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BASIC CRITICAL MASS INFORMATION AND ITS APPLICATION TO OAK RIDGE GASEOUS DIFFUSION PLANT DESIGN AND OPERATION

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OAK RIDGE GASEOUS DIFFUSION PLANT

Operated by

UNION CARBIDE NUCLEAR COMPANY
DIVISION OF UNION CARBIDE CORPORATION

for the Atomic Energy Commission

Acting Under U. S. Government Contract W7405 eng 26

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BASIC CRITICAL MASS INFORMATION AND ITS APPLICATION TO OAK RIDGE GASEOUS DIFFUSION PLANT DESIGN AND OPERATION

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OAK RIDGE GASEOUS DIFFUSION PLANT
A. P. Huber, Plant Superintendent

Union Carbide Nuclear Company
Division of Union Carbide Corporation
Oak Ridge Gaseous Diffusion Plant
Oak Ridge, Tennessee

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Title: BASIC CRITICAL MASS INFORMATION AND ITS APPLICATION TO OAK RIDGE GASEOUS DIFFUSION PLANT DESIGN AND OPERATION

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ABSTRACT

The current minimum experimental values of the basic criticality control parameters for U-235 assays between 2% and approximately 90% are presented together with the basic criticality control methods currently in effect at ORGDP. The fundamental nuclear safety criteria remain essentially unchanged from previous editions of the report with the exception of the neutron interaction specifications, which have been extended considerably, and the approval, for the first time, of the limited use of water in cascade fire control activities. A chart of the organization for nuclear safety control at ORGDP and a glossary are also included.

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BASIC CRITICAL MASS INFORMATION AND ITS APPLICATION TO

OAK RIDGE GASEOUS DIFFUSION PLANT DESIGN AND OPERATION

TABLE OF CONTENTS

INDEX OF TABLES AND GRAPHS

THE USE OF K-1019

Although this report has been prepared specifically for gaseous diffusion plant operations, it is realized, of course, that there are probably many other types of operations for which the guide may be generally useful, and it is understood that the document has proven useful in many other installations. It therefore becomes important to re-emphasize for such users, as well as for ORGDP personnel, that the criteria presented herein are considered specifically applicable only for the U-235 materials normally encountered in the Oak Ridge Gaseous Diffusion Plant, and operating under the limitations given in the section on Basic Assumptions; the most important of these are probably density and the types of moderators and reflectors available. Thus, while the conclusions drawn are considered generally applicable for diffusion plant operations, it is perhaps obvious that they may not necessarily be appropriate for other production or laboratory facilities. In particular, data should be used very cautiously, if at all, for high density U-235 metals, and not at all for other fissionable materials such as U-233 or plutonium; information on these materials is now generally available and may be obtained elsewhere.

BASIC CRITICAL MASS INFORMATION AND ITS APPLICATION TO OAK RIDGE GASEOUS DIFFUSION PLANT DESIGN AND OPERATION

INTRODUCTION TO FOURTH REVISION

As has been the case in previous editions, the current revision of the subject report summarizes available experimental and theoretical data concerned with fissionable materials of interest at the ORGDP and indicates the application of these results to specific plant conditions. Major changes in these basic criteria have been based upon data obtained since the publication of the Third Revision and include a considerable extension of operational interaction specifications and a summary of the results of studies showing conditions under which water may be used in cascade fire-control activities. In addition, a chart showing the organization for nuclear safety at the ORGDP, as outlined by management, is presented for the first time. The authors also hope that the usefulness of this guide has been enhanced by the development of a brief glossary, among the definitions of which is a completely new word, "subcrit", used to identify the general group of normally subcritical units or systems for which nuclear safety considerations are important.

In addition to its own theoretical work on problems of general and specific plant interest, the ORGDP has continued to collaborate in planning the basic criticality research program to provide experimental data for the continuing evaluation of the nuclear safety of plant design and operations. As in previous editions, all criticality design and operational criteria have been approved by the ORGDP Criticality Hazards Committee and the ORGDP Criticality Hazards Consultants' Committee.

The assistance of Mr. W. A. Johnson, Mr. W. A. Pryor, and Dr. J. R. Knight of the ORGDP Nuclear Safety staff in the preparation of material for this fourth edition is gratefully acknowledged as is the courtesy of Dr. A. D. Callihan and his staff of the ORNL Criticality Laboratory in providing unpublished experimental data.

INTRODUCTION TO ORIGINAL EDITION*

In view of the importance of criticality considerations in the design and operation of the K-25 units, a summary of available criticality information and plant design and operation criteria has been prepared. Experimental data, which are given, have been used as the bases for determining the best estimated values for the basic critical mass information.

The basic design and operational criteria given have been approved by the K-25 Special Hazards Consultants' Committee and its forerunners of the early days of plant operation. The methods of meeting these design and operational requirements have been largely developed by the K-25 special hazards field groups working with the Approvals Committee and reporting to the K-25 Special Hazards Committee.

The authors would like to acknowledge the constructive reviews of this compilation by Dr. R. L. Macklin of the K-25 laboratories, Mr. J. W. Morfitt of the Y-12 criticality hazards organization, and Dr. A. D. Callihan, director of the criticality research at X-10.

* Issued on October 5, 1951, as KS-240, Basic Critical Mass Information and Its Application to K-25 Design and Operation. Subsequent revisions issued as K-1019 on 6-8-53, 12-6-54, and 12-30-55.

BASIC INFORMATION

EXPERIMENTAL DATA

The experimental data listed in tables I through IV were used in estimating the minimum mass and geometry parameters from which the various safe operating curves were derived. While several generalizations have been drawn from the more plentiful high assay data, it is recognized that it would be extremely fortuitous if the values compared represent the true values which would be possible with unlimited data. Hence, the generalizations which are listed for each table should be considered as guides only.

Lowest Critical Masses

TABLE I

LOWEST EXPERIMENTAL CRITICAL MASSES

Core Material	Assay (Wt. % U-235)	Geom.	Container	Moderation (H/U-235)	Reflector	Dimensions (cm.)	Dimensions (in.)	Solution Height (cm.)	Solution Height (in.)	U-235 Mass (Kg.)	Ref.
UO_2F_2	~ 90	Sphere	Aluminum	524	Water	32.0	12.6μ	-	-	0.84	1
UO_2F_2	~ 90	Cyl.	Aluminum	499	Air	38.1	15μ	27.4	10.8	1.63	2
UO_2F_2	~ 90	Cyl.	S. Steel	499	Water	30.5	12μ	26.3	10.4	1.00	2
UO_2F_2	~ 90	Cyl.	S. Steel α	499	Water	30.5	12μ	32.8	12.9	1.25	2
UO_2F_2	~ 90	Cyl.	S. Steel	499	Air	38.1	15μ	27.0	10.6	1.61	2
UF_6C	~ 90	Cube	None	None	Paraffin	25.4	10λ	-	-	48.8 σ	3
UF_6C	~ 90	Cube	None	None	Air	25.4	10λ	-	-	48.8 σ	3
UF_6C	37.5	Cube	Rubber Sheet	None	Water and Paraffin	53.3	21λ	-	-	183.8	4
UF_6C	37.5	Cube	Rubber Sheet	10.7 Y	Water and Paraffin	33.0	13λ	-	-	28.4	4
UF_6C	37.5	Pseudo Cyl.	None	None	Air	84.5	33.3μ	-	-	467	5
UF_6C	29.8	Cube	None	128	Paraffin	27.9	11λ	-	-	4.0 ν	6
UF_6C	18.8	Cube	Rubber Sheet	None	Water and Paraffin	91.4	36λ	-	-	452	7
UO_2SO_4	14.7	Sphere	S. Steel	650	Water	30.5	12μ	-	-	0.717β	8
UF_6C	12.5	Cube	Rubber Sheet	3.4	Water and Paraffin	91.4	36λ	-	-	300*	7
UO_2F_2	4.9	Cyl.	Aluminum	530	Water	38.1	15μ	44.7	17.6	2.2	9
UO_2F_2	4.9	Cyl.	S. Steel	645	Air	50.8	20μ	45.7	18.0	3.3	9
UF_6	2.0	Cyl.**	S. Steel	4	Water	76.2	30μ	-	-	123 σ	10

α 0.02 in. cadmium shield (~ 0.44 g./cm.^{2}).
μ Diameter.
λ Edge Length.
ν Value considered high due to inhomogeneities.
β Multiplication of approximately 3 observed.
σ Multiplication of approximately 2 observed.
Y Optimum moderation probably higher.
* Multiplication of approximately 100 observed.
** The UF_6 was in four 30" x 6' cylinders in contact.

Generalizations from table I

1. The smallest measured critical mass of U-235 is 0.84 kg.
2. Removal of the reflector increases the minimum critical mass by 83%.
3. The use of thin stainless steel containers instead of aluminum containers increases the minimum reflected critical mass by 12%, but decreases the minimum unreflected critical mass slightly.
4. A cadmium shield of 0.02 in. thickness (~ 0.44 g./cm.^{2}) increases the minimum reflected critical mass for thin stainless steel containers by 25%.
5. From experiments not quoted in table I:

    a. Stainless steel is as good a reflector as water for thicknesses up to 2.5 in.,[11] and there are indications that for greater thicknesses it is better than water.
    b. Reflection by a 6 in. thick concrete slab immersed in water is equivalent to that of water alone.[12]

Minimum Critical Geometries

The data which are presented in tables II, III, and IV give information for UO_2F_2 water solutions.

TABLE II

EXPERIMENTAL MINIMUM CRITICAL CYLINDER DIAMETERS

Assay (Wt. % U-235)	Container	Moderation* (H/U-235)	Reflector	Minimum Critical Diam. (cm.)	(in.)	Maximum Non-Critical Diam. (cm.)	(in.)	Ref.
~90	Aluminum	52.9	Water	15.2	6.0	14.0	5.5	2
~90	Aluminum	44.3	Air	22.3	8.76	20.3	8.0	13,2
~90	S. Steel	44.3	Water	15.2	6.0	-	-	13
~90	S. Steel[α]	62.7	Water	20.3	8.0	17.8	7.0	2
~90	S. Steel	74.6	Air	22.9	9.0	20.3	8.5[β]	13
4.9	Aluminum	530**	Water	38.1	15.0	-	-	9
4.9	S. Steel	530**	Water	38.1	15.0	30.5	12.0	9

* Moderation for shortest critical length measured; probably near optimum moderation except as noted.
** Optimum moderation probably much lower.
α 0.02 in. cadmium shield (~ 0.44 g./cm.^{2}).
β Solution height 90 in., H/U-235 ratio 44.3.

Generalizations from tables II, III, and IV

1. The minimum critical reflected cylinder diameter is probably greater than 5.5 in. but less than 6 in. In addition, the minimum critical values of the slab thickness and the volume for a reflected geometry are no greater than 2.0 in. and 6.3 liters, respectively.
2. Removal of reflector apparently increases the minimum critical cylinder diameter by about 50%, the minimum critical slab thickness by about 70%, and the minimum critical volume by about 135%.
3. The use of 1/16 in. thick stainless steel as a container increases slightly the minimum critical slab thickness and volume. From data not quoted in table II, it may be inferred that steel has a similar effect on the minimum critical cylinder diameter.
4. A cadmium shield of 0.02 in. thickness (~ 0.44 g./cm.^{2}) increases the minimum critical cylinder diameter by about 25%, the minimum critical slab thickness by about 25%, and the minimum critical volume by about 60%.

TABLE III

EXPERIMENTAL MINIMUM CRITICAL SLAB THICKNESS

Assay (Wt. % U-235)	Container	Moderation* (H/U-235)	Reflector	Slab Dimensions (cm.)	Slab Dimensions (in.)	Slab Thicknesses (cm.)	Slab Thicknesses (in.)	Ref.
~ 90	Lucite	44.7	Water	113x147	45x58λ	5.1	2.0**	14
~ 90	Aluminum	26.9	Water	76.2	30.0μ	5.7	2.3	1
~ 90	Aluminum	57.0	Water (½)	76x152	30x60λ	8.9	3.5	13
~ 90	Aluminum	44.3	Air	76.2	30.0μ	13.3	5.2	13
~ 90	S. Steel	72.4	Air	51x51	20x20λ	13.9	5.5	13
~ 90	S. Steel	62.6	Water	30.5	12.0μ	12.3	4.8	2
~ 90	S. Steel^α	56.7	Water	30.5	12.0μ	15.8	6.2	2
4.9	Aluminum	530***	Water	50.8	20.0μ	25.4	10.0	9
4.9	Aluminum	645***	Air	76.2	30.0μ	28.9	11.4	9

* Moderation for shortest critical height measured; probably near optimum moderation except as noted.

** This value is probably low since part of the reflector was lucite which appears to be slightly more effective than water as a neutron reflector.

*** Optimum moderation probably lower.

α 0.02 in. cadmium shield (~ 0.44 g./cm.^{2}).

λ Edge lengths of parallelepiped.

μ Diameter of cylinder.

TABLE IV

EXPERIMENTAL MINIMUM CRITICAL VOLUMES

Assay (Wt. % U-235)	Container	Moderation* (H/U-235)	Reflector	Diameter (cm.)	Diameter (in.)	Height (cm.)	Height (in.)	Min. Volume (Liters)	Ref.
~ 90	Aluminum	52.9	Water	20.3	8.0μ	19.5	7.7	6.32	2
~ 90	Aluminum	47.3	Water	23.0	9.07ρ	-	-	6.32***	13
~ 90	Aluminum	52.9	Air	25.4	10.0μ	34.0	13.4	17.22	2
~ 90	S. Steel	58.8	Water	20.3	8.0μ	20.8	8.2	6.74	2
~ 90	S. Steel[α]	31.6	Water	25.4	10.0μ	21.1	8.3	10.69	2
~ 90	S. Steel	62.7	Air	25.4	10.0μ	21.7	12.5	16.05	2
4.9	Aluminum	530**	Water	38.1	15.0μ	44.7	17.6	51.0	9
4.9	S. Steel	530**	Air	50.8	20.0μ	38.6	15.2	78.2	9

* Moderation for minimum critical volumes measured; probably near optimum moderation except as noted.
** Optimum moderation probably lower.
*** The critical volume lacked 80 cc. of filling the spherical reactor.
α 0.02 in. cadmium shield (~ 0.44 g./cm.^{2}).
μ Diameter of cylinder.
ρ Diameter of sphere.

Interaction Experiments

1. The following results are limiting values as determined from interaction experiments:

   a. With aluminum reactors of identical geometry and fuel at ~ 90% U-235 assay:[15,16]

      (1) The smallest measured critical mass for 2 interacting and reflected reactors was 680 g. of U-235 per reactor.

      (2) Two 5 in. diameter reactors with water reflector can be made critical when in contact and when separated by as much as 1.65 in. of water; under similar conditions, 7 such reactors can be made critical up to a separation of 4.0 in.

      (3) Seven 6 in. diameter reactors in hexagonal array still interact when separated by 12 in. of water; however, the mass per reactor was about 98% of the critical mass of a similar isolated reactor.

      (4) The interaction effect at a separation of 66 in. between 2 unreflected slab reactors, which were subcritical when isolated, was sufficient to attain criticality; however, the mass per reactor was about 60% of the corresponding critical mass for a similar isolated container.

b. With identical cubic reactors assembled from aluminum boxes which contained gylcerol tristearate-U_3O_8 mixtures at 5% U-235 assay:[17]

(1) Interaction effects were noted when the reactors were immersed in water and spaced 12 in. apart; however, the critical mass per reactor was 97% of the mass for a similar critical reactor completely reflected.
(2) When the reactors were separated by a distance of 12 in., the critical mass of the system was the same whether both reactors were individually completely reflected or the system was reflected but no reflector was between the reactors.
(3) When the individual reactors were completely reflected, the critical mass of the system was greater at separation distances between 2 in. and 12 in. than at similar distances with air as a separating medium, but was slightly smaller for separations below 2 in. and more than 12 in.
(4) With a void between the reactors but with the system otherwise completely reflected, the critical mass per reactor for a separation of 16 in. was 102% of the mass for a similar individual critical reactor completely reflected, and 92% of the mass for a similar individual critical reactor which was reflected on 5 sides only.

c. With 2 aluminum reactors of non-identical geometries but identical H/U-235 ratios at ~ 90% U-235 assay, the spacing required for criticality for an interacting 10 in. diameter cylinder and a 47.5 in. wide x 6 in. thick slab, each containing uranium solution at an H/U-235 ratio of 330, was less than the average of the spacings at criticality when each reactor interacts with an identical "twin".[18]

d. With 2 identical 10 in. aluminum reactors containing uranium solutions at ~ 90% U-235 assay but different H/U-235 ratios, the solution height of the system approached that value for the individual cylinder with the lowest critical height as the separation between these reactors was increased.[18]

e. Two 10 in. diameter aluminum reactors at ~ 90% U-235 assay having different H/U-235 ratios and different solution heights were subcritical at the same separation at which each was critical when interacting with its "twin".[19]

f. The interaction effect was observed between uranium blocks consisting of a non-hydrogenous mixture of UF_4 and CF_2 at 37.5% U-235 assay and a slab geometry of UO_2F_2 solution at ~ 90% U-235 assay. When each interacting component was half the thickness of a similar unit which was individually critical, it was noted that the systems of 2 "half-slabs" were subcritical at all separations for which each slab was critical with a "twin".[18]

2. The following conclusions were drawn from interaction experiments:

   a. With uranium at ~ 90% U-235 assay:[16,19]

      (1) For identical calculated multiplication factors, interaction is more effective between slab geometries than between non-slab geometries.
      (2) The interaction effect is no greater for a system which has its components half reflected than for an unreflected system; however, a half-reflected system in itself is more reactive than an unreflected system.
      (3) With a multiunit system, it is possible to have more reactivity unreflected than if the system is immersed in a moderating and reflecting medium.
      (4) The effect of interaction between reflected containers drops off rapidly for separations beyond a few inches, and the interaction appears to be quite small for separations greater than 8 in.; thus, containers which are separated by 12 in. of water are essentially isolated from each other.

   b. With uranium at 5% U-235 assay, a system of 2 reactors is at least as reactive if the system were completely water reflected but with no reflector between the reactors as it is if each unit were completely water reflected, provided the units are separated by at least 1 ft.[17]
   c. With non-identical reactors:[18]

      (1) The separation for criticality between 2 interacting dissimilar containers is less than the average of the corresponding separations at which each container would be critical when interacting with its "twin".
      (2) Interaction among non-symmetrical components of a system is less effective than that where the components are symmetrical.

Neutron Poisons and Special Geometries

A few criticality experiments were made with neutron poisons and special geometrical configurations to show their effect on the overall criticality conditions of ~ 90% U-235 assay UO_2F_2 solutions. The results, which are presented in tables V and VI, should be considered as tentative only since the true experimental minima for these special parameters have not been established conclusively.

TABLE V

EFFECT OF NEUTRON POISONS ON CRITICALITY OF UO_2F_2 SOLUTIONS

Container[v]	Moderation (H/U-235)	Poison	Dimensions (cm.)	Dimensions (in.)	Critical Ht. (cm.)	Critical Ht. (in.)	Maximum Non-Critical Ht. (cm.)	Maximum Non-Critical Ht. (in.)	Ref.
S. Steel Cylinder	73	Steel Rods	38.1	15.0	95.4 (136 steel rods)[+]	37.6	107.8 (139 steel rods)[++]	42.4	20
Aluminum Slab	79	Boral Partitions*	76x152	30x60	17.6 (10 partitions - 5.9 cm. compartments)	6.9	- (12 partitions - 4.9 cm. compartments)	-	21
Two Aluminum Slabs (separated 2.75")	330	2 Boral Liners*	7.6x121	3x47.5	38.1 (separation med. - H_2O)	15.0	117 (separation med. - Boral, H_2O, Boral)	46	7
Aluminum Cylinder	73	Cadmium Liner[α]	25.4	10.0 (6.0)[β]	64.1 (annulus-H_2O)	25.2	122.0 (annulus-H_2O and Cd.)	47.8	1
Aluminum Cylinder	73	Cadmium Liner[α]	25.4	10.0 (6.0)[β]	76.8 (annulus-air)	30.2	122.0 (annulus-air and Cd.)	47.8	1

v All containers completely water reflected except the 30x60 in. slab which was 1/2 water reflected and the two 3x47.5 slabs which had no top reflector.
α 0.02 in. cadmium sheet (~ 0.44 g./cm.^{2}).
β Diameter of annular container.
\+ 7/8 in. diameter rods occupied 49.2% of core volume.
++ 7/8 in. diameter rods occupied 50.5% of core volume.
* 3/8 in. Boral sheet (~ 0.3 g. B/cm.^{2}).

TABLE VI

EFFECT OF SPECIAL GEOMETRY ON CRITICALITY OF UO_2F_2 SOLUTIONS

Container	Moderation (H/U-235)	Reflector	Geometry	Critical Diam. (cm.)	Critical Diam. (in.)	Maximum Non-Critical Diam. (cm.)	Maximum Non-Critical Diam. (in.)	Ref.
Aluminum	~ 44	Water	90° cross	12.7	5.0*	10.2	4.0	7,22
Aluminum	~ 70	Air	90° cross	-	-	19.1	7.5	1
Aluminum	~ 70	Water	30° lateral	12.7	5.0**	-	-	7

* Critical height in vertical arm was 8.4 cm. above the top of the horizontal arm.
** Critical height in vertical arm was 12.7 cm. above the top of the inclined arm.

BEST VALUES INFERRED FROM EXPERIMENTS

In the following tables, the mass and volume parameters were obtained from experimental data that have been corrected to spherical geometry by elementary pile theory methods[23] which are approximately correct for unreflected assemblies and are considered conservative for reflected assemblies. The experimental values of the cylinder and slab were extended to the corresponding infinite parameters by conservative empirical and theoretic methods.

Minimum Critical Masses

TABLE VII

ESTIMATED MINIMUM CRITICAL MASSES

Assay (Wt. % U-235)	Approximate Moderation (H/U-235)	Reflector	Mass (Kg. U-235)	Ref.
~90	440	Water	0.79	24
~90	500	Air	1.4+	25
~90	None	Paraffin	100++	3
~90	None	Air	130++	3
37.5	None	Water and Paraffin	152	25
37.5	None	Air	414	25
29.8	220v	Paraffin	1.0*	26
18.8	None	Water and Paraffin	373	25
14.7	650v	Water	1.2**	26
12.5	3.4	Water and Paraffin	248β	25
4.9	450	Water	1.8	27
4.9	530	Air	2.9+	25

\+ The container used to obtain the datum was of stainless steel which acts as slight reflector for otherwise unreflected systems.
++ Conservative estimates from extrapolation of multiplication data. Cubical geometry has not been corrected to spherical geometry.
* The value given is predicted from datum which has been corrected for inhomogeneities as well as being corrected to spherical geometry.
** Extrapolation from multiplication data.
v The true moderation for the minimum U-235 mass may be an H/U-235 ratio of about 400. Other moderations, except those marked "None", are approximately optimum.
β Obtained from experimental subcritical mass; multiplication of approximately 100 observed.

Generalizations

The following observations can be made from table VII and data given in the foregoing sections:

1. The predicted minimum critical U-235 mass of a reflected system is less than 841 grams and may be about 790 grams.
2. For a homogeneous system, the minimum critical mass as a function of U-235 assay remains nearly constant for assays down to 15% U-235, increases slowly for assays down to 5%, then increases more rapidly with further decrease in assay and is assumed to become infinite for 0.72% assay.

Minimum Critical Geometries

TABLE VIII

ESTIMATED MINIMUM CRITICAL CYLINDER DIAMETERS

Assay (Wt. % U-235)	Container	Approximate Moderation (H/U-235)	Reflector	Diameter (cm.)	Diameter (in.)	Ref.
~ 90	Aluminum	50	Water	13.5	5.3	29
~ 90	S. Steel	55	Water	14.1	5.5	30
29.8	Aluminum	70	Water	16.8	6.6*	31
14.7	Aluminum	100	Water	19.8	7.8*	31
4.9	Aluminum	345**	Water	28.7	11.3	31
4.9	S. Steel	345**	Air	35.8	14.1*	26

* These values have less experimental justification than the others.
** Estimated from experiments with low density material.[28]

TABLE IX

ESTIMATED MINIMUM CRITICAL VOLUMES

Assay (Wt. % U-235)	Container	Approximate Moderation (H/U-235)	Reflector	Sphere Diam. (cm.)	Sphere Diam. (in.)	Min. Critical Volume (Liters)	Ref.
~ 90	Aluminum	50	Water	21.5	8.5	5.2	32
~ 90	S. Steel	50	Water	21.9	8.6	5.4	32
~ 90	S. Steel[α]	50	Water	26.2	10.3	9.3	32
~ 90	S. Steel	50	Air	29.7	11.7	13.7	32
29.8	Aluminum	70	Water	26.2	10.3	9.2*	31
14.7	Aluminum	100	Water	29.2	11.5	13.2*	31
4.9	Aluminum	345**	Water	41.4	16.3	37.0	31
4.9	S. Steel	345**	Air	48.3	19.0	58.8*	26

* These values have less experimental justification than the others.
** Estimated from experiments with low density material.[28]
α 0.02 in. cadmium shield (~ 0.44 g./cm.^{2}).

TABLE X

ESTIMATED MINIMUM CRITICAL SLAB THICKNESS

Assay (Wt. % U-235)	Container	Approximate Moderation (H/U-235)	Reflector	Thickness (cm.)	Thickness (in.)	Ref.
~ 90	Aluminum	50	Water	3.4	1.34	28
~ 90	S. Steel	55	Water	5.8	2.3	29
~ 90	Aluminum	44	Air	12.3	4.8	25
~ 90	S. Steel	50	Air	9.9	3.9*	2
4.9	Aluminum	345**	Water	15.2	6.0*	9

* These values have less experimental justification than the others.
** Estimated from experiments with low density material.[27]

Interaction Values

The interaction values listed in table XI are slightly conservative estimates of the critical solid angles for non-reflected systems which have been calculated using an interaction theory[16] for approximately 90% U-235 assay material.[2,15]

TABLE XI

ESTIMATED CRITICAL SOLID ANGLE FOR UNREFLECTED INFINITE CYLINDERS AND SLABS

Cyl. Diameter (in.)	Steradians (~ 90% U-235 Assay)	Slab Thickness (in.)	Steradians (~ 90% U-235 Assay)	Ref.
5	5.0	1.25	> 12.6	25
6	3.4	1.34	6.0	25
7	2.4	2.0	4.6	25
8	0.5	3.0	2.6	25
8.1*	0	4.6*	0	25

* Individually critical.

Other Interaction Conclusions Inferred From Experiments and Theory

1. One ft. of water produces a calculated neutron attenuation of greater than 99%.[32]
2. The homogeneous system is more reactive than its heterogeneous counterpart.[18,33]
3. Due to the ORGDP method of determining equipment separation, which is based on additive solid angles, a "larger" solid angle of interaction is apparently necessary for a multi-body system to attain criticality than for a 2-body system; thus, the separation for multi-body systems based on the additive solid angle value considered safe for a 2-body system is highly conservative.

4. Interaction is more effective for the high U-235 assay, well-moderated system than any other system.
5. The effect of interaction in a system of unreflected reactors is essentially independent of the hydrogen moderation of the individual units.

THEORETICAL MINIMUM CRITICAL PARAMETERS

Theoretical predictions[30] based on the Water Boiler Theory[34] are given in tables XII and XIII. Except as noted, values listed are for the water reflected, water moderated, UO_2F_2 system.

Minimum Critical Masses

TABLE XII

THEORETICAL MINIMUM CRITICAL MASSES

Assay (Wt. % U-235)	Approximate Moderation (H/U-235)	(H/U)	Mass (Kg. U-235)	Ref.
~ 90	None	None	191⁺	35
~ 90	400	370	1.00	30
29.8	440	130	1.19	30
14.7	410	60	1.37	30
4.9	410	20	2.06	30
2.0	400	8	7.02	30
0.9	100	1	Infinite	36

\+ Age theory prediction for unreflected, unmoderated UF_6C system.

Minimum Critical Geometries

TABLE XIII

THEORETICAL MINIMUM CRITICAL GEOMETRIES

Assay (Wt. % U-235)	Moderation (H/U-235)	(H/U)	Cyl. Diam. (cm.)	(in.)	Sphere Diam. (cm.)	(in.)	Slab Thickness (cm.)	(in.)	Ref.
~ 90	21.4	20.0	14.1	5.6	22.9	9.0	4.9	1.9	30
29.8	70.5	21.0	16.7	6.6	26.3	10.4	6.8	2.7	30
14.7	102	15.0	18.5	7.3	29.2	11.5	8.4	3.3	30
4.9	173	8.5	24.8	9.8	38.1	15.0	12.0	4.7	30
2.0	290	5.8	53.2	17.0	65.9	25.9	21.8	8.6	30

Minimum Critical Concentrations

Other theoretical predictions[30] based on the Water Boiler Theory indicate that approximately 90% and 4.9% U-235 assay uranium will not become critical where the H/U-235 ratios are greater than 2300 and 2040, respectively.

DESIGN CRITERIA

BASIC ASSUMPTIONS

1. A thermal system requires less U-235 mass to become critical than any other system.
2. A reflected system requires no more mass of U-235 for criticality than an unreflected system.
3. Hydrogen, as found in ordinary water, is considered the most significant of the moderators and reflectors available.
4. No fissionable material having a uranium density greater than 3.2 grams of uranium per $cm.^3$ will be normally encountered.
5. Interaction is considered to be a function of the solid angle only where air is the medium of separation between subcrits, and the effect of interaction is considered to be independent of the U-235 assay.
6. UF_6 in the gaseous phase in the quantities and configuration of existing cascade equipment cannot sustain a chain reaction.[37]
7. Natural uranium, at 0.72% U-235 assay, is considered to be non-reactive.
8. No uranium is more reactive than that of about 90% U-235 assay. (U-233 is not considered.)

DESIGN FUNDAMENTALS

1. In order to anticipate the maximum hazard of equipment designed to handle uranium solids or liquid solutions, the system will be conservatively considered at optimum moderation, completely reflected with water, and at a U-235 assay of about 90%.
2. Geometry limitation is the principal nuclear safety control.
3. Where it is impractical to use systems of safe geometry, equipment of unsafe geometry may be operated on the basis of a safe U-235 mass or concentration.
4. Positive methods are used for the control of the values possible for any nuclear parameter, or parameters, used in maintaining nuclear safety. This includes the following:

    a. Where nuclear safety is dependent upon assay control, positive separation of uranium materials of different assays is assured in order to prevent intermixing of uranium of higher assay than that specified for the equipment.
    b. Where the U-235 assay is unknown, the uranium will be considered to be about 90% assay.

5. In all cases, the spacing between individual subcrits of the same or different systems will meet the basic interaction criteria.
6. Nuclear poisons, such as cadmium or boron, when used internally in equipment, will be considered as additional safety features but will not be relied upon for the inherent safety of subcrits.
7. Materials which have neutron reflecting properties greater than those of water, or which are capable of producing neutrons through nuclear reactions, will not be placed near uranium-containing equipment.

DESIGN CONCEPTS

Safe Parameters

Unless otherwise noted, all references to dimensions in this and succeeding sections refer to the maximum actual dimension of the uranium itself; for example, all pipe diameters are internal diameters. The definitions of "always-safe" and "limited-safe" as applied to those parameters of mass, geometry, and concentration are defined in the Glossary (Appendix C).

"Always-Safe" Parameters

The values of these "always-safe" parameters are given in table XIV together with their safety factors which are the ratios of the estimated minimum critical values to the corresponding "always-safe" value of the parameter concerned.

TABLE XIV

"ALWAYS-SAFE" PARAMETERS

Parameter	Unit	Quantity	Approximate Safety Factor
Infinite Cylinder Diameter	Inches	≤ 5.0	1.05
Infinite Slab Thickness	Inches	≤ 1.25*	1.1
Volume	Cubic Inches	≤ 268	1.2
Concentration (Water Solutions)	Grams U-235/ Liter	≤ 5.0	1.9
Mass	Grams U-235	≤ 350	2.3

* In those cases where stainless steel construction is used or the slab will normally be only half reflected, this thickness may be increased to 1.5 inches.[38]

"Limited-Safe" Parameters

Dependence on Assay Control

The "limited-safe" values of the cylinder diameter, volume, and the U-235 mass are shown as a function of the U-235 assay in tables XV, XVI, and XVII, respectively.[38] A similar table is not available for the slab thickness; however, an infinite slab thickness of 5.5 in. is considered safe for uranium of 5.0% U-235 assay or less.[39]

TABLE XV

DEPENDENCE OF "LIMITED-SAFE" CYLINDER DIAMETERS ON ASSAY

(See also Appendix, Fig. 1)

Assay (Wt. % U-235)	Cyl. Diam. (in.)	Assay (Wt. % U-235)	Cyl. Diam. (in.)
~ 90	5.0*	10	8.2
75	5.2	8	8.7
50	5.7	6	9.6
40	6.0	5	10.25
30	6.3	2	10.25
20	6.9	.8	10.25
15	7.4	.7	Infinite
12	7.8		

* "Always-safe" cylinder diameter.

TABLE XVI

DEPENDENCE OF "LIMITED-SAFE" VOLUMES ON ASSAY

(See also Appendix, Fig. 2)

Assay	Volume		Assay	Volume	
(Wt. % U-235)	(Liters)	(cu. in.)	(Wt. % U-235)	(Liters)	(cu. in.)
~ 90	4.4	268*	10	14.0	854
75	5.0	305	8	16.0	976
50	6.0	366	6	20.5	1251
40	6.7	409	5	27.0	1648
30	7.7	470	2	27.0	1648
20	9.5	580	.8	27.0	1648
15	11.0	671	.7	Infinite	
12	12.5	763			

* "Always-safe" volume.

TABLE XVII

DEPENDENCE OF "LIMITED-SAFE" U-235 MASSES ON ASSAY

(See also Appendix, Fig. 3)

U-235 Assay	Mass U-235		Mass Uranium		U-235 Assay	Mass U-235		Mass Uranium	
(%)	(kg.)	(lb.)	(kg.)	(lb.)	(%)	(kg.)	(lb.)	(kg.)	(lb.)
~ 90	0.350*	0.772	-	-	3.0	1.20	2.65	40.0	88.2
75.0	0.360	0.794	0.480	1.06	2.0	2.00	4.41	100	220
50.0	0.390	0.860	0.780	1.72	1.7	2.70	5.95	159	350
40.0	0.410	0.904	1.03	2.27	1.5	3.60	7.94	240	529
30.0	0.440	0.970	1.47	3.24	1.3	5.60	12.35	431	950
20.0	0.480	1.06	2.40	5.29	1.1	15.0	33.1	1360	3000
15.0	0.520	1.15	3.47	7.65	1.0	22.7	50.0	2270	5000
10.0	0.600	1.32	6.00	13.2	0.8	36.0	79.4	4500	9920
8.0	0.650	1.43	8.13	17.9	0.7	Infinite			
5.0	0.800	1.76	16.0	35.3					

* "Always-safe" mass.

Dependence on Controls Other Than Assay

Cylinder Heights and Diameters

1. Thin-walled stainless steel cylinders whose dimensions do not exceed the values given in table XVIII are considered safe for uranium of any assay or moderation. These values are also considered as being safe for cylinders of aluminum, or other material with similar neutron properties if the cylinder diameters concerned are less than 12 inches.[40]
2. A right prism is safe for uranium of any moderation if the smallest cross sectional area does not exceed that of a cylinder which is safe under the same conditions as given in either table XVIII or XV.

TABLE XVIII

"LIMITED-SAFE" CYLINDER HEIGHTS AND DIAMETERS - ANY ASSAY

(See also Appendix, Fig. 4)

Cylinder Diameter (in.)	Height (in.)	Cylinder Diameter (in.)	Height (in.)
5.5	33.7	10	4.7
6	17.6	11	4.1
7	9.5	12*	3.8
8	6.8	15*	3.0
9	5.5	36*	2.0

* Does not include aluminum cylinders.

U-235 Mass and Concentration

1. A maximum of 5000 lb. of UF_6 at 2% U-235 assay may be placed in a 30 in. diameter and 6 ft. long cylinder provided the amount of intermixed hydrogen is maintained below the H/U-235 moderating ratio of 3.7. Four of these chlorine-type cylinders may be stored safely in any configuration, while any number of such cylinders may be stored in a single row side-by-side with their axes lying in the same plane.[41]
2. Gaseous UF_6 at 2% U-235 assay contained in 2000 cu. ft. surge tanks of 8 ft. diameter may be condensed safely provided each tank contains not more than 20,000 lb. of UF_6 and provided a hydrogen moderating H/U-235 ratio of 3.7 is not exceeded.[42]
3. A maximum of 20,000 lb. of UF_6 at 1.3% U-235 assay may be placed in a 48 in. diameter x 9 ft. long cylinder provided the intermixed hydrogen is maintained below the H/U-235 moderating ratio of 2.0. Similarly, a maximum of 20,000 lb. of UF_6 at 2.0% U-235 assay may be placed in a 48 in. diameter x 9 ft. long cylinder provided the H/U-235 moderating ratio does not exceed 3.7 and provided the cylinder is maintained with its axis of rotation in a horizontal position at all times.[43]
4. Thirty-two thousand pounds of UF_6 at 2% U-235 assay may be placed in a 36 in. diameter cylinder provided the intermixed hydrogen is maintained below the H/U-235 moderating ratio of 3.7.[44]
5. UF_6 of any assay and in quantities in excess of the "limited-safe" amounts may be contained in geometrically unsafe equipment provided the amount of intermixed hydrogen is maintained below the H/U-235 moderating ratios specified in table XIX.[45] Each container holding these quantities is then considered safe, and specified safe spacing must be maintained.

TABLE XIX

"LIMITED-SAFE" MASSES FOR SPECIFIED MODERATION - ANY ASSAY

(See also Appendix, Fig. 5)

Moderation (H/U-235)	Safe Mass (Kg. U-235)	Moderation (H/U-235)	Safe Mass (Kg. U-235)
0.01	43.0	10.0	5.0
0.1	39.8	15.0	3.3
0.5	33.6	20.0	2.5
1.0	28.5	30.0	1.67
1.5	24.2	40.0	1.34
2.0	20.0	50.0	0.95
3.0	14.3	75.0	0.84
4.0	11.5	100.0	0.73
5.0	9.4	200.0	0.41
8.0	6.5	No Limit	0.35*

* "Always-safe" Mass.

Safe Interaction

The following criteria are used in the spacing of subcrits:

1. Interaction is considered between all equipment items which contain uranium in the solid or liquid phase except:

    a. Those where the subcrits are shielded by other subcrits whose interaction has been previously calculated.
    b. Those where the subcrits are separated by 1 ft. of material with hydrogen density as great as that of water.
    c. Among components of a system which contains a safe quantity of uranium.
    d. Those which contain homogeneous solutions with a U-235 concentration no greater than 5 grams per liter.
    e. Those where the interaction solid angle from any component is less than 0.04% of 4π (0.005 steradian).
    f. From slabs of 1/2" height or less, such as drip pans, which are perpendicular to the longitudinal center line of the cylinder or slab under consideration, or from single lines of 1/2" diameter or less, such as sight gauges.

2. Two subcrits which are dissimilar or which contain dissimilar quantities of fissionable materials will be safe if they are separated by a distance which is not less than the average of the corresponding distances by which each would be safe if separated from a subcrit which is identical to itself. This principle is also applicable to truck shipments of uranium and to other fissionable materials not normally handled at ORGDP.[33]
3. Two or more subcrits may subtend a maximum solid angle, at the most central or reactive unit, based on the calculated multiplication factor, k, for an unreflected system by the following relations:[46]

    a. For $k < 0.30$, $\Omega = 48\%$ of 4π (6.0 steradians).
    b. For $0.30 < k < 0.80$, Ω will be a straight line interpolation between 48% of 4π (6.0 steradians) and 8% of 4π (1.0 steradian). (See Appendix, Figure 6.)
    c. For cases where $k > 0.80$, direct experimental data or values reduced directly from such data will be used.

4. In all cases, subcrits must be maintained at least 1 ft. apart, edge-to-edge.
5. Where interaction consideration involves more than 2 subcrits, the interaction solid angle subtended at one component due to the other units is conservatively considered to be the simple sum of the contributory solid angles from these other components.

6. The maximum solid angle for 2 interacting subcrits may be increased to values greater than the allowable values indicated in Section 3 above provided the neutron shielding used is sufficient to absorb that fraction of available neutrons by which the actual solid angle exceeds the allowable solid angle.[47]
7. For systems such as low U-235 assay shipments of UF_6 and other conditions where the multiplication factor, k, cannot readily be calculated, but from experiment the system is known to be as safe as the subcrits meeting the "always-safe" parameters, the k value is assumed to be equal to 0.8.
8. The concrete or other structural materials used in ORGDP buildings are not normally considered as a neutron shielding medium.
9. Where the safe quantity of uranium is based upon a limited H/U-235 moderation, the total quantity is usually contained only in a single vessel; however, if it is contained in several smaller vessels, they will be individually separated by at least 1 ft.

Safe Systems

Two or more subcrits are considered to form a safe system provided:

1. Each subcrit meets the specified safe requirements for control of the U-235 mass, concentration, assay, or geometry.
2. Each subcrit is spaced to satisfy the requirements for safe interaction.

APPLIED DESIGN METHODS

Interaction

Equipment Connections and Turns

1. For 90° equilateral 'L', 'T', and '+' connections, a 5 in. diameter pipe is reduced by factors of 1.1, 1.2, and 1.3, respectively; thus, the maximum pipe diameters for these connections are 4.6 in., 4.2 in., and 3.8 in.[48] These same reduction ratios apply to similar connections for pipe diameters which are "limited-safe" at lower U-235 assays.[49]
2. A 5 in. pipe, or a pipe which is "limited-safe" at a lower assay, may not connect directly into a pipe of equal diameter; however, 'L', 'T', and '+' connections may be effected by reducing each pipe in the connection by the respective ratio given in No. 1 above, for a distance of 3 times the safe diameter from the intersections of the pipe walls.
3. A 5 in. pipe may not 'T' into a 1.25" slab; however, a 'T' connection may be effected if the slab is reduced to a 1 in. thickness for a radius of 7.5 in. from the center of the connection.
4. A 5 in. pipe may be curved in a circle of 2 ft. radius provided neutron absorbing materials equal in efficiency to water are placed inside the curve. In a similar manner, a 4 in. pipe may be curved in a circle of 1 ft. radius.

5. A 4 in. pipe may 'T' into an "always-safe" 1.25 in. slab or a 1.5 in. half-reflected slab.
6. Any number of 1 in. pipes may 'T' into a 5 in. pipe provided the points are 15 in. apart.
7. In determining the interaction effects of '+s', 'Ts', 'Ls', or curves, the solid angle is calculated from a position 15 in. from the point of intersection of the '+', 'T', or 'L' or 15 in. from the end of a curve.

Special Geometrical Shapes

1. Subcrits of "always-safe" geometry, such as slabs of 1.25 in. depth or pipes with diameters of less than 5 in., are assumed to be infinite in extent except for the controlled dimensions; hence, interaction is not considered between subcrits or sections of subcrits which lie in the same plane and which have a safe slab height, or between pipes of safe geometry with the same longitudinal axis.
2. If a group of adjacent parallel pipes can be contained in a 5 in. pipe, the pipe grouping is considered to be geometrically safe and is treated as a 5 in. pipe for interaction calculation.
3. Several small pipes having a total cross sectional area less than that of a 4 in. pipe may 'T' into an "always-safe" slab.

Safe Mass

Where mass is the parameter of nuclear safety control, the interaction effect is computed on the basis that the multiplication factor, k, is 0.65 and that the mass is contained in a spherical volume where the H/U-235 ratio is approximately 800. For the "always-safe" mass of 350 g. of U-235, this sphere is 11.4 in. in diameter.[19]

"Always-Safe" Parameters

The maximum multiplication factor and the allowable interaction solid angle value for each of the "always-safe" parameters are presented in table XX.

TABLE XX

ALLOWABLE INTERACTION VALUES

"Always-Safe" Parameter	Maximum Multiplication Factor, k	Solid Angle Fractional	Solid Angle Steradians	Ref.
5 in. Cylinder	0.58	0.256	3.2	19
8 in. Sphere	0.67	0.184	2.3	25
1.25 in. Slab	0.24	0.480	6.0	19
350 g. U-235 (11.4 in. Sphere)	0.65	0.200	2.5	19

Maintenance of Safe Geometry

Liquid Level Control

Wherever items of equipment, such as spray tanks or piping enclosures, are of basically unsafe geometry and may contain more than a safe quantity of uranium, provisions are incorporated in the design to insure that a safe geometric configuration will not be exceeded.

1. Pipes or overflow slots are provided in large tanks at a safe height to provide visible overflow indications of difficulties to the operator and to prevent safe dimensions from being exceeded.
2. Uranium solution feed pumps are equipped with relays which automatically shut off the pumps when the safe slab height is exceeded.
3. Steel plates are placed above drain connections to maintain a 1 in. solution depth for the specified area above the connection.

Piping and Equipment Enclosures

Where steam is used for heating process piping and equipment enclosures, provisions are made to minimize the possibility of steam inleakage to the process.

1. Steam lines are welded construction.
2. The enclosures may be sealed and provided with dry ambient air under pressure and routine humidity checks are made of the enclosure air.
3. Where the enclosures are not of air-tight construction,

   a. routine humidity checks are made of the air in the enclosure,

   or

   b. drain holes are provided at low points of the housing for the removal of condensate accumulation resulting from possible steam leakage.

4. Steam traps, valves, condensate lines, and accessory equipment are placed outside of the piping and equipment enclosures.

Piping and Equipment Insulation

Where piping or equipment must be insulated but leakage of uranium is considered possible, the effect of such leakage entering the insulation is considered in establishing safe conditions which are maintained by several methods.

1. Insulation directly applied to the piping or equipment is considered to be a part of the overall geometry of the container.

    a. Where geometry is the control factor, the maximum dimensions of the container and insulation will not exceed the values given in tables XV, XVI, and XVIII.
    b. For containers which are safe because of mass limitations, appropriate reductions in the U-235 mass limits are made based on the amount of the insulation concerned and its absorption properties.

2. Where insulation is not applied directly to the piping, a safe condition is maintained by enclosing or shielding the insulation and by providing openings between the piping and the insulation shield for solution drainage in the event of leaks.
3. Where a uranium container is concentrically placed in a second geometrically safe container, leakage of uranium solution is considered possible from the inner cylinder but highly improbable from two such containers. The shielding of insulation applied to the outer container or the installation of drains is not considered necessary for this arrangement.

OPERATION CRITERIA

BASIC OPERATION PHILOSOPHY AT ORGDP

1. The possibility of sabotage is not considered a factor in establishing criteria for safe operation.
2. An operation will be considered safe if it requires at least 2 independent contingencies to occur simultaneously in order for uranium materials to be accumulated in a configuration of unsafe geometry.
3. If the assay and amount of any uranium material are unknown, the material will be considered to be ~ 90% U-235 and will be placed in geometrically safe containers until analyses are obtained to show the safe disposition of the material.
4. Only specifically designated groups are authorized to make up safe amounts of uranium and to process these safe amounts through recovery operations.
5. No uranium-containing equipment other than that specifically approved for an operation may be brought into an operating area.
6. No more than 1 subcrit may be in motion at any one time in an operating area, and it must reach the approved destination via an approved route before another subcrit may be moved in that area.
7. Routine surveys for the detection of uranium will be made of all unsafe equipment where material accumulations are not normally expected but where they might occur as a result of equipment failure, misoperation, or other abnormal conditions. This applies particularly to cascade operations.
8. Radiation detection instruments with automatic alarms are installed at intervals throughout the process and decontamination and recovery areas for the detection of suspected critical mass occurrences.

9. In the absence of wet air inleakage, all condensations are considered to be essentially unmoderated, a maximum hydrogen to uranium ratio of 0.1 being used in determining equipment safety.
10. The presence of enriched uranium in any location is not alone sufficient justification to prohibit the planned use of water in fire control activities, but such usage should be carefully controlled.[51]

APPLIED OPERATION TECHNIQUES

General

1. Where it is impractical to obtain isotopic analyses, chemical analyses are obtained and uranium material is handled in unsafe equipment on a total uranium mass basis of 350 grams.
2. Properly spaced safe containers are used for temporary storage and handling of reactive uranium materials.
3. Physical spacers in the form of guide rails, posts, and chains, as well as painted guide lines are used to aid employees in storing and moving subcrits so that a safe geometry is maintained at all times. Specially built dollies and trucks are also used to maintain correct spacing of subcrits during transit.
4. Monitoring of cascade equipment with portable radiation detection instruments is done on both a routine and special check basis for the detection of accumulations of uranium material which may be caused by small air leaks or other operational difficulties.
5. Where "dead-end" systems result from operational changes, they are removed from operation by cutting and blanking the lines, or are isolated by border valves.
6. When equipment is removed from the cascade, the openings are immediately covered to reduce the absorption of atmospheric moisture by any uranium compounds contained therein.
7. In liquid UF_6 withdrawal operations, a safe H/U-235 ratio based on solubility of HF in UF_6[52] is maintained by controlling condenser temperatures and pressures within specified limits.

Other Operations

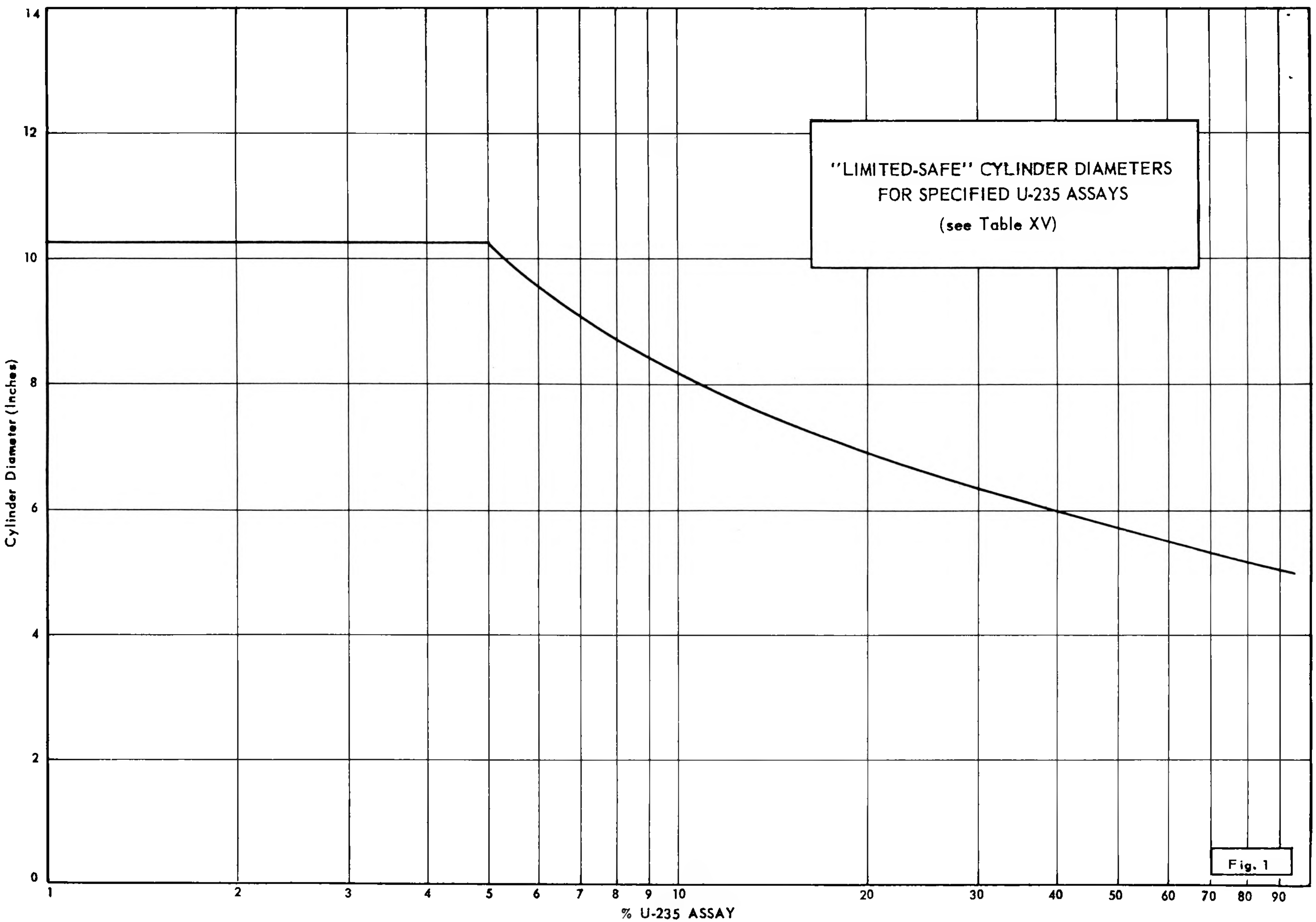
1. For decontamination purposes, the U-235 assay of material removed from cascade equipment is considered to be the maximum assay at which the equipment was operated as indicated by uranium accountability records.
2. In general, uniformity of sampling is controlled through the use of 2 separate samples taken at different times during the blending operation and individually analyzed. The results of the analyses should agree within 5%.
3. Unsafe equipment, which is decontaminated in spray booths or wash tables, is positioned so that solution is not held up in the equipment.

4. The identity of a safe amount of uranium contained in each of 2 unsafe equipment items may be maintained by:

    a. Breaking connections between the equipment items.
    b. By opening a drain or "tattle-tale" valve between the block valves in the interconnecting line.

APPENDIX A

GRAPHS


"LIMITED-SAFE" CYLINDER DIAMETERS
FOR SPECIFIED U-235 ASSAYS
(see Table XV)
Cylinder Diameter (Inches)
0
2
4
6
8
10
12
14
% U-235 ASSAY
1
2
3
4
5
6
7
8
9
10
20
30
40
50
60
70
80
90
Fig. 1

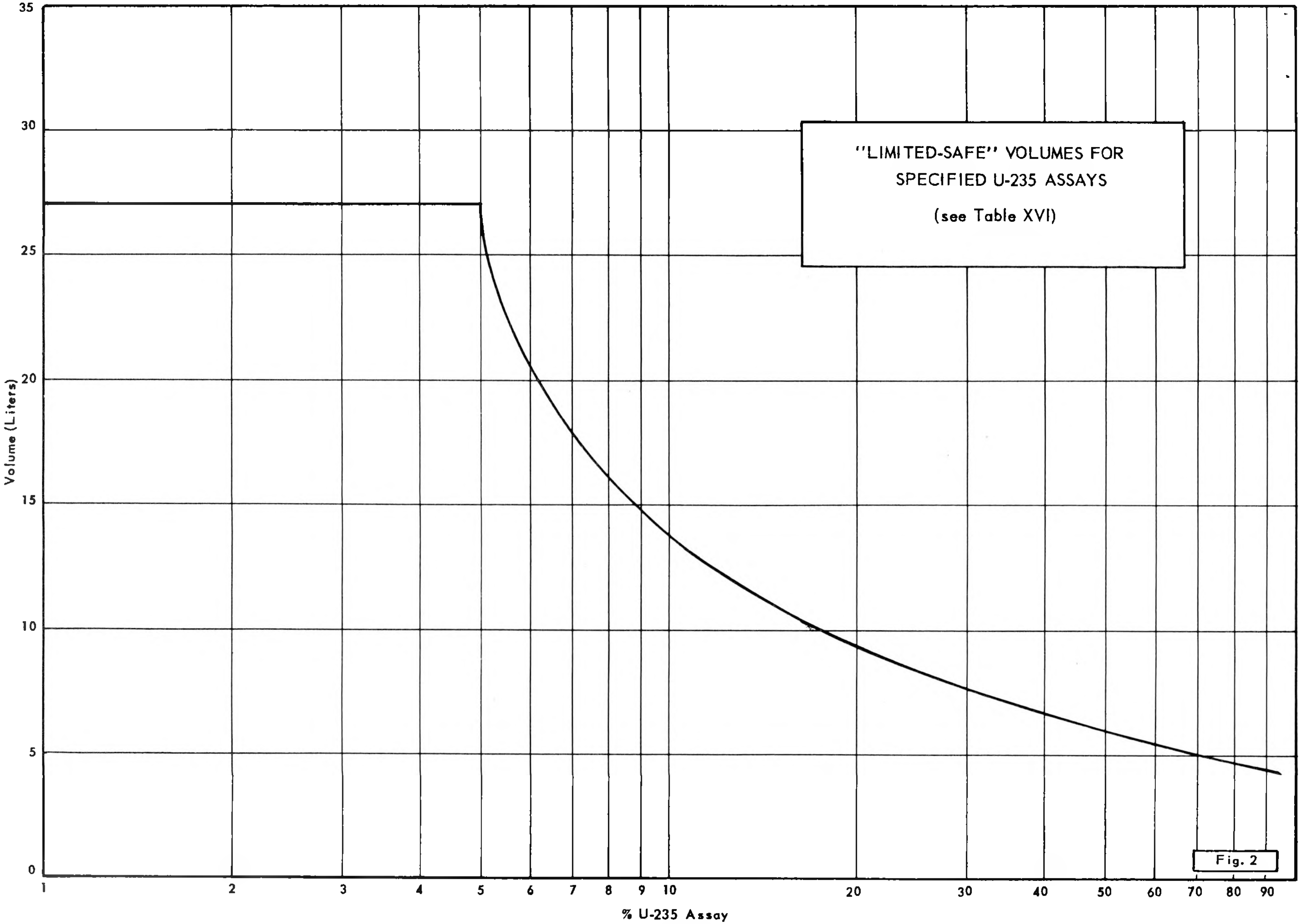

"LIMITED-SAFE" VOLUMES FOR
SPECIFIED U-235 ASSAYS
(see Table XVI)
Volume (Liters)
0
5
10
15
20
25
30
35
1
2
3
4
5
6
7
8
9
10
20
30
40
50
60
70
80
90
% U-235 Assay

Fig. 2

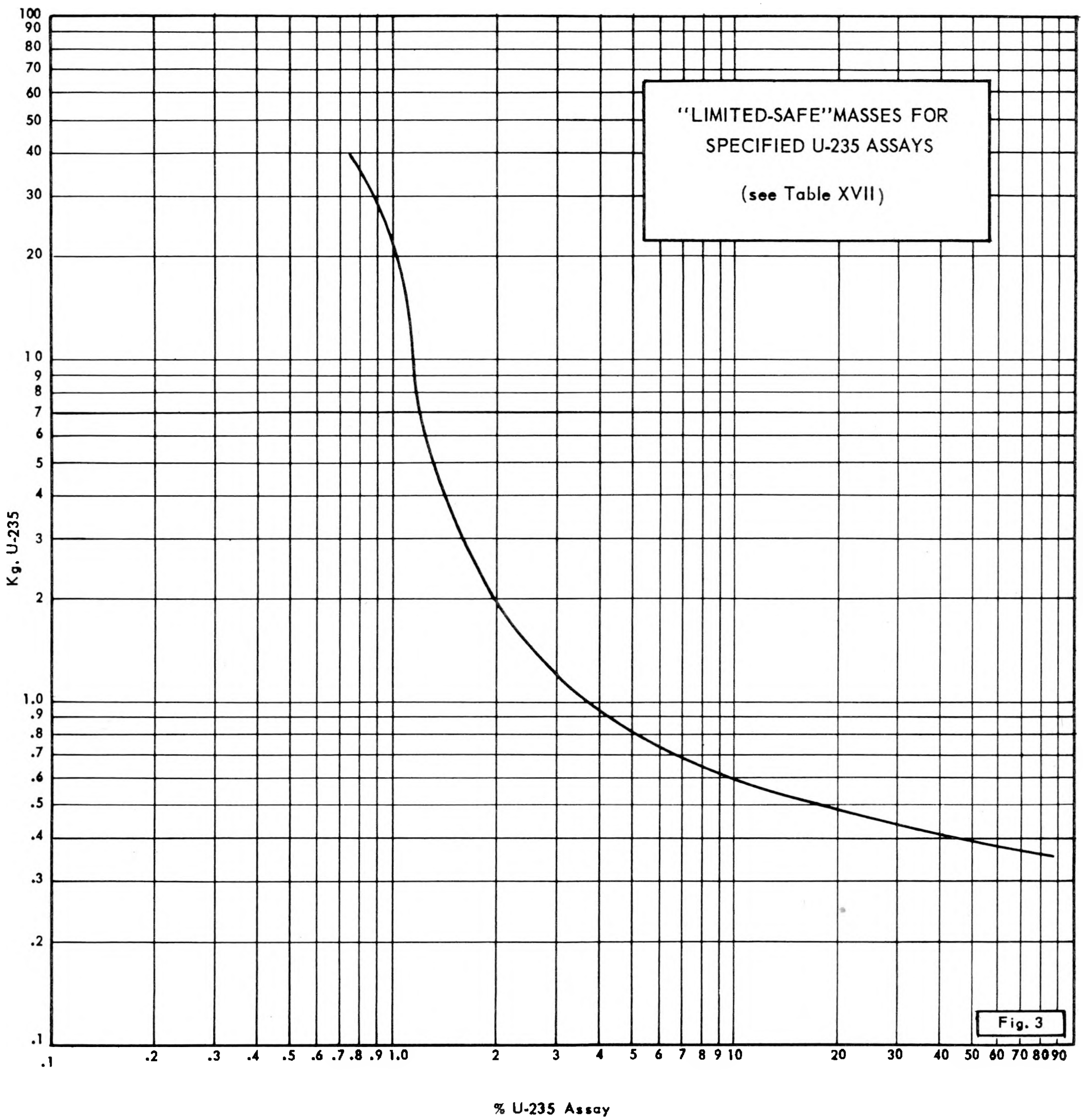

"LIMITED-SAFE" MASSES FOR
SPECIFIED U-235 ASSAYS
(see Table XVII)
Kg. U-235
% U-235 Assay
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
2
3
4
5
6
7
8
9
10
20
30
40
50
60
70
80
90
100

Fig. 3

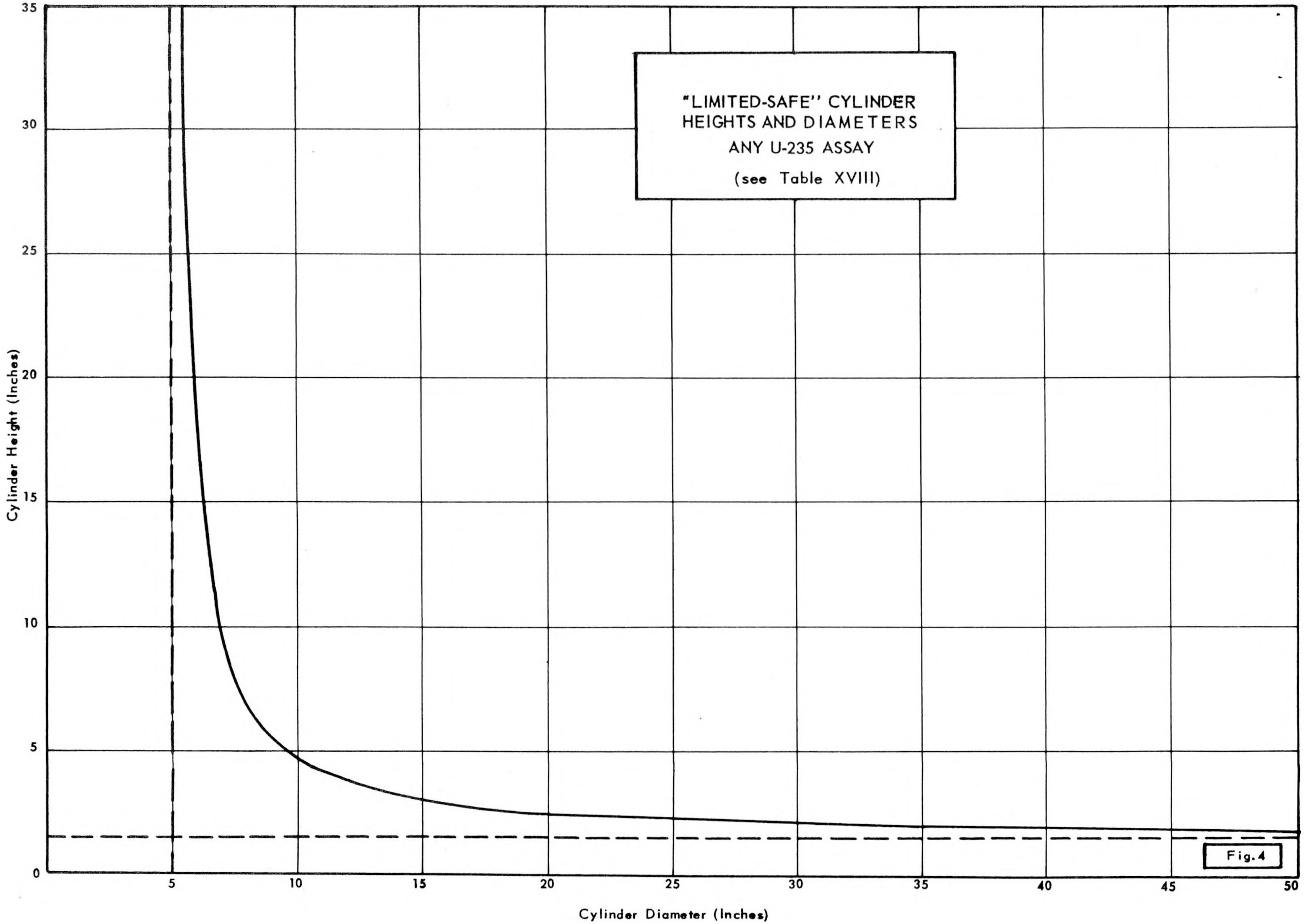

"LIMITED-SAFE" CYLINDER
HEIGHTS AND DIAMETERS
ANY U-235 ASSAY
(see Table XVIII)
Cylinder Height (Inches)
Cylinder Diameter (Inches)
0
5
10
15
20
25
30
35
40
45
50

Fig. 4

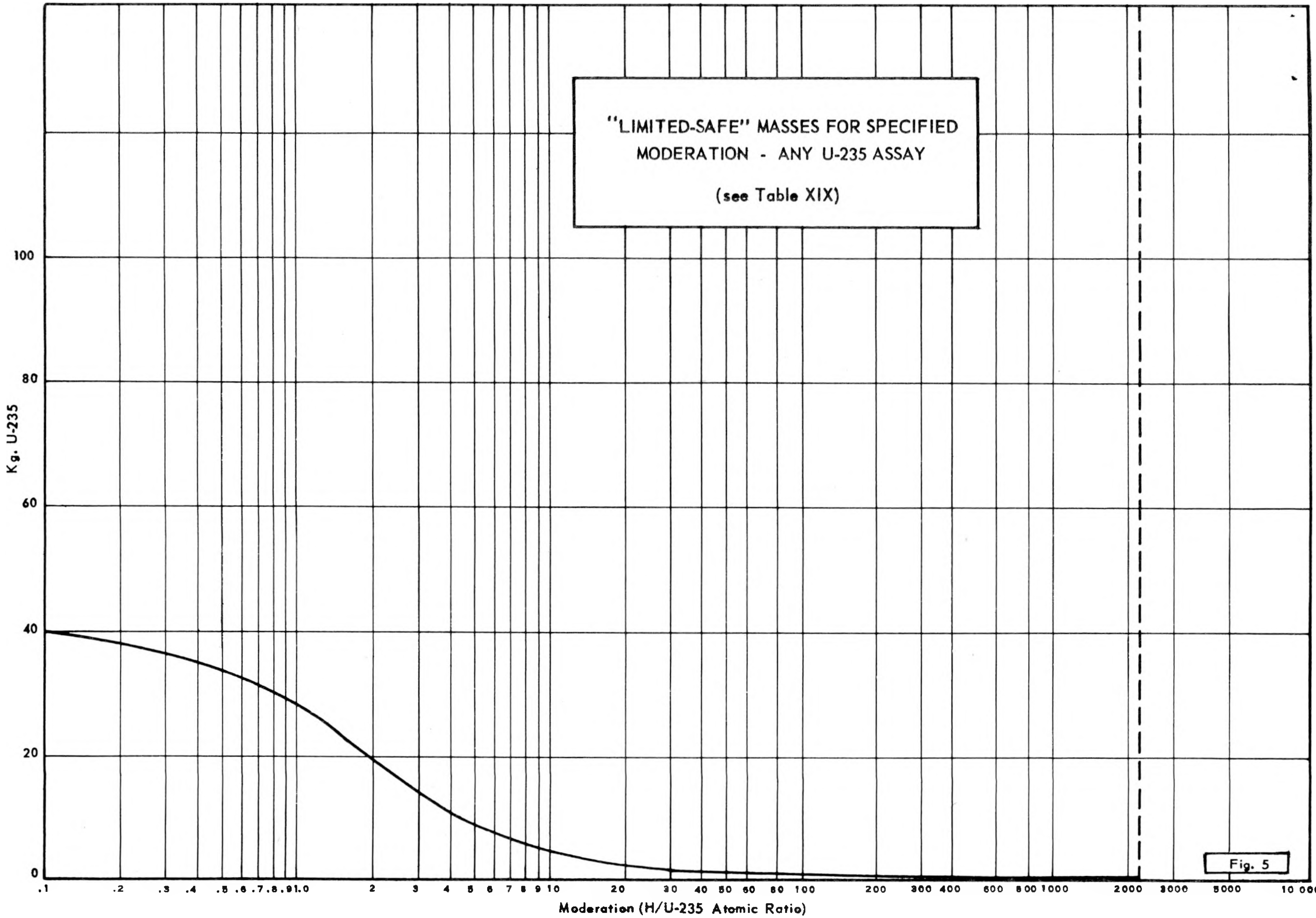

"LIMITED-SAFE" MASSES FOR SPECIFIED
MODERATION - ANY U-235 ASSAY
(see Table XIX)
Kg. U-235
0
20
40
60
80
100
.1
.2
.3
.4
.5 .6 .7 .8 .9 1.0
2
3
4
5
6
7
8
9
10
20
30
40
50
60
80
100
200
300
400
600
800
1000
2000
3000
5000
10 000
Moderation (H/U-235 Atomic Ratio)

Fig. 5

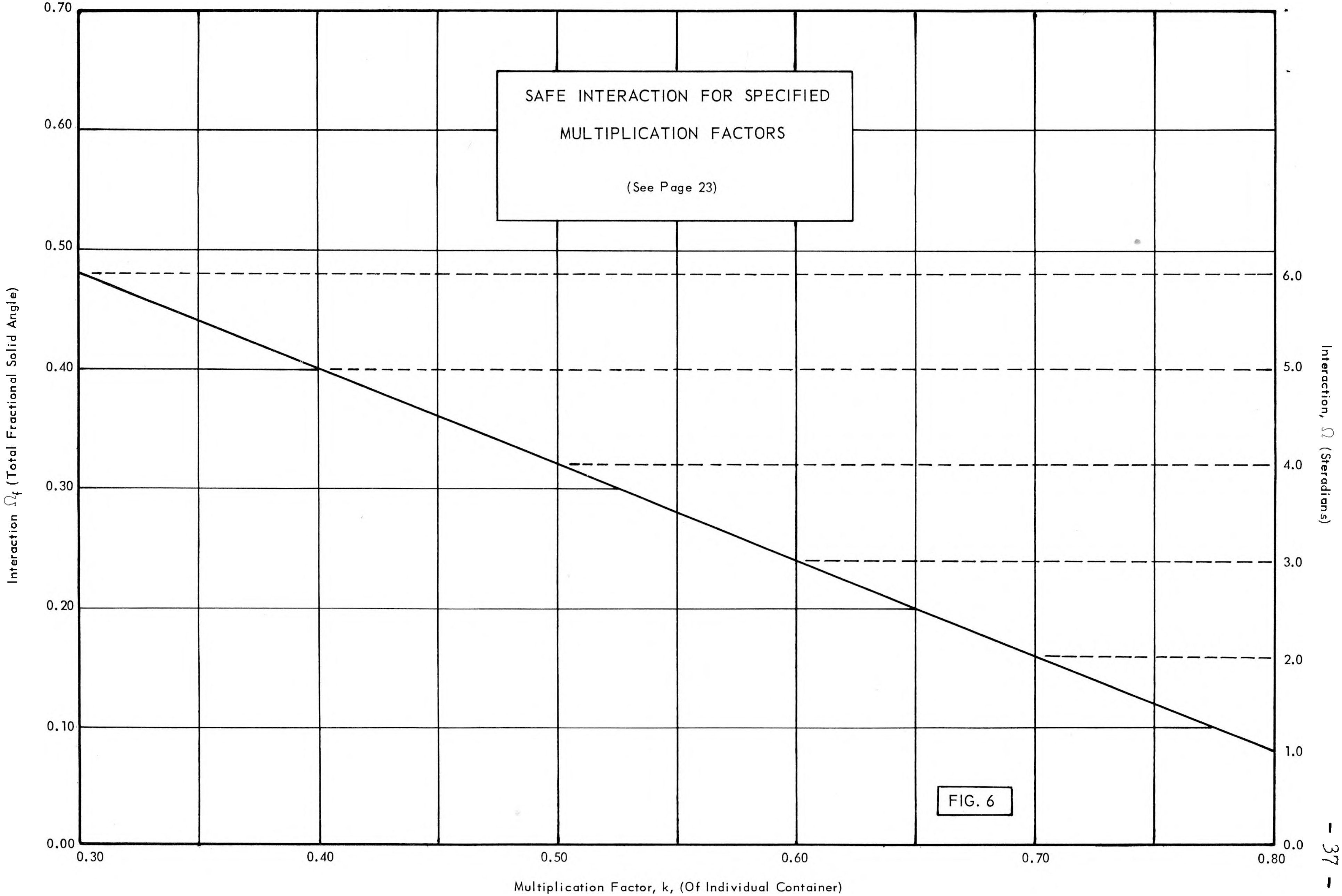
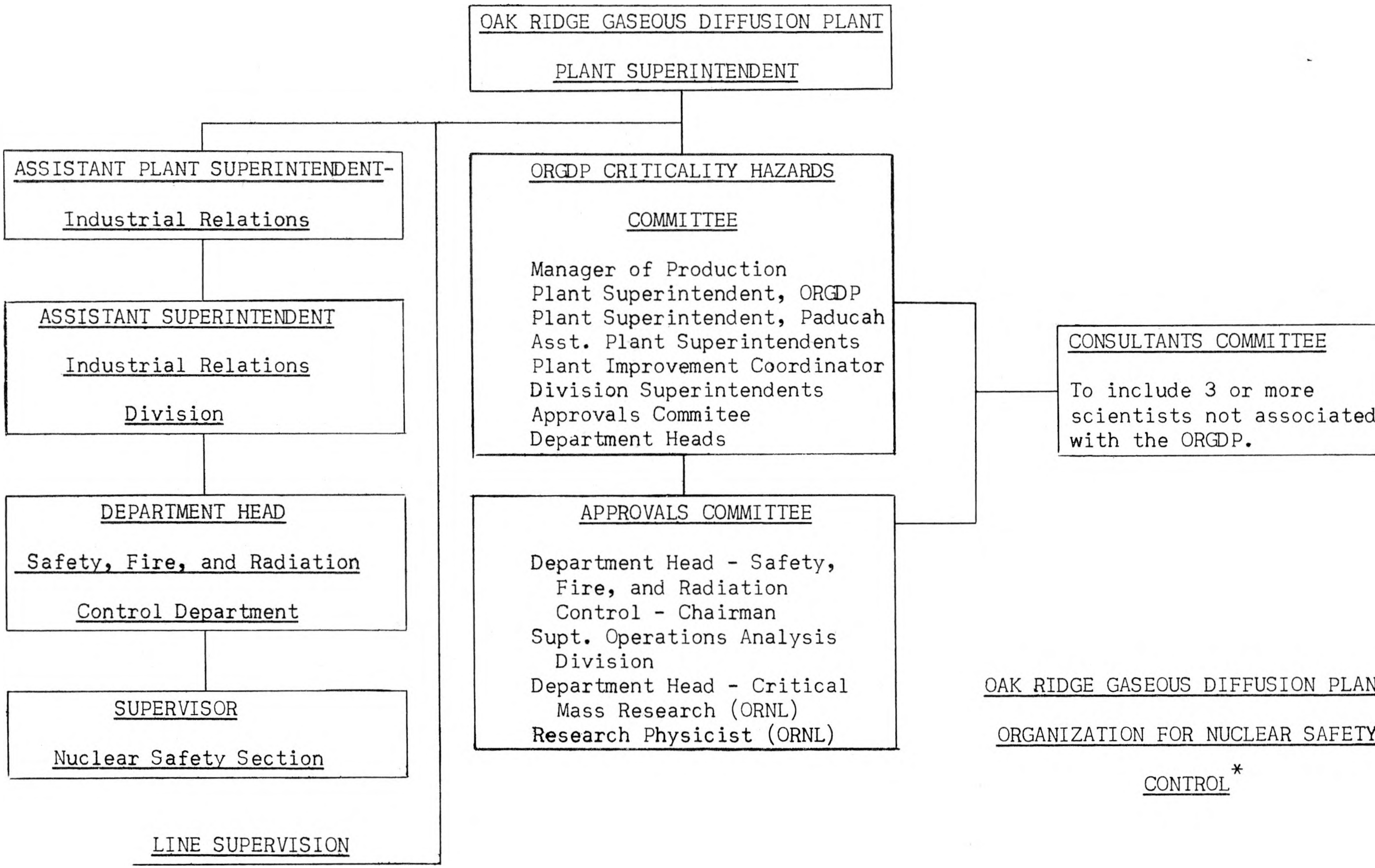

SAFE INTERACTION FOR SPECIFIED MULTIPLICATION FACTORS
(See Page 23)
Interaction Ωf (Total Fractional Solid Angle)
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Interaction, Ω (Steradians)
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0.30
0.40
0.50
0.60
0.70
0.80
Multiplication Factor, k, (Of Individual Container)

FIG. 6

APPENDIX B

ORGANIZATION FOR NUCLEAR SAFETY CONTROL - OAK RIDGE GASEOUS DIFFUSION PLANT



OAK RIDGE GASEOUS DIFFUSION PLANT

ORGANIZATION FOR NUCLEAR SAFETY

CONTROL*

* Reference 58

APPENDIX C

GLOSSARY

GLOSSARY

Brief definitions of some of the special terms used in this report are given below. In a few cases, the terms may have rather special meanings with respect to nuclear safety as compared to other fields of nuclear technology, and one word, "subcrit", is completely original.

"ALWAYS-SAFE" — A system where control of a single parameter of mass, geometry, or concentration makes a subcrit safe when all other parameters are unlimited and may thus assume any value; the value of this single parameter. (Note: In this report, values of these parameters apply only to materials of the types encountered at the ORGDP.)

ASSAY, U-235 — U-235 isotopic concentration, usually expressed as the weight percent of U-235 in uranium; also sometimes referred to as U-235 enrichment. Since 0.72% of naturally occurring uranium is the U-235 isotope, this uranium is said to be at a 0.72% U-235 assay.

ATTENUATION — A reduction in the intensity of neutron flux upon passage through material.

BORAL — A boron carbide-aluminum complex with high neutron absorption properties.

CONSERVATIVE — A term applied to calculations or other estimates where the factors are so chosen that criticality is predicted for an experimentally subcritical assembly, and, correspondingly, a critical assembly is predicted to be supercritical.

CORE — The region containing the fissionable material in a reactor or a subcrit; sometimes refers to the fissionable material itself.

CRITICAL(ITY) — The state of, or attaining the status of, a self-sustaining nuclear chain reaction; maintenance of a chain reaction with a constant neutron flux in the absence of a neutron source; at low flux levels, this is sometimes referred to as "just-critical". (See Subcritical and Supercritical.)

CRITICAL MASS — The mass of fissionable isotope in a reactor at criticality; the minimum mass of U-235 which can be made critical under a specific set of conditions.

FISSION — The division of a heavy nucleus into two approximately equal parts with an attendant release of neutrons and relatively large amounts of energy in the form of heat and radiation.

HALF REFLECTION — Interpreted as that condition where a core is completely reflected over 50% of its surface area. (See Reflection.)

HETEROGENEOUS — Non-homogeneous; a core wherein segregated masses of moderator and fissionable material can be either randomly or regularly spaced. (See Homogeneous.)

HOMOGENEOUS — The arrangement of nuclei in a core such that the density of both fissionable and other atoms, averaged over regions small compared to the neutron mean free path, is constant. For example, water solutions of uranium compounds are homogeneous.

H/U-235 RATIO — The ratio of the number of hydrogen atoms to the number of U-235 atoms in a core. (See Moderation.)

INTERACTION — The mutual interchange of neutrons between the units in a system of subcrits; a probability that an escaping neutron will enter another subcrit.

INVENTORY — The total amount of U-235 present in a unit or vessel; usually given in terms of the total uranium and the U-235 assay. As applied to production equipment, this may also refer to the total quantity of uranium or UF_6 in the unit.

"LIMITED-SAFE" — A system or unit for which the nuclear safety depends upon the control of the mass, geometry, or concentration, and one other parameter which may also be one of those named or may be a different parameter or variable; the values of these control parameters. (See "Always-Safe".)

MODERATION — A slowing down of neutrons from the high velocities (and correspondingly high energies) at which they are produced, to velocities (and energies) at which the probability of fission capture in U-235 nuclei is relatively large; usually expressed as a ratio of the number of moderator atoms and fissionable atoms. (See H/U-235 Ratio; Moderator.)

MODERATOR — A material having nuclear properties producing moderation. As a general premise, materials whose atomic weights are not significantly different from that of a neutron are good moderators; of these, hydrogen is the most effective moderator encountered at ORGDP.

MULTIPLICATION FACTOR, k — The ratio of the number of neutrons present at a given time to the number present one neutron generation earlier in the absence of a neutron source. For criticality, $k = 1$.

NEUTRON	An elementary particle of mass number 1 and no electrical charge; in nuclear reactions, it is important as the fundamental particle that initiates fission in U-235.
NEUTRON MULTIPLICATION, M	The ratio of the total number of neutrons in a subcrit or subcritical reactor containing a neutron source to the smaller number of primary source neutrons. Given by the relation: $M = \frac{1}{1 - k}$. As k, the multiplication factor, approaches 1, M approaches infinity.
POISON	A material with non-fission neutron absorption properties which are comparatively high with respect to other nuclear properties of the same material.
REACTOR	A container or assembly of fissionable materials designed to permit a controlled nuclear chain reaction; a planned critical system. The term "reactor" may be modified by the words thermal or fast to indicate the energy of the neutrons which predominate in maintaining the reaction.
REFLECTION	The return of neutrons escaping from a core. (See Reflector.)
REFLECTOR	A configuration of material having the nuclear properties of reflection placed around a core. Since all materials reflect neutrons to some extent, this becomes an important factor in determining nuclear safety. For general safety considerations at the ORGDP, a subcrit is designed to be safe when completely surrounded by a water reflector.
SHIELD	A layer of material around a core with the primary function of preventing the escape of neutrons into the space surrounding the core; also, material reducing or eliminating interaction between cores. Since 1 foot of water has over 99% attenuation of fission neutrons, it is considered to be a good neutron shield.
SLAB	A container having 2 parallel plane surfaces whose combined area is greater than 50% of the total surface area.
SOLID ANGLE	The ratio of that portion of the area of a sphere which is enclosed by the conical surface forming the solid angle, to the square of the radius of the sphere; denoted by the Greek letter, Ω. (See Steradian.)
STERADIAN	A unit of solid angle defined as that angle which is subtended by a surface on the sphere equivalent to the square of the radius. The total solid angle in space is thus 4π steradians.

SUBCRIT	A container or vessel used for handling fissionable materials under such conditions that a self-sustaining chain reaction is impossible under the specified limitations; a subcritical core or system.
SUBCRITICAL	Refers to an accumulation of fissionable material under such conditions that a nuclear chain reaction will not occur; a system with a multiplication factor, k, of less than 1.
SUPERCRITICAL	Refers to a critical accumulation of fissionable material with an increasing neutron population and a correspondingly rising rate of neutron fission; a system with a multiplication factor, k, larger than 1.
"TWIN"	A reactor or subcrit having nuclear properties identical to those of another reactor or subcrit.

APPENDIX D

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