APEX-715

NUCLEAR MATERIALS and PROPULSION OPERATION

FLIGHT PROPULSION LABORATORY DEPARTMENT

FORMERLY

AIRCRAFT NUCLEAR PROPULSION DEPARTMENT

Aircraft Nuclear Propulsion Department Nuclear Safety Guide

William A. Pryor

GENERAL ELECTRIC

DISCLAIMER

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AIRCRAFT NUCLEAR PROPULSION DEPARTMENT
NUCLEAR SAFETY GUIDE

William A. Pryor

June 1961

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GENERAL ELECTRIC

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ABSTRACT

This guide summarizes the limitations and operating techniques which were in effect at ANPD for the prevention of criticality accidents. The standards followed by the atomic industry have been followed; however, the safe mass of U-235, which is moderated with beryllium oxide and hydrogenous materials is based upon criticality experiments conducted at ANPD. Although the guide was primarily for the use of the ANPD nuclear safety control organization, it may also be of assistance to designers and operating management in maintaining nuclear safety.

APPROVALS

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AIRCRAFT NUCLEAR PROPULSION DEPARTMENT

NUCLEAR SAFETY GUIDE

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I INTRODUCTION

In the many operations associated with the development of high temperature fuel elements at ANPD, the hazards of a criticality accident have been one of the more important considerations. This guide was recommended by the ANPD Nuclear Safety Advisory Committee and summarizes the limitations and operating techniques which are in effect for the prevention of this type of accident.(1) It was prepared primarily for the benefit of the organization which administers nuclear safety control; however, it may also assist engineers in the safe designing of new facilities and management in the safe operation of development and production facilities.

The criteria are generally consistent with the nuclear safety standards followed by the atomic industry with the nuclearly safe operating curves and other sections being taken directly from the Nuclear Safety Guide;(2) however, the safe mass quantity for U-235, which is moderated with beryllium oxide and hydrogenous material, is based upon criticality experiments conducted at ANPD.

The preparation of this guide was based upon operating conditions existing at ANPD; however, since these conditions are subject to change, a selected list of references on various phases of nuclear safety is also included.

II PHILOSOPHY OF NUCLEAR SAFETY CONTROL AT ANPD

A. General

1. Nuclear Safety Control is basically concerned with the protection of Department personnel, plant facilities, and the surrounding community from the hazards of radiation and contamination associated with a criticality accident.

2. Maximum protective effort is directed to the prevention of criticality accidents; however, since criticality accidents are possible, the basic protection includes the provisions for handling an accident of this type in order to minimize the hazards.

3. Areas of responsibilities for nuclear safety control are formalized within Department instructions.[3]

B. Criteria

1. The criteria for nuclear safety control are based on the results of criticality experimentation.

2. In the absence of direct experimentation,

   a) Conservative reductions are made of existing criteria.

   b) Calculations in conjunction with experimental data may be made to bridge the gap between experimental points where limits of error may be assigned.

3. Criteria are not based upon calculations alone; however, calculations may be used as a back-up type verification.

4. Nuclearly safe geometry is used for nuclear safety control in preference to limitations which require administrative control.

5. In situations where nuclearly safe geometry is impractical, non-geometrically safe equipment may be operated under administrative control on a nuclearly safe mass basis.

6. The use of internal neutron poisons for the inherent safety control of equipment is generally avoided due to the problem of maintaining the poison in the required configuration; however, where adequate administrative controls are in effect poisons may be used.

7. An operation is considered safe if it requires that 2 independent contingencies must occur before a uranium configuration can become unsafe. Additional random factors of safety, which are known to exist, are not included as a basic nuclear safety specification.

8. If the U-235 enrichment and amount of any uranium material are unknown, the material will be considered to be fully enriched and will be handled according to the fully enriched rules until analyses are obtained to show the safe disposition of the material.

9. The possibility of malicious or intentional damage is not considered a factor in establishing criteria for nuclearly safe operation.

C. Emergency Planning

1. Radiation detection instruments with automatic alarms for the detection of any criticality are installed at intervals within Department facilities where fissionable material is handled.

2. A comprehensive plan of action is maintained in an up-to-date status in order to cope with a criticality accident.(4)

3. Provisions are made in event of a criticality to detect immediately personnel who have been irradiated significantly and to make estimates of their exposures.

D. Assumptions

1. U-235 is the only fissionable material which is processed within the Department.

2. A thermal system requires less U-235 mass to become critical than any other system.

3. The hydrogen of ordinary water and beryllium oxide are the most readily available moderators and reflectors.

4. Homogeneous mixtures of hydrogenous materials and uranium at a U-235 enrichment $\leq 0.95\%$, cannot be made critical.

5. Nuclear safety controls in this guide apply only to U-235 materials outside of nuclear reactors; this includes reactor fuel elements, cartridges, inserts, etc., in manufacture, storage and shipment. Nuclear safety precautions for loading reactors and conducting criticality experiments in the Nuclear Experiments Area are specified in other applicable operating instructions.

III NUCLEAR SAFETY CRITERIA

FOR U-235 MODERATED WITH HYDROGENOUS MATERIALS AND FOR UNMODERATED U-235

A. Basic Criteria

The criteria in Table I, which are compared with the minimum critical, are generally recommended as being nuclearly safe for U-235 when moderated, as indicated, and reflected with light water.(2)

TABLE I

	Recommended Nuclearly Safe	Minimum Critical
Mass - kg:		
Solution	0.35	0.82
Metal*	10.0	22.8
Diameter of Infinite Cylinder - inches:		
Solution	5.0	5.4
Metal*	2.7	3.1
Thickness of Infinite Slab - inches:		
Solution	1.5	1.7
Metal*	0.5	0.6
Solution Volume - liters:	4.8	6.3
Chemical Concentration of Aqueous Solution, grams of U-235/liter -	10.8	12.1
U-235 Enrichment of Homogeneous Hydrogen-Moderated Uranium, wt. % -	0.95	1.0**

* Solid Uranium

** Uranium at U-235 enrichments below this value when mixed homogeneously with hydrogenous materials cannot be made critical.

B. Handling Rules

The following handling rules are applicable primarily in a fuel element fabrication facility:[5]

1. For non-moderated uranium (H/U-235 ≤ 2):

   a) Individual batches of U-235 are ≤ 2000 g.

   b) The minimum separation between batches, which is maintained by physical spacers, is 1 ft. edge-to-edge.

   c) Where more than 6 batches are being processed at an accountability station, each group of 6 is separated at least 4 ft. edge-to-edge.

   d) In addition, positive controls are in effect to prevent water and other moderating materials from being mixed with the fuel.

2. For moderated uranium (H/U-235 >2) or where the positive controls indicated in No. 1.d above are not in effect:

   a) Individual batch sizes are ≤ 350 g.

   b) The limitations indicated in 1.b and c above are also in effect.

C. Storage Rules

The following precautions for storage are nuclearly safe for uranium materials in cubic arrays. The separation indicated provides safety for both flood and non-flood conditions. Table II indicates the specification for non-moderated uranium (H/U-235 ≤ 2) while Table III indicated specifications for uranium at any moderation.[6] Rules 1-3 are applicable to Tables II and III.

1. The volume of the individual mass units is ≤ 4 liters.

2. Individual containers are water tight.

3. Individual containers are in fixed positions while in storage.

4. Arrays are isolated when separated by the larger of:

   a) 12 ft., or
   b) the maximum dimension of the arrays.

TABLE II

Unit Mass (Kg.U-235)	Center-to-Center Spacing (in.)	Min. Edge-to-Edge Spacing (in.)	Kg./ft.^{3}	Units/Array	Kg./Array
4.5	12.5	12	4	205	925
4.5	14.6	12	2.5	290	1300
4.5	19.0	12	1.19	494	2220
2.0	14.3	12	1.19	1110	2220
1.0	--	12	<1.00	2220	2220
4.5	22.5	12	.685	823	3700
2.0	17.2	12	.685	1850	3700
1.0	13.6	12	.685	3700	3700
.5	--	12	$<.50$	7400	3700

TABLE III

Unit Mass (Kg.U-235)	Center-to-Center Spacing (in.)	Min. Edge-to-Edge Spacing (in.)	Kg./ft.^{3}	Units/Array	Kg./Array
4.5	20.0	12	.97	50	225
2.0	15.2	12	.97	112	225
1.0	--	12	1.0	225	225
4.5	24.0	12	.563	80	360
2.0	18.3	12	.563	180	360
1.0	14.6	12	.563	360	360
.5	--	12	.5	720	360
4.5	30.0	12	.288	120	540
2.0	22.9	12	.288	270	540
1.0	18.2	12	.288	540	540
.5	14.5	12	.288	1080	540
4.5	36.0	12	.166	200	900
2.0	27.5	12	.166	450	900
1.0	21.8	12	.166	900	900
.5	17.3	12	.166	1800	900
.35	13.8	12	.166	2670	900

D. Special Storage

The following special storage cases are also applicable:[6]

1. Unmoderated:

   a) 4.5 Kg. of U-235 in combination with non-moderating materials (such as scrap) are stored in cylinders whose dimensions do not exceed 5 in. I.D. X 30 in. provided, 1) the uranium is uniformly distributed over the length of the container and does not tend to slide to one end; 2) the containers are stored in a plane array having centerlines parallel with a center-to-center spacing ≥20 in. and an edge-to-edge spacing ≥15 in.

   b) Incoming uranium oxide in individual units of ≤8 kg. is received in standard 20 in. cubic birdcages having a fuel volume ≤4 liters. Up to 20 birdcages are temporarily stored as an array; however, the subsequent transfer and storage of this material is according to the criteria previously specified in Table II.[7]

2. Moderated:

   Moderated U-235 in plane arrays of the following containers having parallel centerlines are nuclearly safe for the spacings* indicated in Table IV.[8]

TABLE IV

Container	Minimum Spacing (in.) Center-to-center	Edge-to-edge
5-1/8 in.I.D. X ≤48 in.	≥24	≥29
5 in. I.D. X ≤30 in.	≥18	≥23
5 in. I.D. X ≤24 in.	≥16	≥21

* Physical spacers are required to maintain the specified spacings.

E. Pipe Connections

The criteria for safe pipe connections in Table V are applicable only to solutions (H/U-235 ≥ 20).[2]

TABLE V

	Pipe Diameters (in.)* Equilateral		
	Ells (l)	Tees (T)	Crosses or Wyes (+ or Y)
Full Reflector (Thick H_2O)	4.6	4.2	3.8
Nominal Reflector** (≤ 1 in. H_2O)	5.3	5.1	4.9

* Reduced diameters should extend 18 in. from intersection.

** Must be positioned ≥ 30 in. above Building D ground floor elevation.[9,10]

In addition, a 1 in. I.D. pipe may tee directly into a 5 in. I.D. pipe.

F. Use of Curves

The curves in Figures I-IV, Section VI, are applicable to isolated units of homogeneous mixtures of U-235 at any enrichment and water.[2] Since fuel is handled by personnel and since processing equipment requires periodic maintenance, the use of the curves for minimal reflection is extremely limited and only after positive provisions are made to control reflection. Figure V is restricted to the full reflector curves of Figures I-IV for aqueous homogeneous solution of U-235 only.[2]

IV NUCLEAR SAFETY CRITERIA FOR U-235

MODERATED WITH BERYLLIUM OXIDE

A. Basic Criteria

The criteria indicated in Table VI are considered to be nuclearly safe when reflected with light water and unreflected, respectively, for U-235 moderated with beryllium oxide where the Be/U-235 ratio <500 and where the H/U-235 ratio is unlimited.[11]

TABLE VI

	Reflected	Nominally Reflected
Mass - Kg.	0.35*	0.35
Diameter of Infinite Cylinder - in.	3.5	5.0

* This value is based upon criticality experiments conducted in the Nuclear Experiments Area of ANPD.[12]

B. Handling Rules

The handling rules described below are applicable to operations in production and development facilities:

1. Individual safe batches of U-235 ≤ 350 g. and are contained in a volume ≤ 1 ft.^{3}.

2. In-process storage of the safe batch-volume indicated above is shown in Table VII.

TABLE VII

Unit Mass (Kg. 235)	Center-to-Center Spacing (in.)	Edge-to-Edge Spacing (in.)	Kg.U-235 per ft.^{3}	Units/Array	Kg.U-235/Array
.350	24	12	.044	100	35
.250	24	12	.031	140	35

Note: The spacing indicated above is maintained by physical spacers.

3. Fuel is stored in 3 - 17 in. X 14 in. X $1\frac{1}{2}$ in. slabs which are positioned ≥30 in. above the ground floor elevation and which are spaced ≥12 in. edge-to-edge.[13]

C. Special Processing Rules

Processing rules applicable to fuel element production are summarized below:

1. Up to 2 kg. of U-235 as uranium oxide is milled in a ball mill jar having a volume ≤4.8 liters and using beryllium oxide balls where the Be/U-235 ratio is <100; 8 ball mills jars are spaced 12 in. edge-to-edge in process or in storage.[13,14]

2. In high temperature furnaces continuous ribbons of fuel are safe in the following configurations:[15]

   a) Width ≤12 in., depth ≤2 in.

   b) Width ≤5.5 in., depth ≤3.4 in.

   (See also the general requirements under Furnaces, Page 18).

D. Storage Rules

The following are safe storage arrangements for U-235 moderated with beryllium oxide:

1. An unlimited number of 3.5 in. I.D. X 42 in. cylinders is stored with parallel centerlines in plane array with an edge-to-edge separation of 1 ft.[8]

2. Up to 105 kg. of U-235 in units of 0.35 kg. in a volume ≤4 liters are stored as an array where the center-to-center separation is ≥18.5 in. and the edge-to-edge separation is 12 in.

V APPLICATIONS OF NUCLEAR SAFETY CRITERIA

A. Furnaces

1. All high temperature, hydrogen atmosphere furnaces used for fuel element development are equipped with the standard controls and safety devices to prevent explosions.

2. Furnace cooling water jackets are designed such that water leakage will not flood the interior of the furnace.

3. Fuel channels in all furnaces are ≥30 in. above ground floor level.

4. Specially designed fixtures, guides, etc., are used for maintaining fuel in a safe geometry while being processed in furnaces.

B. Storage of Fuel

1. Moderated and non-moderated fuel are not intermixed in the same array.

2. Racks for the storage of fuel are specially designed to maintain appropriate spacings and the fuel containers will be held in fixed positions by straps, etc.

3. Beryllium oxide and natural uranium are not stored in fuel storage areas.

C. Shipment of Fuel

1. The following array sizes are applicable to the safe shipment of fuel:

   a) One-half the arrays specified in Tables II or III or Item No. 2 under Storage Rules for U-235 Moderated with Beryllium Oxide, Page 17.

   b) A single plane array of the containers specified in Table IV, or Item No. 1 under Special Storage for Unmoderated U-235, Page 14, or in Item No. 1 under Storage Rules for U-235 Moderated with Beryllium Oxide, Page 17.

2. Moderated and non-moderated fuels are not intermixed in the same shipment.

3. All shipping containers are nuclearly safe when totally reflected and are water-tight.(16)

4. Physical spacers such as "birdcages" are used to maintain safe container separations.

5. In order to effect total isolation in event of flooding, the physical spacers will maintain ≥12 in. edge-to-edge separation.

6. For shipments having exclusive use of the vehicle shipping space, containers are shored to prevent relative movement during transit.

7. Designs of shipping containers are submitted to the Bureau of Explosives for approval prior to usage.

D. Material Handling

1. Only specially designated personnel such as material handlers are permitted to transfer fuel between accountability stations.

2. Fuel is transferred with carts, fixtures, containers, etc., which are designed to maintain safe geometry and spacing. Hand carrying of fuel is generally avoided.

E. Waste Handling

1. Liquid Waste:

a) Geometrically safe containers are used to collect liquid waste when the uranium content is unknown or for concentrations greater than the values indicated in 1.b) below.

b) Prior to transfer of liquid waste to non-geometrically safe containers analyses for uranium content are made to determine that transfer will be safe as indicated below.

For 55-gal. drum storage the following conditions are nuclearly-safe:

U-235 Concentration (g. U-235/liter)	Edge-to-Edge Container Separation (ft.)
≤ 0.45	None
>0.45 to ≤ 1.7	2

Note: Solution transfers should be based upon two independent analyses.

2. Burnable Contaminated Waste:

a) Burnable contaminated waste is collected in plastic bags having holes to prevent any liquid accumulation.

b) Prior to transfer to shipping containers (55-gal. drums), the waste bags are monitored with scintillation counters in order to verify that the U-235 content is $\leq$100 g. for U-235 moderated with beryllium oxide and $\leq$200 g. for other U-235 mixtures.

F. Enriched and Non-enriched Uranium

1. When U-235 enriched and non-enriched uranium is in the same laboratory, production facility, storage vault, etc., the non-enriched uranium is handled as if it were enriched.

2. When transfers of any uranium are made, the enrichment is verified by analyses or appropriate instrumentation such as scintillation counters.

G. Decontamination Operations

1. In general, geometrically safe equipment is used for the wet decontamination of small items of equipment contaminated with uranium.

2. Geometrically safe, liquid-dry vacuum cleaners are used to decontaminate floors in uranium processing areas.(14) (If the collectors are not safe under flooded conditions, the liquid is transferred after each use).

3. Solution transfers are made as previously described under liquid waste.

H. Use of Nominally Reflected Criteria

1. The equipment involved must be positioned above Mill Creek Valley maximum flood level which is 30 in. above the Building D ground floor elevation.(9,10)

2. For continuous operations with components at elevations between the Building D ground floor level and maximum flood level, nominally reflected criteria are used when administrative controls are in effect to take adequate corrective action in event of flood conditions. In-process storage may be considered to meet this condition.

I. General

1. U-235 inventories are maintained at minimal levels which are compatible with current operations.

2. All non-geometrically safe as well as safe containers which are not specifically required for operations are removed from fuel processing areas.

3. Empty containers of fuel are handled as if they are full in fuel processing areas.

4. Operating procedures are formalized and include the applicable nuclear safety precautions.

5. Routine inspections are made as a precaution against the build-up of fuel in inaccessible locations such as under equipment, in ventilation plenums, in dry boxes, etc.

VI CURVES

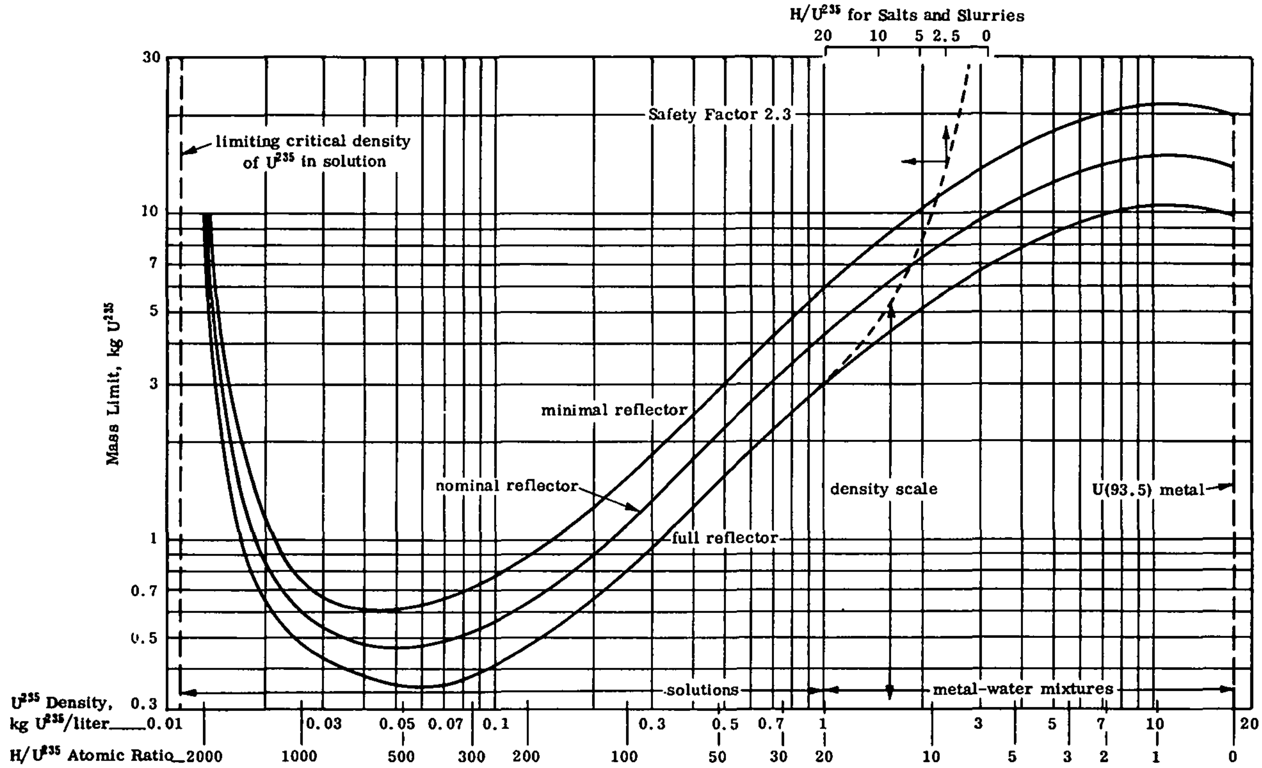

FIG. 1. MASS LIMITS FOR ISOLATED UNITS OF HOMOGENEOUS WATER-MODERATED U SPHERES (93.5% U^{235}) (Reference 2)

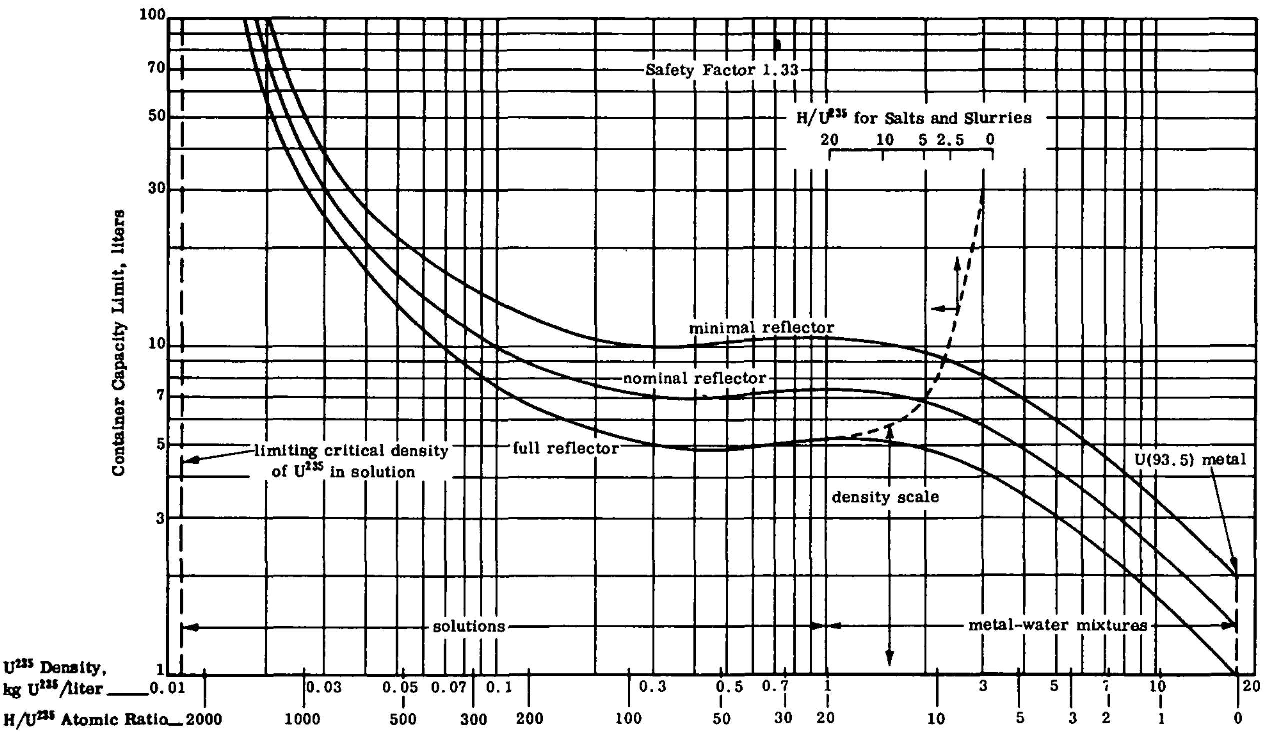

FIG. 2. CONTAINER CAPACITY LIMITS FOR ISOLATED UNITS OF HOMOGENEOUS WATER-MODERATED U SPHERES (93.5% U^{235}) (Reference 2)

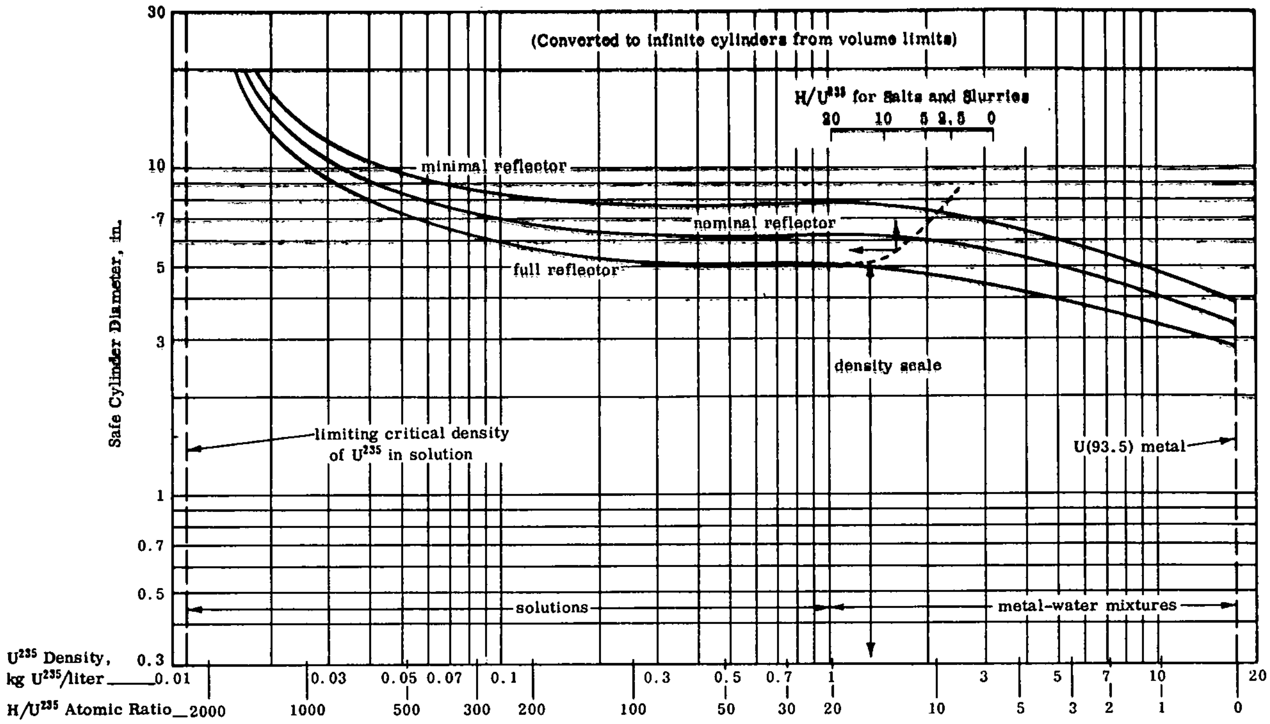

FIG. 3. SAFE DIAMETERS OF ISOLATED CYLINDERS OF HOMOGENEOUS WATER-MODERATED U (93.5% U^{235}) (Reference 2)

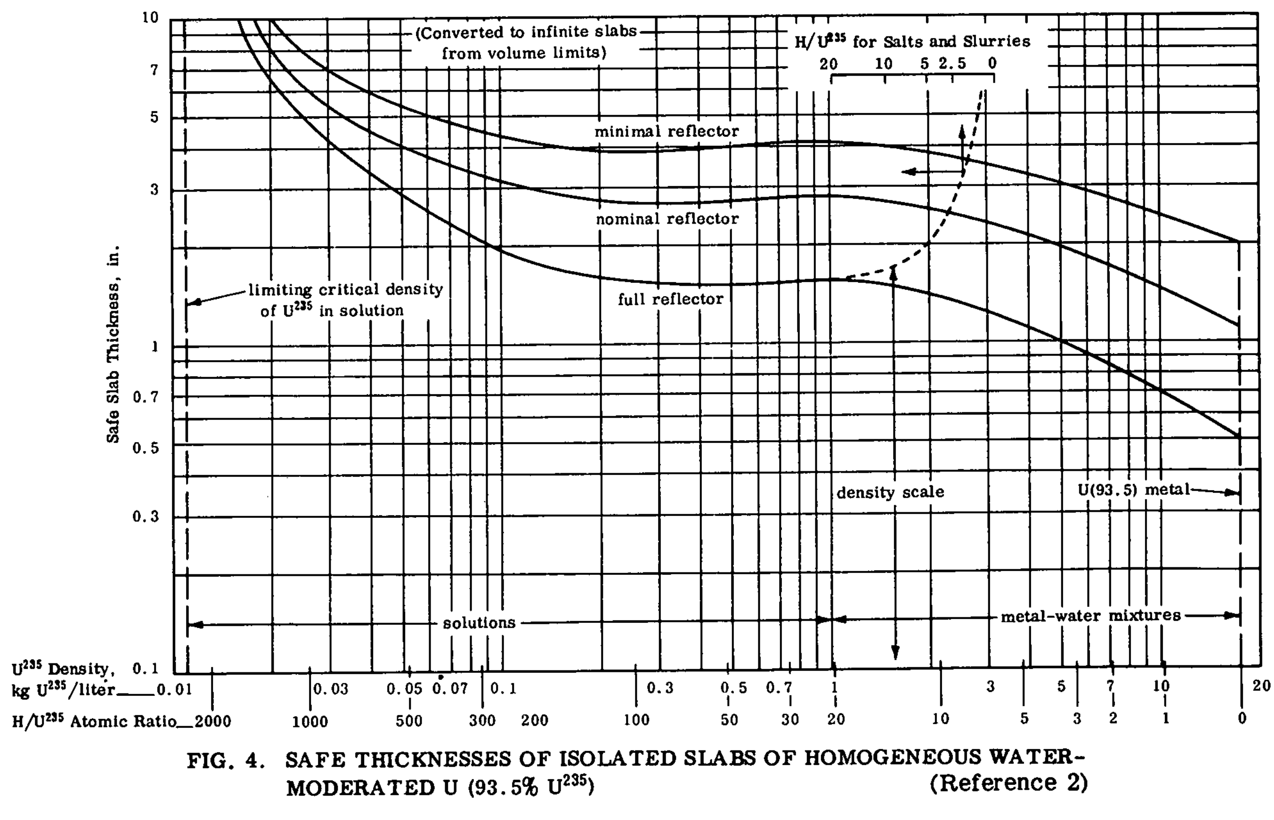

FIG. 4. SAFE THICKNESSES OF ISOLATED SLABS OF HOMOGENEOUS WATER-MODERATED U (93.5% U^{235}) (Reference 2)

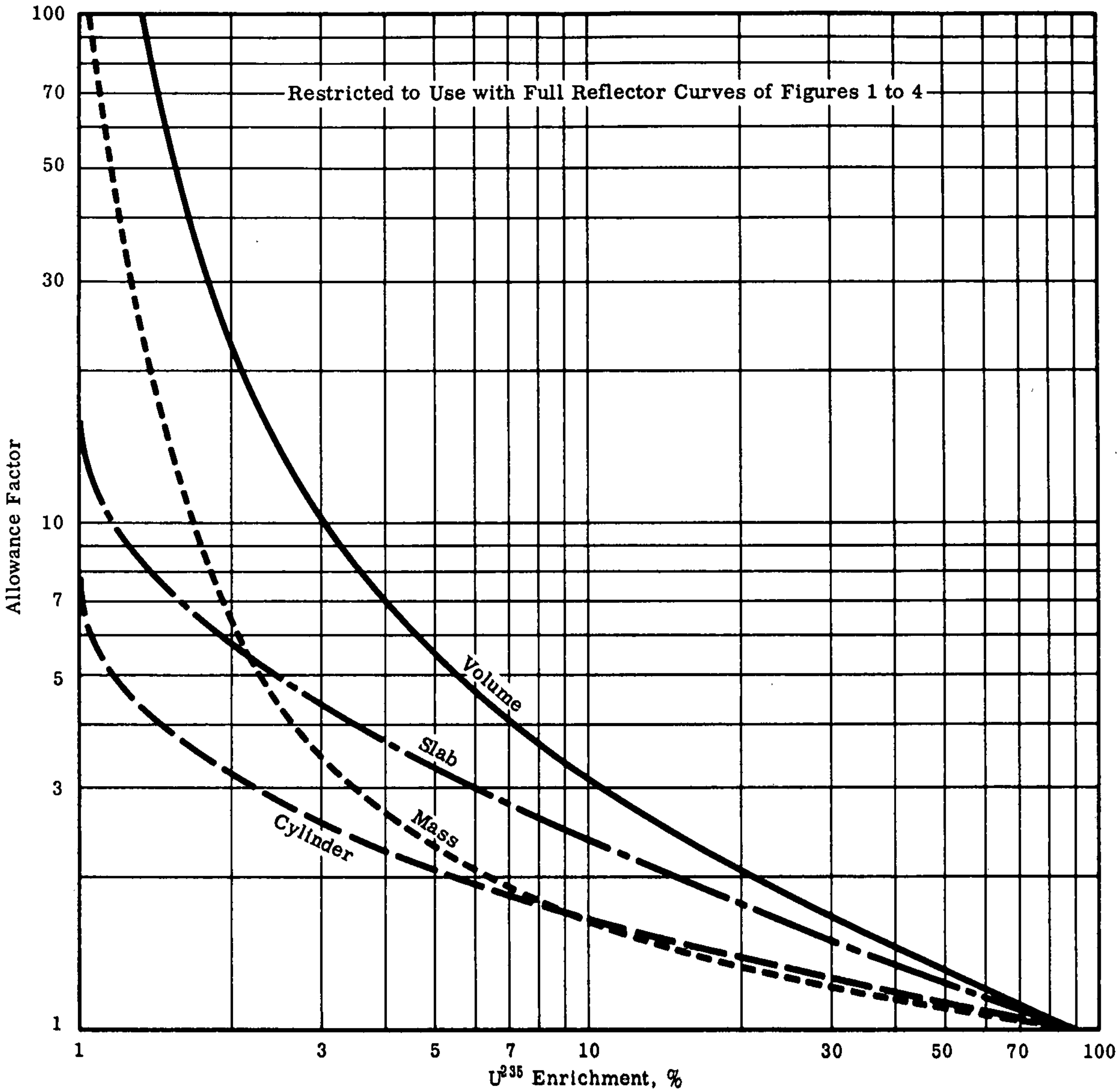

FIG. 5. ALLOWANCE FACTOR FOR AQUEOUS HOMOGENEOUS SOLUTIONS OF U^{235}
(Reference 2)

VII NOMENCLATURE

Administrative Control	A term used to denote that nuclear safety control is based upon strict adherence to operating procedure and which is checked by supervisory personnel.
Array	An arrangement of containers of fissionable material in storage. Arrays may be designated as: a) Plane - with container centers lying in a plane; having parallel center lines. b) Cubic - with container centers forming a latticed, three dimensional configuration.
Beryllium Oxide	A moderating material used in the fabrication of high temperature fuel elements.
"Birdcage"	An outer framework or container which surrounds and rigidly centers a container of fissionable material; the birdcage provides the positive separation among individual containers of fissionable material in storage and shipment.
Contaminated Wast (Burnable)	Paper, etc., which contains <10 g. of U-235/container.
Contingency	A possible but unlikely and uncontrollable change in one or more of the conditions originally specified as essential to the nuclear safety of a specific operation such that the nuclear safety of the operation is decreased.
Critical(ity)	The state of a self-sustaining nuclear chain reaction.
Criticality Accident	An unplanned and unexpected attainment of criticality in a system other than that of a reactor or a facility specifically for conducting critical experiments.
Critical Mass	The mass of fisionable material (U-235) at criticality; the minimum mass of fissionable material (U-235) which can be made critical under a specific set of conditions.

Enrichment	U-235 isotopic concentration, expressed as weight % of U-235 in uranium. (Example: Naturally occurring uranium - also known as normal uranium - contains 0.7115% U-235; thus, the U-235 enrichment is 0.7115%).
Flood-safe	Nuclearly safe for the anticipated maximum flood level in the Mill Creek Valley which is considered to be 563 ft. above mean sea level or 30 in. above the ground floor elevation in Building D.
Fissionable Material or Fuel	Material in which nuclear fission can result in a chain reaction with the emission of a large amount of energy. (Note: U-235 is the only fissionable material or fuel available at this site.)
Handling Rules	Conditions for processing fissionable material when appropriate operating personnel are in attendance and when administrative controls are in effect; handling rules are applicable above ground floor elevations only.
Inventory	The total quantity of U-235 in a unit, container, accountability station, or the Department. It may also refer to the quantity of total uranium.
Isolated	Fissionable material containers are considered to be isolated when separated by 1) 12 in. of water or hydrogenous material having a hydrogen density equivalent to water or 2) 8 in. of solid concrete. Arrays of fissionable material are considered to be isolated when the surface-to-surface separation is the larger of (1) the maximum dimension of the array or (2) 12 ft.
Material Handler	An individual specifically assigned to transfer material among accountability stations.
Moderation	A slowing down of neutrons from high velocities (and correspondingly high energies) at which they are produced to velocities at which the probability of fission capture in U-235 nuclei is relatively large; usually expressed as a ratio of the number of atoms to the number of fissionable atoms.
Moderator	A material having nuclear properties producing moderation. Generally, materials whose atomic weights are not significantly different from that of a neutron are good moderators; the hydrogen in ordinary water and the beryllium in beryllium-oxide are the moderators of greatest concern.
Neutron Poison	A non-fissioning material with absorption cross sections which are comparatively high with respect to other nuclear properties of the same material or those of other materials in the same system.

Nuclear Experiments Area — A facility for experimentally determining the critical size and operating and control features of a new reactor prior to operation. The facility is equipped with equipment consisting of a fixed and a movable component for the gradual assembly of fissionable material in the controlled approach to criticality and is located behind appropriate shielding.

Nuclear Fission — The division of a 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.

Nuclearly Safe — Refers to the containers of fissionable materials or systems thereof where the specified limitations for nuclear safety control are such that criticality cannot occur even though no limitation is placed upon other conditions. Concurrent limitations may also be involved.

Reactor — Assembly of fissionable materials designed to permit a controlled nuclear chain reaction.

Reflection — The return of neutrons escaping from a container of fissionable material.

Reflector — Materials having, in various degrees, the capability of returning or reflecting neutrons into a container of fissionable material. Reflectors are designated as:

a) Full - A layer of water ≥ 3 in. thick.

b) Nominal - A layer of water ≤ 1 in. thick.

c) Minimal - A layer of stainless steel or other common container metals such as iron, copper, aluminum, nickel, or titanium $\leq 1/8$ in. thick.

Slab — A container having 2 parallel plane surfaces whose combined area is greater than 50% of the total surface area.

Spacer — Framing, fencing, etc., which is designed to maintain a minimum separation between containers or systems of fissionable material. A "Birdcage" is a specific type of spacer.

Storage — Fissionable material is considered to be in storage when it is unattended by appropriate operating personnel.

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