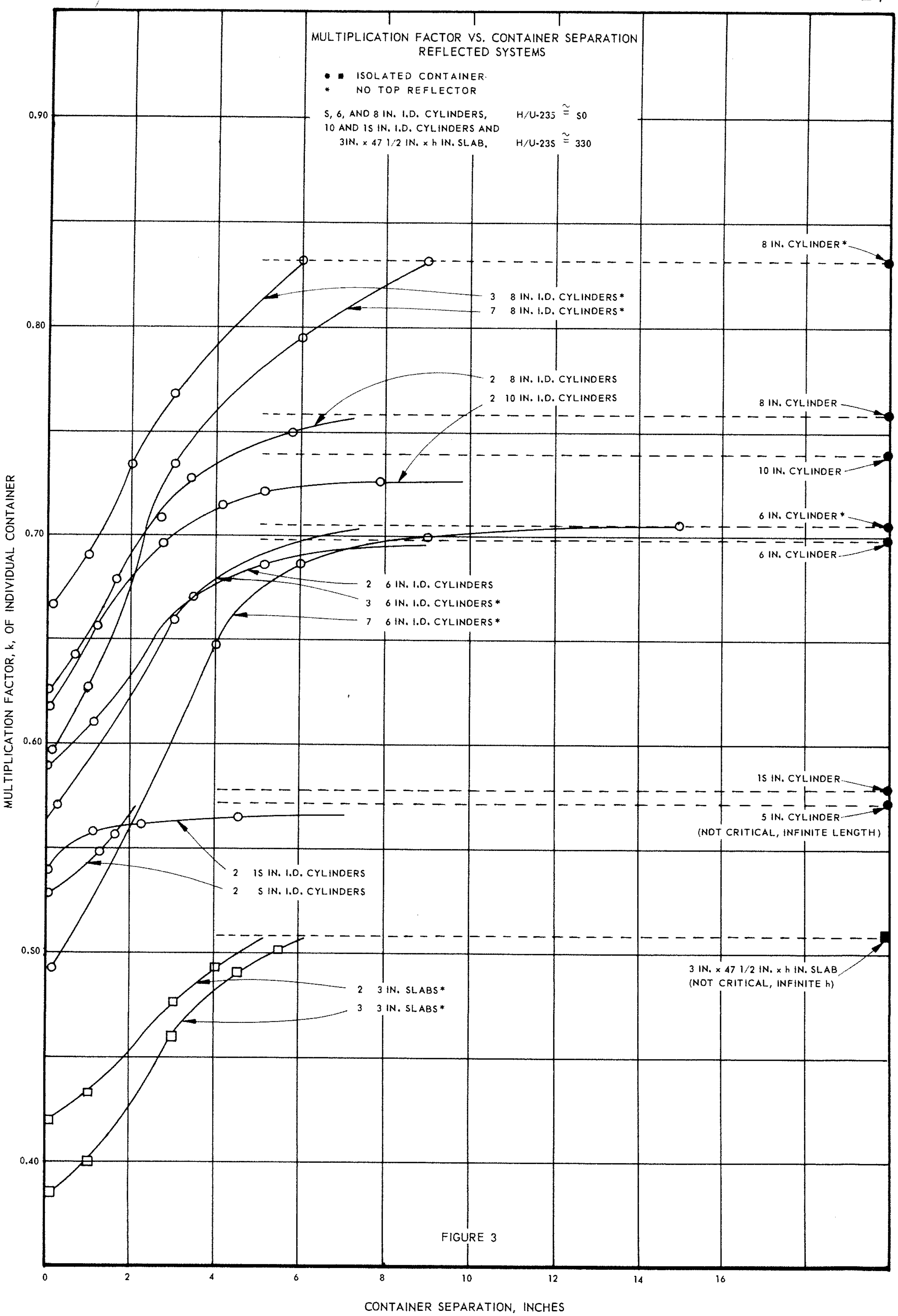
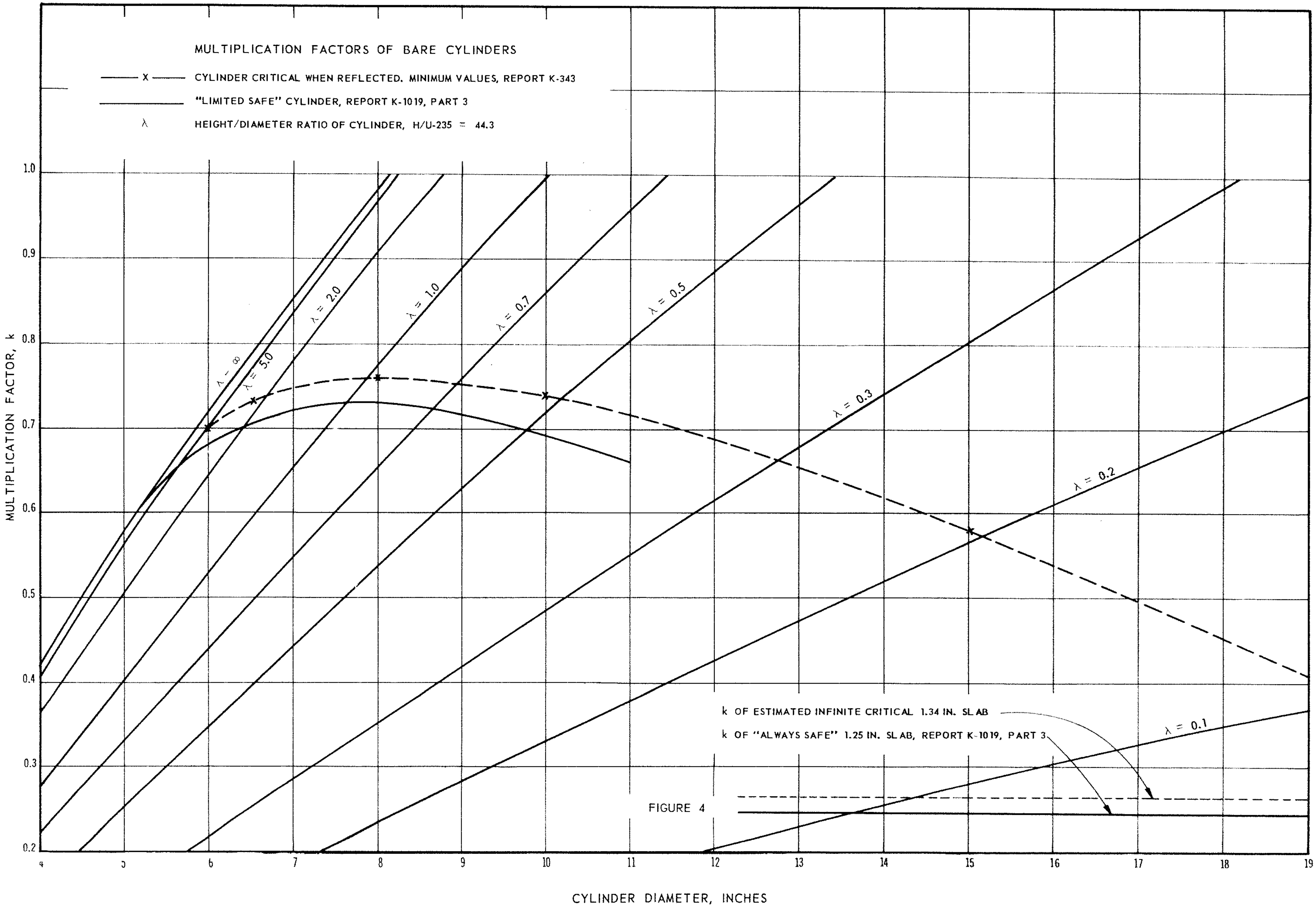

MULTIPLICATION FACTOR VS. CONTAINER SEPARATION
REFLECTED SYSTEMS
● ■ ISOLATED CONTAINER
* NO TOP REFLECTOR
5, 6, AND 8 IN. I.D. CYLINDERS, H/U-235 ≅ 50
10 AND 15 IN. I.D. CYLINDERS AND
3IN. x 47 1/2 IN. x h IN. SLAB, H/U-235 ≅ 330
0.90
0.80
0.70
0.60
0.50
0.40
8 IN. CYLINDER*
3 8 IN. I.D. CYLINDERS*
7 8 IN. I.D. CYLINDERS*
2 8 IN. I.D. CYLINDERS
2 10 IN. I.D. CYLINDERS
8 IN. CYLINDER
10 IN. CYLINDER
6 IN. CYLINDER*
6 IN. CYLINDER
2 6 IN. I.D. CYLINDERS
3 6 IN. I.D. CYLINDERS*
7 6 IN. I.D. CYLINDERS*
15 IN. CYLINDER
5 IN. CYLINDER
(NOT CRITICAL, INFINITE LENGTH)
2 15 IN. I.D. CYLINDERS
2 5 IN. I.D. CYLINDERS
3 IN. x 47 1/2 IN. x h IN. SLAB
(NOT CRITICAL, INFINITE h)
2 3 IN. SLABS*
3 3 IN. SLABS*
MULTIPLICATION FACTOR, k, OF INDIVIDUAL CONTAINER
0
2
4
6
8
10
12
14
16
CONTAINER SEPARATION, INCHES

FIGURE 3



MULTIPLICATION FACTORS OF BARE CYLINDERS
—— X —— CYLINDER CRITICAL WHEN REFLECTED. MINIMUM VALUES, REPORT K-343
"LIMITED SAFE" CYLINDER, REPORT K-1019, PART 3
λ HEIGHT/DIAMETER RATIO OF CYLINDER, H/U-235 = 44.3
λ = ∞
λ = 5.0
λ = 2.0
λ = 1.0
λ = 0.7
λ = 0.5
λ = 0.3
λ = 0.2
λ = 0.1
k OF ESTIMATED INFINITE CRITICAL 1.34 IN. SLAB
k OF "ALWAYS SAFE" 1.25 IN. SLAB, REPORT K-1019, PART 3
MULTIPLICATION FACTOR, k
CYLINDER DIAMETER, INCHES
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19

FIGURE 4

Evaluation of Other Factors

Since the safety criteria were developed from experimental interaction data with highly enriched and well-moderated uranium in slab and cylindrical geometry, some comments are made regarding the use of these criteria for other systems of interest which are less well-known experimentally.

1. Low U-235 Assay. The considerations detailed below indicate that use of the safe criteria for low assay systems should also result in conservative container separations.

   a. There are some theoretical[9] as well as experimental[10,11] indications that the reactivity changes, Δk, due to the reflector saving is somewhat greater for approximately 90% assay uranium than for 4.9% assay uranium; this applies to the minimum critical reflected cylinders with an identical shape factor which may be defined as the ratio of the cylinder height to cylinder diameter. From this, it may be inferred that the multiplication factor, k, determined from the bare dimensions of such units becomes larger as the U-235 assay decreases; thus, it appears that for a specific k value, a low assay unit will, in general, be less sensitive to external neutron sources than will a high-assay unit with an identical k. With respect to interaction, this means that the low-assay unit would probably require interaction from a larger solid angle to attain criticality than the high-assay unit.

   b. The theory of neutron interaction considered[5] assumes that the interaction probability is directly proportional to some function of the fractional solid angle, Ω, and the fast neutron leakage probability $(1 - U_f)$. Thus, since the fast neutron leakage probability tends to become smaller as the assay decreases, the interaction probability at the lower assays will also be lower than it is at the higher ones with the result that a smaller Δk, or reactivity change per unit solid angle, occurs for interacting units of low U-235 assay than for higher assays. Obviously, then, for a given k value, the solid angle must be greater at the low assays than at the higher ones for criticality to be attained; this is a conservative factor.

   c. From a very practical viewpoint, the use of criteria based upon half-reflection considerations introduces an additional conservative safety factor since the possibility of half-reflection of 2 interacting containers as reviewed herein appears to be much less for the larger containers considered safe for low assays than for the small containers which are safe for high assays. For example, it appears the intimate material contact between a container and its reflector, which is necessary for effective reflection and which can result either from inadvertent personnel handling or from poor storage positioning, is more readily attainable with 2 "always-safe" 5 in. cylinders than for two 10 in. cylinders which are safe for U-235 assays to 5%.

2. Low Moderation. The comments noted below are made with respect to the applicability of the safety criteria to poorly-moderated systems which may be arbitrarily defined as those with H/U-235 atomic ratios of 20 or less.

   a. Scanty experimental data with uranium blocks as shown in table III indicate that the reactivity change, Δk, due to the reflector savings is essentially the same for a poorly-moderated unit as it is for a well-moderated unit under otherwise similar conditions. This result may not be entirely unanticipated since, although the increased size of unmoderated reactors tends to decrease the neutron leakage and thus decrease the effectiveness of the reflector, the fact that a reflector, such as water, also has moderating properties makes it more effective for poorly-moderated units than for well-moderated ones.

   Thus, since the effect of interaction is somewhat similar to that of reflection, it may be roughly concluded from the above that the Δk due to interaction will not vary widely with change in moderation. It is, of course, recognized that no direct quantitative relation between the effect of reflection and that of interaction has been inferred.

   b. Although there are essentially no experimental interaction data for unmoderated systems, it appears improbable from theoretical considerations that the Δk, or reactivity increase per unit solid angle, will be greater in an inefficient unmoderated system than in an efficient well-moderated system.

   c. The multiplication factors as given in table III for unmoderated assemblies were computed using a multi-group method[12] since the approximations inherent in the 2-group theory used give poor results with unmoderated assemblies. However, it may be noted that, where used, both methods give conservative results in that a calculated k greater than unity is determined for an experimentally-determined critical assembly and that use of the 2-group theory apparently gives greater conservatism than the more accurate multi-group theory.

   d. Since the safe dimensions are somewhat larger for unmoderated than for well-moderated containers, the possibility of half-reflecting such unmoderated units is considered to be less for the reasons previously outlined above.

TABLE III

CALCULATED k FOR LOW MODERATION CRITICAL ASSEMBLIES

U-235 Assay	H/U-235	k (Bare)	k (Reflected)*	Δk (Due to Reflection)	Calculation Method
37.5%	0.1	1.0491	0.6898	0.3593	Multi-group
37.5%	5.1	1.1995	0.8272	0.3888	Multi-group
30.0%	32.0	1.0414	0.6904	0.3510	Multi-group
30.0%	32.0	1.1368	0.8972	0.2396	2-group

* k computed using dimensions of the unreflected assembly which was critical when reflected.

3. Safe Mass. Although uranium materials are, in general, stored in vessels of safe geometry, it is desirable, in some cases, to store material by limiting the contained U-235 mass rather than by restricting the geometry of the container itself. The multiplication factors for spherical vessels of varying size with a contained U-235 mass of the "always-safe" amount of 350 g. are plotted in figure 5. It may be noted that, since the U-235 mass is constant, the k value varies with the container volume and reaches a maximum of about 0.65 at 12.5 liters. As the container volume becomes larger than 12.5 liters, the k value decreases, this being primarily due to the increasing non-fission neutron capture in the dilute uranium solution; on the other hand, for smaller volumes, the k value decreases due to the increased neutron leakage probability from the container itself. It is obvious, of course, that, in a practical case, it may be possible for the uranium solution concentration to change during solution storage, for example by precipitation; in this case, the maximum k value of 0.65 should be used in determining the safe solid angle from figure 1.

   Also shown in figure 5 are the k values of a "double batch" quantity of 700 g. of U-235; this value is ordinarily used in assessing the individual safety of a container since such an occurrence is considered a single contingency. While the safety which is provided by an interaction specification based on a "safe" mass will be reduced if this mass is inadvertently exceeded, it does not appear that interaction criteria need be predicated upon a "double batch" as is the case

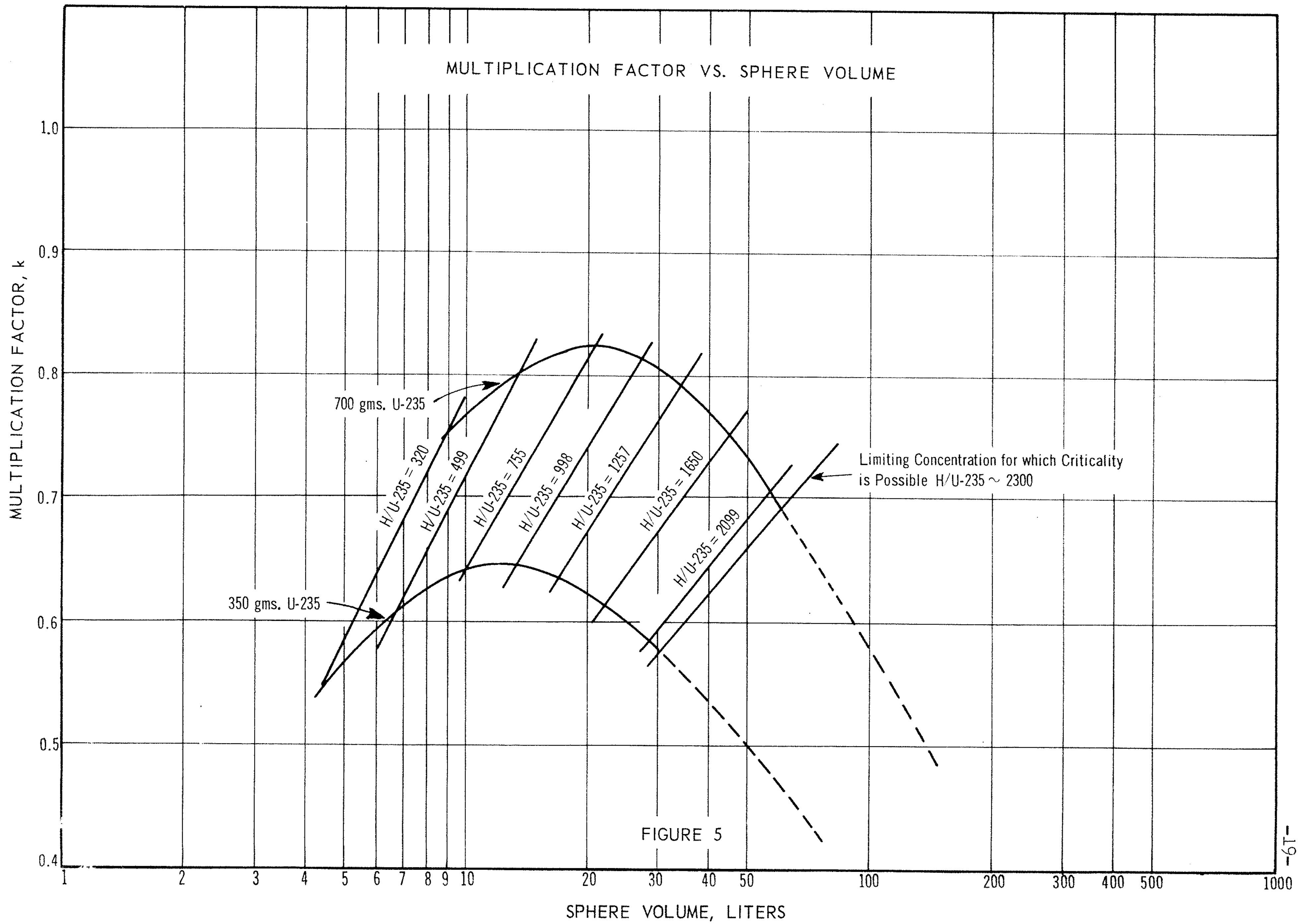

MULTIPLICATION FACTOR VS. SPHERE VOLUME
MULTIPLICATION FACTOR, k
1.0
0.9
0.8
0.7
0.6
0.5
0.4
700 gms. U-235
350 gms. U-235
H/U-235 = 320
H/U-235 = 499
H/U-235 = 755
H/U-235 = 998
H/U-235 = 1257
H/U-235 = 1650
H/U-235 = 2099
Limiting Concentration for which Criticality is Possible H/U-235 ~ 2300
1
2
3
4
5
6
7
8
9
10
20
30
40
50
100
200
300
400
500
1000
SPHERE VOLUME, LITERS

FIGURE 5

for individual units which are safe mass-wise. Since the interaction relation considered assumes identical containers, more than one "double batch" would be required; this is a double or second order contingency which is not considered as a factor in the ORGDP safety considerations.[1] In addition, the random safety factors normally inherent in the specification of safe batches, such as non-optimum moderation and geometry, also apply as well as those originally assumed in specifications of safe interaction limits.

4. Safe Concentration. A U-235 concentration of 5 g./liter has been considered safe since this is approximately one-half the limiting concentration at which criticality could occur. Although the infinite multiplication factor, k_{∞}, is 0.68 for this safe U-235 concentration, it appears that interaction from vessels with such dilute solutions need not be considered since the fast neutron leakage probability and thus the interaction probability both approach zero as the container size becomes larger and approaches infinity. Thus, in this case, the normal safety factors inherent in individually safe containers, plus the standard requirement of at least 1 ft. separation between all uranium containers are considered to be adequate for nuclear safety.

Conclusions

The set of self-consistent interaction criteria developed, using the geometric concept of a solid angle for the separation of individually safe containers of enriched uranium materials, appears to provide adequate nuclear safety for systems of such containers, even under the most reactive conditions considered possible at the ORGDP.

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