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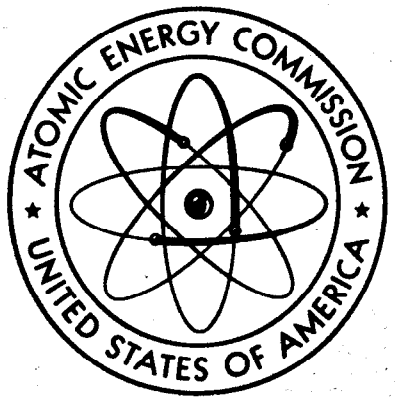
nuclear safety guide



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FOREWORD

The Nuclear Safety Guide was first issued in 1956 as a classified AEC report (LA-2063). Since it can now be more widely distributed with no significant changes, it is appropriate to restate the intended purposes of the information it contains and to emphasize the caution with which it must be used.

The recommendations in the Guide are intentionally conservative, and they may, therefore, be applied directly and safely provided the appropriate restricting conditions are met. In this usage it is believed that the Guide will be of value to organizations whose activities with fissionable materials are not extensive. The Guide is also expected to be a point of departure for members of established nuclear safety teams, experienced in the field, who can judiciously extend the specifications to their particular problems. The references in this report will be of especial value to them since reference to the experimental results will aid in guided extrapolations.

Particular reference is made to the recommendations of the Guide relating to arrays of individually subcritical units that may be applied to storage conditions and, a priori, to the arrangement of materials in shipment. A note of caution is added to the arrangement of materials in shipment. Recognition must be made of the continually increasing frequency of shipments of fissionable materials and of the necessity of exercising some control prohibiting risks which could arise if two or more individually nonhazardous shipments met in transit. In many instances such occurrences are not probable because the container arrangements are controlled by their escort or by the exclusive use of the carrier. The preparation of shipments by common carriers, where controls of this type will not, in general, be exercised, must be very carefully planned.

Recently published reports of importance to the subject material have been included in the reference section.

PREFACE

The Nuclear Safety Guide was conceived by a group that met at the Rocky Flats Plant, October 1955, to discuss industrial nuclear safety problems. A committee was selected to prepare a draft for consideration by the group during the following meeting at the Hanford Atomic Products Operation, June 1956. Although the resulting Guide remains controversial in form and general content, differences of opinion concerning specific regulations have been resolved (quite generally in favor of the more restrictive versions). In addition to the committee of authors, the following are members of the nuclear safety group who reviewed drafts of the Guide and contributed suggestions.

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It is recognized that the Guide is neither handbook (too ambitious for a start) nor manual (a separate problem for each installation). It is hoped, however, that it serves immediate needs for guidance and that it encourages continuing, more comprehensive efforts toward organizing nuclear safety information.

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isting experimental data and extrapolations thereof. In Part III there is a description of a few methods and examples illustrating applications to actual industrial equipment.

In concluding these introductory remarks, it seems appropriate to say that this Guide is by no means to be considered as an authoritative "last word" on the subject. It is rather a preliminary compilation based on experimental data for use in industrial nuclear safety work. At the present time a systematic and thorough treatment is not possible. As mentioned before, we do not know how to calculate critical masses accurately, even in simple idealized geometries. Further, we do not have the necessary data on the nuclear cross sections and other constants. Thus much experimentation remains to be done before definitive theoretical methods can be developed and a systematic and complete treatment of critical masses can be given. Meanwhile, it is hoped that this preliminary Guide will assist those whose purpose and responsibility it is to achieve nuclear safety in industrial plants.

CRITICAL PARAMETERS

As a background for criteria applicable to the problems of nuclear safety, it is appropriate to review the factors which govern the critical condition of an assembly of fissionable material and to discuss some other aspects including the origin of the criteria and their administration.

For an accumulation to be chain-reacting, there is required, of course, a quantity of the fissionable isotope, referred to as the critical mass, which is not single valued but depends very strongly on a number of factors which will be described briefly.

One factor of importance is the leakage, from the system, of neutrons which would otherwise produce fissions. The leakage depends on the shape of the fissionable system and on the neutron-reflecting properties of surrounding materials. It is possible, for example, to specify solution container dimensions, such as pipe diameters, which give a sufficiently unfavorable surface area to volume ratio to prevent a chain reaction regardless of the quantity of material contained. If the pipe is encased in a cooling jacket, or is near other process equipment or structural materials, its dimensions must be less than it would be if there were no neutron reflector proximate. In the treatment presented here, it is assumed that water, concrete, graphite, and stainless steel are typical reflector materials. Although more effective reflectors are known—heavy water and beryllium as examples—they are uncommon in processing plants. Consideration is given, therefore, to reflectors of three thicknesses in an attempt to make the specifications more generally applicable. The equipment may be nominally unreflected, i.e., the only neutron reflector is the container itself, the wall of the stainless-steel pipe, for example; it may be completely reflected by a surrounding layer of water at least 6 in. thick; the third reflector considered is a "thin" one consisting of a 1-in.-thick layer of water (or the equivalent) exemplified by the water in a cooling jacket.

The value of the critical mass is extremely sensitive to the presence of hydrogen, or other neutron moderating elements, intimately mixed with the fissionable isotope. In nuclear physics considerations the hydrogen concentration is usually expressed as the ratio of the number of hydrogen atoms to the number of fissionable atoms and may range from zero for metal or a dry unhydrated salt to several thousand for dilute aqueous solutions. Over this concentration range the critical mass may vary from a few tens of kilograms, through a minimum of a few hundred grams, to infinity in very dilute solutions where the neutron absorption by hydrogen makes chain reactions impossible. In this latter limit nuclear safety is assured by the chemical concentration alone. The following recommendations are based on homogeneous and uniform distributions of the fissionable materials in the moderator.

The critical mass of any process material varies inversely as its density in a manner depending on other characteristics of the assembly; it depends, in a somewhat similar manner, on the isotopic concentration of the fissionable element.

Strong neutron absorbers have not been generally used to increase capacities because they must be homogeneously mixed with the process materials for effects to be predictable, thereby presenting subsequent purification problems. Coating a thin-wall, otherwise unreflected, vessel with cadmium, for example, actually increases the reactivity since additional neutron reflection is provided by the cadmium. If the vessel were submerged in water, the reactivity would

be significantly less with the cadmium than without it. The presence of nitrogen in the nitrate solutions often used in chemical processing, or of Pu^{240} as an impurity in plutonium solutions, increases the margin of safety.

Most homogeneous accumulations of fissionable materials have negative temperature coefficients of reactivity which are due to density changes, including the formation of vapors in liquid systems, and the change in neutron energy distributions. Although this property is important in reactor designs where it facilitates shutdown in case of a power excursion, it does not contribute to the prevention of such excursions. Much damage can occur before the temperature effect begins to control a reaction initiated at a low temperature. The values of the temperature coefficient depend on the material, the geometry of the system, and the temperature range. The presence of resonances in the energy distribution of cross sections may alter the relative importance of the density and neutron energy contributions to the over-all coefficient.

The preceding comments have referred to single volumes. In most plant problems the effect of the exchange of neutrons between individual components of an array of vessels must be considered in order to assure safety in the whole system.

DESIGN CRITERIA

It is possible to avoid nuclear hazards by designing into a process one or more of the full limitations outlined above, but it is equally apparent that the result probably would be very inefficient and uneconomic. The practical approach to design problems has been through a combination of partial limitations whereby each one of several contributes some safety and none is sufficiently stringent to greatly impair the over-all economy.

As mentioned in the Introduction, the bases for the design of equipment and processes for the fissionable isotopes are almost entirely predicated on results from necessarily restricted critical experiments or on interpolations or extrapolations of these results. Many experiments have also been performed which show that particular situations were not critical—important results but of limited application. In spite of an impressive accumulation of background data, many gaps exist which must be covered by extremely conservative estimates. Thus the recommendations given in the succeeding sections are, in some cases, probably overly conservative; it is hoped that none errs in the other direction. Further, in practice, it has been customary to assume operating conditions to be more severe than they probably will be. Most piping, for example, has been designed on the assumption that it may become surrounded by a thick layer of water—perhaps it will because of the rupture of a water main and the stoppage of drains—but a more important reason for such conservative designs is the unknown neutron-reflecting properties of nearby concrete walls, floors, neighboring water lines, and process vessels and of personnel. The recommendations presented below for partial or "nominal" reflectors are truly applicable in borderline cases if the user can assure to his satisfaction that the stated conditions will not be violated. As more confidence is gained, not only in the bases for nuclear safety but also in the predictability of operating conditions, more liberal approaches to the problems will evolve.

INSTRUMENTATION

Radiation-detecting instrumentation is not useful in indicating margins of safety in operations except, possibly, in a few special instances. Any approach to a critical condition is manifested by the multiplication of the ambient neutron field by the fissionable nuclei so some supply of neutrons is necessary in order to detect the multiplying medium. Spontaneous fissions occur in subcritical arrays, frequently at an almost undetectable rate, and the product neutrons produce more fissions, establishing a low-level steady-state activity. In some special cases neutrons may be produced in reactions between the constituents of some process materials—in aqueous solutions of plutonium salts, for example, where the neutrons arise from the interaction of plutonium alpha particles with oxygen. These neutrons can also be multiplied and can establish an activity level which may be detected adequately. As more fissionable material is added to the system, this level increases but usually does not reach

a significant value until the system becomes supercritical. Then, the time rate of change of radiation level increases rapidly. To have observed the changes in the subcritical neutron multiplication would have been practically impossible in most instances because of the low initial level and because it is the rate of change in this level that is indicative of the approach to criticality. A possible solution to this difficulty is the inclusion of a strong neutron source in the system and the observation of changes in the level as material is added. This is the way critical experiments are performed, and experience has shown that the neutron source, the detector, and the fissioning material must be carefully located with respect to each other in order to achieve results which yield meaningful values of the so-called neutron multiplication. To equip process operations in the necessary elaborate manner is generally not practical. Instrumentation has, however, been installed in many operations to indicate the radiation hazard which would exist after a radiation accident had occurred, and reference is made to standard Health Physics procedures for the description of recommended equipment. The utility of other than very specially installed detectors can be summarized by saying they are important after an accident, not in predicting that one is imminent.

CONSEQUENCES OF A NUCLEAR ACCIDENT

It is obviously impossible to predict the results of an accidental accumulation of a supercritical quantity of fissionable material because the neutron background, rate of assembly, type of material, excess mass over that required to be critical, and degree of confinement are among the factors which determine the magnitude of the occurrence. Several supercritical assemblies have occurred, however, in the programs of critical experiments, which perhaps set lower limits on the damage to be expected. These experiments have, for the most part, resulted from the accidental achievement of an effective neutron-reproduction factor only 2 or 3 per cent greater than unity, the value required for the system to be chain-reacting. This condition has resulted from the addition of the order of a few per cent excess mass in experiments where water was present as a neutron moderator. A decrease in the density of the water, due to vaporization and dissociation, was, no doubt, a significant factor in limiting the extent of the excursions. The energy released in each of these accidents has originated in about 10^{17} fissions and amounted to about 1 kw-hr. The containing vessels were open to the atmosphere so no explosion occurred, although vessel deformations were observed. Monitoring equipment has shown the excursions to have been accompanied by neutron and gamma radiation of sufficient intensity to have produced lethal exposures at distances up to a few feet from the source.

It is of interest to consider an example of the margin between a subcritical, "safe" system, and one which is prompt critical, i.e., chain-reacting on prompt neutrons only. The latter is completely out of control. A mass of 2.2 kg U^{235} in an aqueous solution of U^{235} at a concentration of 459 g/liter contained in a cylinder 10 in. in diameter and 3.8 in. high has an effective neutron-reproduction factor of 0.9 when surrounded by a neutron reflector. As increment of 900 g U^{235} will make the reproduction factor unity; i.e., the cylinder will be delayed critical at a height of 5.3 in.; only 67 g additional is now required to make the vessel prompt critical. If the reproduction factor should be made greater than unity by even an infinitesimal amount, the activity would increase with the ultimate release of lethal quantities of radiation. This condition would be reached immediately if the cylinder became prompt critical. It is pointed out that this is a randomly selected example, and there are probably combinations of parameters, certainly with plutonium solutions, where the reactivity is even more sensitive to mass additions.

ADMINISTRATION OF NUCLEAR SAFETY

The administration of nuclear safety practices is determined in detail by the functions of the organization. Those installations having continuing problems as a consequence of their inventory of fissionable materials, or because of frequent alterations in their process, have, in the past, assigned to staff groups the responsibility for advising design and operating personnel in these matters. The infrequent problems of facilities processing only small amounts of material have often been referred to qualified persons in other organizations. A representative

example of the administrative practices in an organization of the former class is described here. It is recognized that modification will be necessary to meet the needs of others.

The responsibility for nuclear safety in the plant considered is placed on line organization. Individuals directing activities of such a nature as to involve nuclear hazards are responsible for control in these activities to the same extent that they are responsible for research, design, maintenance, and operations. An approvals committee, reporting to the plant manager and composed of personnel familiar with the potential hazards and methods of their control, approves the procedures and equipment to be used on the operational processes and in storage and shipment procedures.

In the administration of the safety practice, line supervision responsible for any design or operations obtains approval of those parts which involve nuclear safety. Necessary information is furnished to the approvals committee, including the type, quantity, and chemical composition of the material; its concentrations and density; the dimensions and geometric shapes of the containers; and a flow sheet of the process. The committee investigates each problem, advises the originating group on the hazards which may be incurred, and approves the final design and procedure. In general, such approval specifies necessary operating restrictions.

The nuclear safety of any process will be assured, wherever possible, by the dimensions of the components, such as pipe sizes and container capacities, including spacing between individual components of the same or adjacent systems. Where safety based on geometry alone is precluded, designs may be predicated on batch sizes and/or chemical concentrations, or combinations of them with geometry, and such designs will be considered satisfactory only if two or more simultaneous and independent contingencies must occur to promote a chain reaction. In the use of these nongeometric safety criteria, operational supervision is responsible for accuracy in sampling and analytical procedures.

PART II

BASIC NUCLEAR SAFETY RULES

RULES FOR INDIVIDUAL SYSTEMS

From the discussion of Part I, it is clear that the potential hazard of a system of fissionable material may be influenced by a multitude of factors that defy generalization. Special equipment may be crowded between vessels for emergency repairs; a large bucket may be placed under a leaking geometry-safe column; a janitor may stack spaced cans into a neat pile. A container volume that is safe for all foreseen external conditions may be unsafe with re-entrant water-filled passages. These are examples of the factors not included in the following rules that may lead to difficulty unless margins of safety are generous.

Basic Rules for Individual Systems

Basic regulations for simple, homogeneous, individual systems are stated alternatively as mass limits in Table 1 (kilograms of fissionable isotope), as container capacity limits in Table 2, and as dimensional limits in Tables 3 and 4. References in the tables give critical parameters on which the limits are based and include some supporting calculations. The mass limits include factors of safety of slightly more than 2 as a safeguard against double batching. Capacity limits include factors of safety of at least $1\frac{1}{3}$, and the equivalent margins appear in dimensional limits (even with unspecified dimensions infinite).* Added to normal safety factors are allowances for uncertainties in critical data on which the limits are based.

Specifications are given for various ranges of H/X atomic ratio (X ≡ U^{235}, Pu^{239}, or U^{233}) and for limited types of reflector. Although thick beryllium, D_2O, uranium, or tungsten reflectors are more efficient than thick water,[6] the latter is considered the most effective reflector that is likely to be encountered in ordinary processing or handling operations. "Nominal reflector" refers to water no more than 1 in. thick. Surrounding fissionable metal systems, $1\frac{1}{2}$-in.-thick graphite (or $1\frac{1}{2}$-in.-thick steel) is equivalent in effect to 1-in.-thick water (in small thicknesses water is one of the more effective reflectors). For solutions, equal thicknesses of steel and water are nearly equivalent.[13] "Minimal reflector" refers to no more than $\frac{1}{8}$-in.-thick stainless steel, or the same thickness of other common metal including iron, copper, aluminum, nickel, or titanium. Unless conditions are rigidly controlled, the appropriate limit for thick water reflector should be used for all applications, and for solutions the limit also should be the most restrictive of those given for the various H/X ranges.

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*Upper limits for values in Tables 3 and 4 were obtained from constant-buckling conversions of capacities in Table 2 (for metals, Table 1 volumes increased 50 per cent). Extrapolation lengths used were: 5.5 cm for solutions, 4.1 cm for U^{235} metal, 2.8 cm for Pu^{239} metal, 3.1 cm for U^{233} metal in thick water reflector; 3.5 cm for solutions, 3.2 cm for U^{235} metal, 2.3 cm for Pu^{239} metal, 2.5 cm for U^{233} metal in nominal reflector; 2.4 cm for solutions, 2.2 cm for U^{235} metal, 1.7 cm for Pu^{239} metal, 1.8 cm for U^{233} metal in minimal reflector.

Table 1—MASS LIMITS FOR INDIVIDUAL SYSTEMS

(Maximum mass in kg of X ≡ U^{235}, Pu^{239}, or U^{233})

	Metal, low H mixtures, compounds	Principally hydrogenous compounds, mixtures	Principally solutions	
	0 ≤ H/X ≤ 2	H/X ≤ 20	H/X ≤ 100	H/X unlimited*
U^{235} (Refs. 1–6)				
Thick water reflector	11.0	2.5	0.80	0.35
Nominal reflector (≤ 1 in. water)	15.0	3.5	1.04	0.43
Minimal reflector (≤ 1/8 in. S.S.)	22.0	5.0	1.40	0.55
Pu^{239} (Refs. 4, 6–8)				
Thick water reflector	2.6†	2.2	0.50	0.25
Nominal reflector (≤ 1 in. water)	3.3†	3.2	0.70	0.32
Minimal reflector (≤ 1/8 in. S.S.)	4.4†	4.8	1.00	0.43
U^{233} (Refs. 4, 6, 8–10)				
Thick water reflector	3.0	1.3	0.48	0.25
Nominal reflector (≤ 1 in. water)	4.1	1.7	0.69	0.33
Minimal reflector (≤ 1/8 in. S.S.)	6.0	2.3	0.90	0.45

* See p. 9 for values of H/X beyond which no limit is required.

† These limits apply to Pu metal at ρ = 19.6 g/cm^3; for alloy at ρ = 15.8 g/cm^3, the corresponding limits are 3.5 kg with thick water reflector, 4.8 kg with nominal reflector, and 7.0 kg with minimal reflector.

Table 2—CONTAINER CAPACITY LIMITS FOR INDIVIDUAL SYSTEMS

(Maximum volume in liters)

	Principally solutions		
	20 ≤ H/X	400 ≤ H/X	800 ≤ H/X
U^{235} (Refs. 2–5)			
Thick water reflector	4.8	9.5	20.0
Nominal reflector (≤ 1 in. water)	6.0	11.3	24.0
Minimal reflector (≤ 1/8 in. S.S.)	8.0	14.0	30.0
Pu^{239} (Refs. 4, 7, 8)			
Thick water reflector	3.3	6.8	11.4
Nominal reflector (≤ 1 in. water)	5.0	9.3	14.7
Minimal reflector (≤ 1/8 in. S.S.)	6.6	13.0	19.7
U^{233} (Refs. 4, 9, 10)			
Thick water reflector	2.0	6.0	12.0
Nominal reflector (≤ 1 in. water)	3.0	8.4	14.4
Minimal reflector (≤ 1/8 in. S.S.)	4.0	12.0	18.0

Table 3—SAFE CYLINDER DIAMETERS FOR INDIVIDUAL SYSTEMS

(Maximum diameter of cylinder of fissionable material in inches; for solution, ID of containing cylinder)

	Metal at full density	Principally solutions		
		20 ≤ H/X	400 ≤ H/X	800 ≤ H/X
U^{235} (Refs. 2, 4–6)				
Thick water reflector	2.5	5.0	6.9	9.1
Nominal reflector (≤ 1 in. water)	3.0	5.8	7.7	10.2
Minimal reflector (≤ 1/8 in. S.S.)	3.8	6.7	8.5	11.0
Pu^{239} (Refs. 4, 6–8)				
Thick water reflector	1.4*	4.5	6.1	7.4
Nominal reflector (≤ 1 in. water)	1.7*	5.7	7.2	8.5
Minimal reflector (≤ 1/8 in. S.S.)	2.0*	6.8	8.3	9.6
U^{233} (Refs. 4, 6, 10)				
Thick water reflector	1.5	3.7	5.8	7.4
Nominal reflector (≤ 1 in. water)	1.9	4.7	6.9	8.4
Minimal reflector (≤ 1/8 in. S.S.)	2.3	5.7	8.1	9.4

* These limits apply to Pu metal at ρ = 19.6 g/cm^3; also to be used for alloy at reduced density.

Table 4—SAFE SLAB THICKNESSES FOR INDIVIDUAL SYSTEMS

(Maximum slab thickness in inches)

	Metal at full density	Principally solutions		
		20 ≤ H/X	400 ≤ H/X	800 ≤ H/X
U^{235} (Refs. 4, 6, 11, 12)				
Thick water reflector	0.7	1.4	2.5	4.0
Nominal reflector (≤ 1 in. water)	1.2	2.4	3.6	5.2
Minimal reflector (≤ 1/8 in. S.S.)	2.0	3.3	4.4	6.1
Pu^{239} (Refs. 4, 6–8)				
Thick water reflector	0.2*	1.5	2.5	3.3
Nominal reflector (≤ 1 in. water)	0.5*	2.6	3.7	4.6
Minimal reflector (≤ 1/8 in. S.S.)	0.9*	3.6	4.8	5.6
U^{233} (Refs. 4, 6, 10)				
Thick water reflector	0.2	0.5	1.9	2.9
Nominal reflector (≤ 1 in. water)	0.5	1.7	3.2	4.2
Minimal reflector (≤ 1/8 in. S.S.)	1.0	2.5	4.2	5.1

* These limits apply to Pu metal at ρ = 19.6 g/cm^3; also to be used for alloy at reduced density.

The type of limit most convenient for a given application may be chosen. Mass limits are particularly appropriate for handling of metal or compounds or for processing solution batches where there is no volume or dimensional control. Container capacity limits and "safe" cylinder diameters are best suited for solutions. The principal value of safe slab thicknesses is for the design of catch basins for solutions in case of leakage of the normal container and for the control of isolated metal sheet.

Conditions That Require Special Consideration

The basic rules do not apply to "reactor compositions" such as dilute fissionable material in heavy water, beryllium, or graphite (where D/X, Be/X, or C/X > ~100) or to systems with thick reflectors of these materials, normal uranium, or tungsten.

The rules also fail to apply in the cases in which the densities of fissionable material (vs. H/X) exceed the values[2,7] of Figs. 1 and 2. In the event that the density of fissionable material, ρ, is greater than the density, ρ_0, from Figs. 1 or 2, mass limits of Table 1 should be reduced by the ratio $(\rho_0/\rho)^2$, the container volume limits of Table 2 by $(\rho_0/\rho)^3$, and the container linear dimension of Tables 3 and 4 by (ρ_0/ρ). If ρ is less than ρ_0, limits must not be increased by these ratios.

Again, the rules for nominal or minimal reflector, or for solutions in a limited range of H/X, may be applied only if these conditions are rigidly controlled.

Conditions Under Which Basic Limits Are Not Required

For solutions or other homogeneous hydrogenous mixtures, no further restriction is required[14] if (1) for U^{235}: the atomic ratio $H/U^{235} \geq 2300$, which corresponds to the concentration $c(U^{235}) \leq$ g/liter in aqueous (light water) solution; (2) for Pu^{239}: $H/Pu^{239} \geq 3600$, which corresponds to $c(Pu^{239}) \leq 7.8$ g/liter in aqueous solution; and (3) for U^{233}: $H/U^{233} \geq 2300$, which corresponds to $c(U^{233}) \leq 11$ g/liter in aqueous solution. These values contain no factor of safety; in application a margin compatible with control errors should be maintained.

Any mass of natural or depleted uranium homogeneously distributed in light water is safe.

Uranium in which the atomic ratio U^{235}/U^{238} is equal to or less than 0.05 needs no further restriction provided it is (1) in the form of metal with no interspersed hydrogenous material, e.g., a single piece; (2) in a nonhydrogenous chemical compound; or (3) intimately mixed, either as metal or a nonhydrogenous compound, with any element of atomic number, Z, greater than 13 if the atomic ratio $Z/U^{235} \leq 100$ (Ref. 8).

Conditions Under Which Basic Limits May Be Increased

For certain intermediate shapes of fissionable system, such as elongated or squat cylinders, mass and container capacity limits may be increased by the appropriate factor[4,6,7] from Fig. 3.

For undiluted fissionable metal* at density less than normal (17.6 g/cm^3 for U^{235}, 19.6 g/cm^3 for Pu^{239}, and 18.3 g/cm^3 for U^{233}), such as metal turnings, the mass limit may be increased by the appropriate factor[6] from Fig. 4. Factors from this figure also may be applied to solutions with uniformly distributed voids ($\leq$ 1 in. in one dimension), for which $H/X \geq 100$, provided "fraction of total density" is interpreted as the ratio of average density of solution plus void to the solution density.[13] Figure 5 shows factors by which the mass limits in the first column of Table 1 may be increased if fissionable atoms are mixed uniformly with any of the listed elements either as physical mixtures or chemical compounds.[8,15] It is emphasized that no H_2, D_2, or beryllium can be present if these factors are applied. Although intended primarily for homogeneous systems, these factors may be used for similar units of X distributed uniformly in the diluent provided one dimension of the unit does not exceed $\frac{1}{8}$ in. for U^{235} or $\frac{1}{16}$ in. for

* Uranium metal enriched in U^{235} is sometimes referred to as "Oralloy," abbreviated Oy, with a suffix designating the U^{235} enrichment. For example, Oy(93) indicates uranium that is 93 wt. % U^{235}.

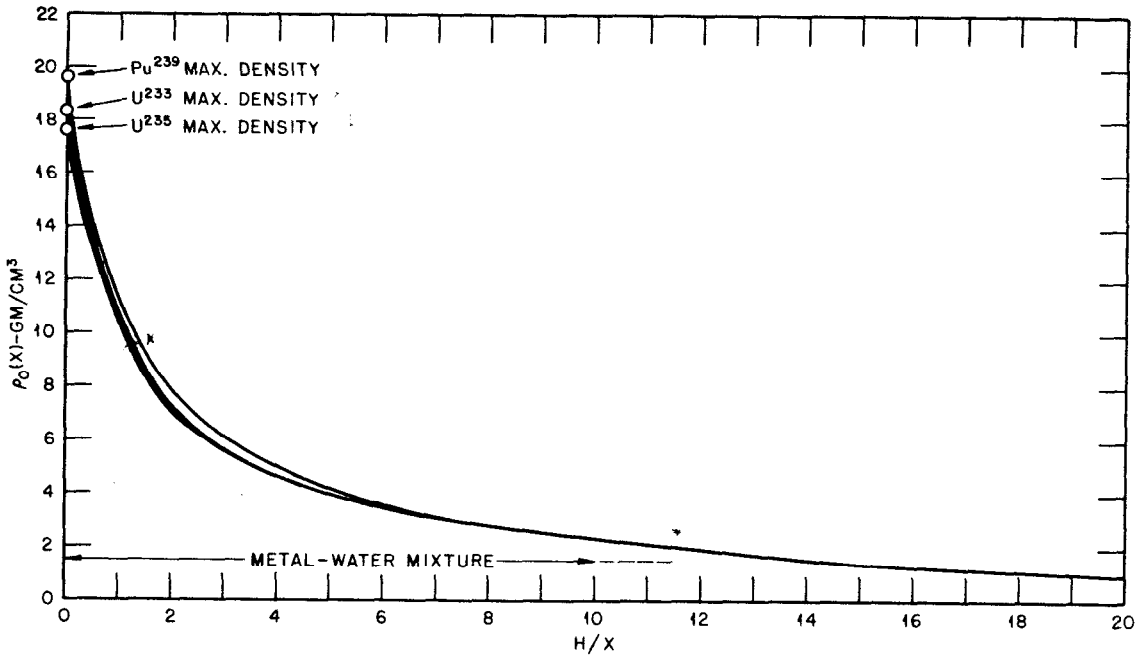


Fig. 1—Assumed densities of U^{235}, Pu^{239}, or U^{233} at $H/X \leq 20$. (If a density exceeds the indicated value by the ratio n, reduce mass limits by the factor $1/n^2$, volume limits by $1/n^3$, and linear dimension limits by $1/n$.)

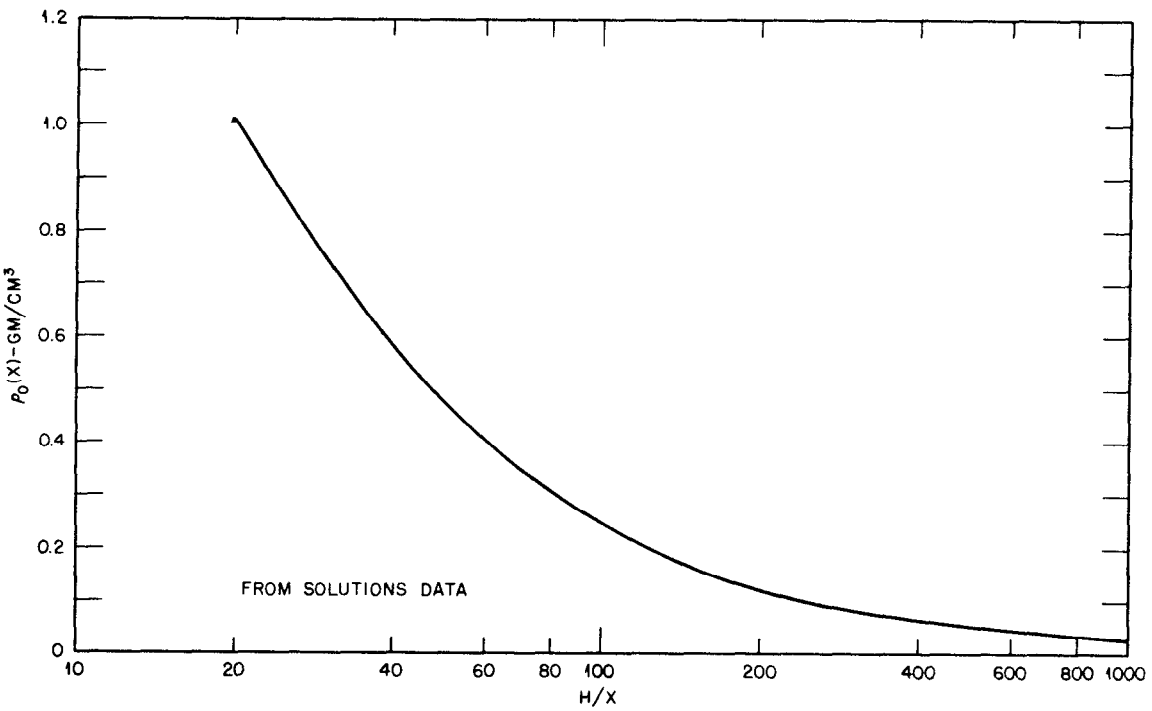


Fig. 2—Assumed densities of U^{235}, Pu^{239}, or U^{233} at $H/X \geq 20$. (If a density exceeds the indicated value by the ratio n, reduce mass limits by the factor $1/n^2$, volume limits by $1/n^3$, and linear dimension limits by $1/n$.)

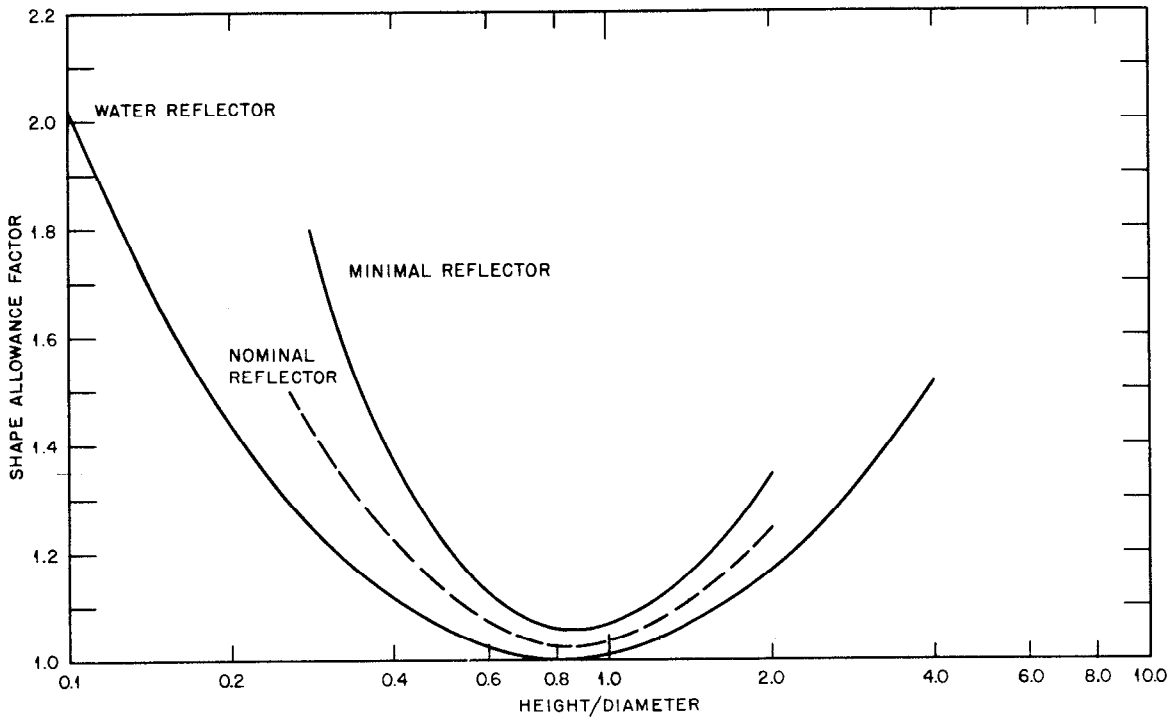


Fig. 3—Shape allowance factors for cylinders (factor by which mass and volume limits may be increased for elongated or squat cylinders).

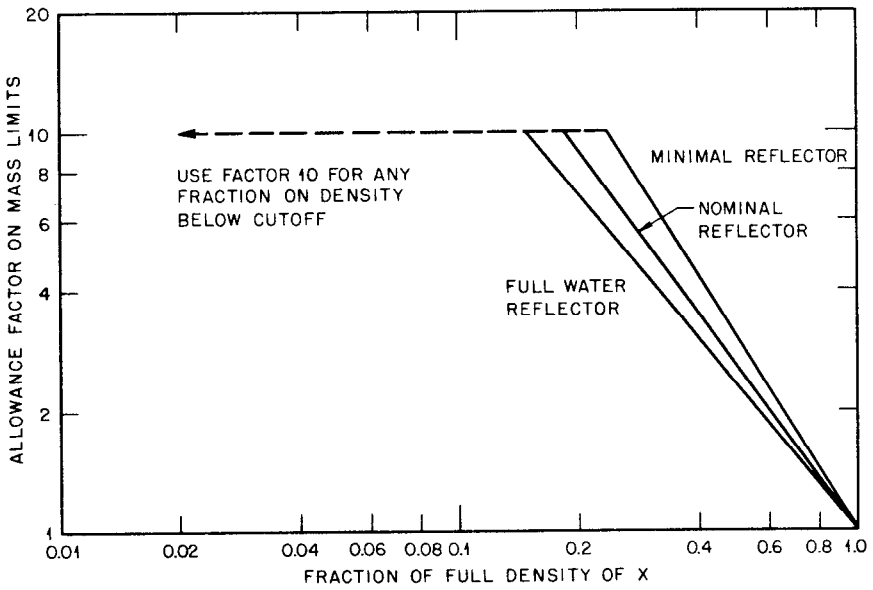


Fig. 4—Allowance factors for reduced density of U^{235}, Pu^{239}, and U^{233} as metal only. Full U^{235} density = 17.6 g/cm^3, full Pu^{239} density = 19.6 g/cm^3, and full U^{233} density = 18.3 g/cm^3.

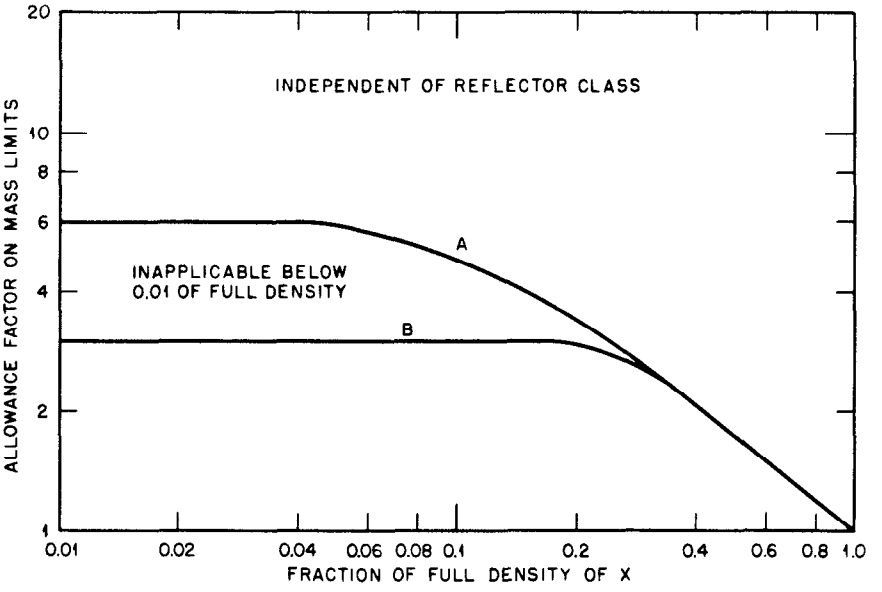


Fig. 5—Allowance factors for reduced density of U^{235}, Pu^{239}, or U^{233} mixed homogeneously with elements listed (H, D, and Be excluded). Curve A: any element for which $11 \leq Z \leq 83$ (from Na to Bi). Curve B: compounds of X and C, N, O, F, and elements $11 \leq Z \leq 83$, with at least 1 atom of X per 7 others, e.g., UC, UO_2, U_3O_8, UO_3, UO_2F_2, UF_4, and UF_6). Full U^{235} density = 17.6 g/cm^3, full Pu^{239} density = 19.6 g/cm^3, and full U^{233} density = 18.3 g/cm^3.

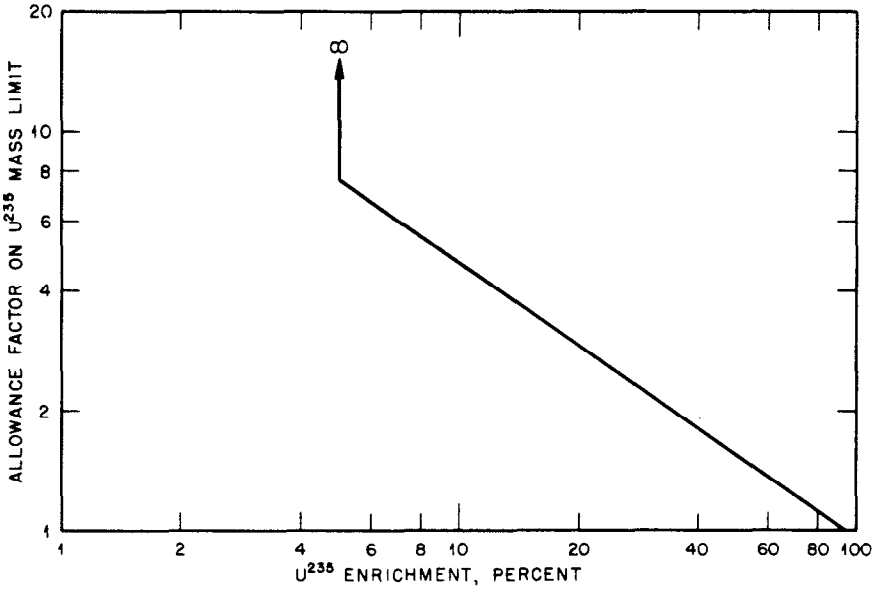


Fig. 6—Allowance factors on U^{235} mass limits for uranium metal at intermediate U^{235} enrichments.

Pu^{239} or U^{233}. (The factors are not applicable to mixtures having X densities less than 1 per cent of the full density in order to guard against moderation by relatively large proportions of nuclei of intermediate atomic number.)

In the special case of undiluted uranium metal in which the U^{235} content is less than 93 per cent, the U^{235} mass limit may be increased by the appropriate factor[6] from Fig. 6. A factor for reduced density of total uranium (not U^{235}), from Fig. 4, may be applied in addition to this enrichment factor.

As stated before, the mass limits of Table 1 contain a factor of safety of slightly more than 2 as protection against a double-batching error. (The capacity limits have a somewhat smaller safety factor.) Where the possibility of over-batching is excluded, the basic mass limit may be increased by the factor 1.5.

RULES FOR INTERACTING UNITS

General Criteria

Empirically formulated specifications for the spacing of individually subcritical units in an array which is also subcritical have been established.[16–19] These specifications are predicated on the assumptions that the over-all neutron multiplication factor, k, of several vessels is determined by the values of k of the individual components and by some probability that neutrons leaking from one vessel will be intercepted by another. This probability, in turn, is related to a geometric parameter which is a simplified expression for the total solid angle subtended at the most centrally located unit by the other components of the array. In the method referred to here this solid angle is calculated by a "point-to-plane" method where the point is on the most centrally located unit and the planes either define the boundaries of the other units or are appropriate projections of the boundaries. Examples of this calculation are given in Fig. 7. The total solid angle is, of course, the sum of the angles subtended by the individual units.

Currently applicable specifications for unit spacings are determined by a method, detailed in the above references, in which the reactivity of each unit is estimated by a two-group diffusion theory and the total solid angle then set by an empirical relation. This method is strongly supported by extensive experimental measures of the critical conditions of a large assortment of arrays of various shaped vessels containing U^{235} in a variety of forms.[5,20,21]

For the purposes of this Guide a total solid angle of one steradian is selected as a conservative limit on the solid angle, calculated by the method described above, subtended at the unit which "sees" the others to the greatest extent. The units referred to here are those described in Tables 1 to 4, including appropriate allowance factors. In calculating the total solid angle, fully shielded units may be ignored; e.g., the first and fifth of five identical cylinders with axes coplanar do not contribute to the solid angle at the center one. In those instances where flooding of the array by water is a possibility, a concomitant specification is the requirement that each vessel be spaced from its nearest neighbor by at least 12 in. or by 8 in. if there are only two units. This specification is based on the observation that these thicknesses of water or materials of comparable hydrogen density effectively isolate the unit.[20,22]

Storage and Transportation Rules for Special Units

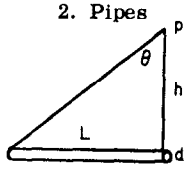
Consideration, based on experiments to establish storage and transportation rules, is given here to arrays of units of relatively small volume and possibly high density. It is assumed that the control of the size of individual units is more stringent than in the production operations of a process, thereby allowing a relaxation of the double-batching safety factors imposed above. It is further assumed that the units are either bare or are in relatively light containers (nominal reflectors) and are spaced by birdcages, compartments, or specifically located anchorages. Table 5 specified maximum units of this class. These units may be in-

A. Formulae

1. General

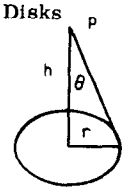
$$\Omega = \frac{\text{Cross Sectional Area}}{(\text{Separation Distance})^2}$$

2. Pipes



$$\Omega = \frac{d}{h} \sin \Theta$$

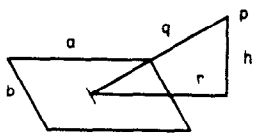
3. Disks



$$\Omega = 2\pi (1 - \cos \Theta)$$

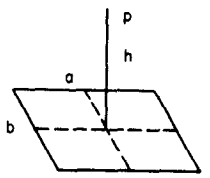
4. Planes

a.



$$\Omega = \frac{ab \cos \Theta}{q^2}$$

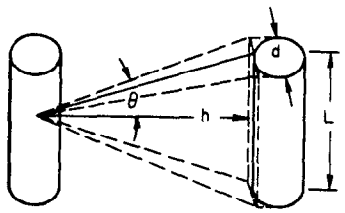
b.



$$\Omega = 4 \sin^{-1} \frac{\left(\frac{a}{2}\right) \left(\frac{b}{2}\right)}{\sqrt{\left(\frac{a}{2}\right)^2 + h^2} \sqrt{\left(\frac{b}{2}\right)^2 + h^2}}$$

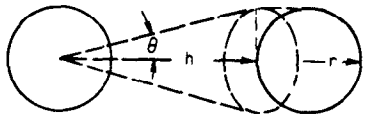
B. Applied Methods

1. Cylinders



$$\Omega = \frac{2d}{h} \sin \Theta$$

2. Spheres



$$\Omega = 2\pi (1 - \cos \Theta)$$

Fig. 7—Solid angle calculations.

Table 5—MAXIMUM SIZES OF UNITS TO WHICH TABLES 6 AND 7 APPLY

	Maximum unit*		
	U^{235}	Pu^{239}	U^{233}
Metal, compounds, or mixtures, H/X ≤ 2; mass limits, kg†	18.5‡	4.5§	4.5
Hydrogenous compounds or mixtures, 2 < H/X < 20; mass limits, kg†	4.5	4.5	2.5
Solutions, or hydrogenous mixtures, H/X ≥ 20, in non-safe containers;¶ volume limits, liters	4.0	4.0	2.0

* If density (ρ) is greater than the reference value (ρ_0) in Fig. 1 or 2, reduce mass limits by the factor $(\rho_0/\rho)^2$, volume limits by $(\rho_0/\rho)^3$.

† Material volume of unit is not to exceed 4.5 liters.

‡ This corresponds to 20 kg of uranium enriched to about 93 per cent in U^{235}.

§ This limit holds for Pu metal at $\rho = 19.6$ g/cm^3; for the alloy at $\rho = 15.8$ g/cm^3, the corresponding limit is 6.0 kg.

¶ For safe containers defined in Table 3, there is no mass or volume limit for stable solutions (H/X ≥ 20).

creased by the shape allowance factors of Fig. 3 and the metal density and U^{235} enrichment factors of Figs. 4 to 6 but not, of course, by the allowance for perfect batch control.

Again, certain reactor compositions, as dilute mixtures with D_2, beryllium, or carbon, must be treated as special cases.

Storage

The storage rules of Table 6 allow a factor of safety greater than 2 (in number of units) for arrays in a concrete vault that is not less than 9 ft in smallest dimension. Arrays that are safe in a concrete vault also will be safe in vaults of other materials such as steel, wood, or earth. For convenience the storage rules are given in terms of number of maximum units at a given center-to-center spacing between units. A maximum unit may consist of a close-packed group of smaller units provided the total quantity specified for a maximum unit is not exceeded. Storage arrays defined in Tables 5 and 6 will be safe if fully flooded by water provided the edge-to-edge separation between maximum units is at least 12 in. and not more than 10 per cent of the volume of composite units can be occupied by water.

Isolated and associated arrays referred to in Table 6 are described in the following manner. Two arrays are effectively isolated from one another if they are completely separated by concrete at least 8 in. thick.[22] Two plane (i.e., items with centers coplanar) or cubic (i.e., items with centers in three dimensions) arrays are also isolated if the separation (minimum edge-to-edge spacing between any unit in one array and any unit in the other) is the larger of the following quantities: (1) the maximum dimension of one array and (2) 12 ft (Ref. 23). Two linear arrays are isolated regardless of length if the separation is at least 12 ft. Nonisolated plane arrays are associated if the minimum edge-to-edge spacing between units in the two arrays is at least 7½ ft.

Transportation

Table 7 is a set of rules for shipment of units of fissionable materials defined in Table 5. "Maximum density established by birdcage or shipping case" is based on a unit packaged in a 20-in. birdcage.

Table 6 — LIMITS FOR STORAGE ARRAYS OR UNITS DEFINED IN TABLE 5

Type of array	Minimum center-to-center spacing of units within array, in.*	Storage limit per array (No. of max. storage units)†
Isolated linear or plane array	≥ 16	No limit
Isolated cubic array	36	200
	30	120
	24	80
	20	50
Two associated plane arrays	30	120/array, 240 total‡
	24	90/array, 180 total‡
	20	50/array, 100 total‡

* Edge-to-edge separation of units must be at least 12 in.

† In the case of safe containers for solution ($H/X \geq 20$) defined in Table 3, there is no limit for a parallel in-line array at a minimum axis-to-axis spacing of 24 in. or for two associated in-line arrays where the spacing in each array is 24 in.

‡ The same total storage limit applies to more than two associated arrays.

Table 7 — LIMITS FOR SHIPMENTS OF UNITS DEFINED IN TABLE 5

	Max. density established by birdcage or shipping case*			Normal carload limit (50 max. shipping units except for safe cylinders)†		
	U^{235}	Pu^{239}	U^{233}	U^{235}	Pu^{239}	U^{233}
Metal, compounds or mixtures, $H/X \leq 2$; mass limits	4 kg/ft^3	1 kg/ft^3	1 kg/ft^3	925 kg/car	225 kg/car	225 kg/car
Hydrogenous compounds or mixtures, $2 < H/X \leq 20$; mass limits	1 kg/ft^3	1 kg/ft^3	0.5 kg/ft^3	225 kg/car	225 kg/car	125 kg/car
Solutions, or hydrogenous mixtures, $H/X \geq 20$, in non-safe containers‡	0.8 liter/ft^3	0.8 liter/ft^3	0.4 liter/ft^3	225 liters/car	225 liters/car	100 liters/car

* This density is (mass of unit)/birdcage volume; birdcages or cases shall define at least 1 ft edge-to-edge separation between units; unit container shall be sealed against inleakage of water.

† For combined shipping (excluding safe cylinders), the carload limit is any combination of 50 appropriate maximum shipping units (or the equivalent in smaller units); the listed mass limits increase if allowance factors are applied to the shipping units of Table 5.

‡ For the safe solution cylinders of Table 5, the storage conditions of Table 6 may be used for transportation provided spacings are expected to be maintained in case of accident.

The assumption underlying these rules is that the integrity of birdcages or shipping cases and of the sealed container will be preserved, but the possibility of accidental flooding or the combination of the contents of two carriers is admitted. "Carload limits" in Table 7 allow a normal factor of safety of at least 4, of which a factor of 2 is for the combination of two carloads. If flooded, individual units will be less than 80 per cent of the critical mass, and requirements are such that units will not interact through the intervening water.

PART III

APPLICATION OF PROCESSING PLANTS

GENERAL DISCUSSION

It should be emphasized again that the typical process plant contains a crowded arrangement of tanks, pipes, and columns with interconnections and nearby structures instead of the simple, isolated units of Part II. Because of the complexity of some process layouts, nuclear measurements on portions of the system mocked up in a critical assembly laboratory may be necessary to utilize, in the most advantageous manner, available plant floor area and equipment. In some cases where this procedure is impractical, it may be desirable to make controlled *in situ* measurements within a plant. The latter method has been used effectively.

Generally, however, safe, but perhaps overconservative, restrictions for plant equipment can be established in terms of the rules stated above for simple systems. For example, an isolated cylinder of rectangular cross section will obviously be safe if the diagonal dimension does not exceed the diameter of a safe circular cylinder. For the evaluations of multiple unit systems, Rules For Interacting Systems, Part II, may be applied.

Incidental Reflectors

A wall of concrete, steel, or wood (or the equivalent in columns, etc.) within six volume-average radii of the center of a vessel increases minimal inherent reflection to nominal effective reflection, or nominal inherent reflection to the equivalent of full-water reflection.[24] It does not influence a system with the equivalent of a full-water reflector. Beyond six volume-average radii the effect of such a structure may be ignored. For nominally or fully water reflected systems, the effect of extraneous human body reflection may be neglected provided the bodies in question are not in gross contact with the systems.

Minimal reflector conditions rarely occur in a chemical processing plant. A system which by itself has this type of reflector is quite sensitive to interaction with other process vessels containing fissionable material and to the effects of incidental (or accidental) reflectors.

Adaptation to Standard Volumes and Pipe Sizes

In principle, the limits of Tables 1 to 4 might be represented as a series of curves as a function of H/X atomic ratios. In view, however, of gaps in experimental data on which tables are based (and of the relative ease of scanning compact tables), it is believed that finer subdivisions than afforded by these tables are not presently justified. In applications to plant equipment there will be situations where the appropriate limit of Table 2 will fall just below the volume of a convenient standard vessel or where the safe dimensional limit of Table 3 is slightly smaller than a standard pipe or tubing diameter. In such a case it is suggested that a nuclear safety specialist help determine whether there may be safe adjustment to the size of

standard equipment. It should be emphasized that linear interpolation between some of the tabulated limits in Part II will be unsafe.

RULES FOR SPECIAL SYSTEMS

This section contains rules for a few specific situations occurring in plants that are not covered by the generalizations of Part II.

Pipe Intersections

Table 8 describes conservative uniform pipe intersections for aqueous solutions of U^{235}, Pu^{239}, and U^{233} salts.[25] These data do not apply to metals. The examples may be extended to nonuniform intersections by the method outlined in the reference.

Table 8—CONSERVATIVE INSIDE PIPE DIAMETERS (IN INCHES) FOR UNIFORM 90-DEG INTERSECTIONS CONTAINING FISSIONABLE SOLUTIONS ($H/X \geq 20$)

	U^{235}	Pu^{239}	U^{233}
Tees:			
Full water reflector	3.5	3.2	2.6
Nominal reflector (≤ 1 in. water)	4.1	4.0	3.3
Minimal reflector (≤ 1/8 in. S.S.)	4.7	4.8	4.0
Crosses:			
Full water reflector	2.9*	2.6	2.1
Nominal reflector (≤ 1 in. water)	3.3	3.3	2.7
Minimal reflector (≤ 1/8 in. S.S.)	3.9*	3.9	3.3

*Experiments indicate that these values are highly conservative.

If a pipe is to contain multiple intersections, no two intersections may occur within 18 in. (axis-to-axis) of one another.

Metal Machine Turnings

Machine turnings immersed in a hydrogenous moderator should be handled in the same manner as aqueous solutions of the metal salts. Table 1 applies if densities are consistent with Fig. 2 (Ref. 26).

Compounds and Solutions of U^{235}

Safety specifications applicable to chemical compounds and aqueous solutions of U^{235} have been published.[27]* These limits, applicable to dry compounds in which the uranium density is no greater than 3.2 g/cm^3 and to solutions and mixtures with water having uranium densities characterized by typical solubility relations, can be used extensively by uranium processing plants. Tables 9 and 10 are typical examples, in condensed form, of the nuclear safety limits presented in this reference.

*This document, which undergoes revision as new basic data become available, provides an excellent illustration of nuclear safety regulations for a specific class of operations.

Table 9—MASS LIMITS FOR MIXTURES OF U^{235} AS UF_6 AND HYDROGENOUS MATERIAL, $H/U^{235} \leq 10$
(For any reflector class)

Max. uranium density, g/cm^3	H/U^{235} atomic ratio	Safe mass kg U^{235}
1.8	10	5.0
2.3	5	9.4
2.6	3	14.3
2.8	2	20.0
3.0	1	28.5
3.2	0.1	39.8
3.2	0.01	43.0

Table 10—DEPENDENCE OF SAFE MASS, VOLUME, AND CYLINDER DIAMETER ON U^{235} CONTENT OF URANIUM
(For total uranium densities that do not exceed 1.07 times the values for U^{235} in Figs. 1 and 2, any H/U^{235} ratio, and thick water reflector)

U^{235} content of uranium, wt.%	Mass, kg U^{235}	Volume, liters	Cylinder I.D., in.
40	0.41	6.7	6.0
20	0.48	9.5	6.9
10	0.60	14.0	8.2
5	0.80	27.0	10.2
2	2.00	27.0	10.2
0.8	36.00	27.0	10.2
$\leq 0.7_1$	Infinite	Infinite	Infinite

Table 11—BATCH LIMITS FOR URANIUM METAL IN WATER
(U^{235} Enrichment = 1.03 per cent)

Solid rod diameter, in.	U^{235} batch limit, kg
0.39	8.1
0.60	6.9
0.75	7.1
0.93	8.1
1.66	13.1

Uranium Metal, Low U^{235} Content

The critical mass of uranium metal rods only slightly enriched in U^{235} and dispersed in water depends on the dimensions of the units and the manner in which they are arranged. Permissible batch sizes of solid metal rods, enriched to 1.03 per cent in U^{235}, of several diameters, and latticed in water in the manner giving the greatest reactivity, are listed in Table 11. It is emphasized that these values refer to solid rods. Annular pieces of uranium metal have smaller critical masses than do solid pieces having the same outside diameter.

EXAMPLES OF PLANT APPLICATION

This section contains several problems typical of those arising in chemical or metallurgical plants processing sizable quantities of fissionable materials.

Pouring Crucible and Mold Limits for 40 Per Cent Enriched-uranium Metal

The problem is to suggest the weight of a safe charge of uranium containing 40 wt.% U^{235} and 60 wt.% U^{238} in a large pouring crucible and mold having no safety features imposed by their shape. Graphite crucible and mold walls plus insulation and heating coils are sufficiently thin to be classed as nominal reflector, and there is no possibility of internal flooding.

The basic mass limit from Table 1 is 15.0 kg U^{235} for nominal reflector. Figure 6 then gives an allowance factor of 1.8 for reduction of U^{235} concentration from ~93 to 40 per cent. This leads to an allowable charge of 27 kg U^{235} which corresponds to 67 kg of uranium of this enrichment.

Pouring Crucible and Mold Limits for a 10 Wt.% U^{235} – 90 Wt.% Aluminum Alloy

The problem is to suggest a safe charge weight of a 10 wt.% U^{235} – 90 wt.% aluminum alloy for a melting crucible and mold with compact shapes. As crucible and mold walls, etc., exceed 2 in. in thickness, the equivalent of full-water reflection must be assumed. Charge is to be introduced as the alloy, and melting and casting conditions are controlled to avoid segregation. There is no possibility of flooding within the furnace.

The volume fraction of U^{235} in this alloy (or the fraction of full U^{235} density) is about 0.016. From Table 1 the basic mass limit is 11 kg U^{235}, and Fig. 5 gives an allowance factor of 6 for aluminum dilution. Thus the limit is 66 kg U^{235} which corresponds to about 660 kg of alloy. [*Note:* If the alloy were to be compounded during melting, the allowance factor would be disregarded and the limit would be 11 kg U^{235} (thick aluminum reflector is less extreme than thick water)].

Pulse Column (Infinite Pipe System)

The problem is to choose a safe diameter for a pulse column given the following pertinent data:

1. The column, $^3/_{32}$-in.-thick stainless steel, is to be mounted against a concrete wall at a distance of six column radii (column is not to be recessed into a cavity).
2. There are no other interacting columns or tanks, and the possibility of flooding is excluded.
3. The concentration of U^{235} occurring in the column is not to exceed 150 g U^{235} per liter of solution.
4. The column length is 5 ft or more and must be considered effectively infinite.

The safe diameter is 6.7 in., from Table 3 and Fig. 2.

CAUTION: It is common practice to design a pulse column with phase separation units at the top and bottom of the column, which are of larger diameter than the column proper. It is to be understood that the 6.7 in. diameter is the maximum safe diameter for all parts of the system.

Determination of a Safe Batch Size for Enriched-uranium Slugs in a Chemical Plant Dissolver

This final example illustrates both the relatively sophisticated approach that some nuclear safety problems require and a method by which the recommendations in Table 11 were derived.

It is known that natural uranium containing 0.71 wt.% U^{235} cannot be made critical when homogeneously distributed in a water moderator; thus a chemical plant may be designed for processing this kind of uranium with no concern for critical mass problems. Sometimes it is desirable to use slightly enriched uranium in reactors, and the question then arises of how enriched slugs may be safely processed. The following problem is considered. Slugs of 1.36 in. in diameter and containing 1 wt.% U^{235} are to be dissolved in a large tank. Large numbers of natural-uranium slugs may also be undergoing dissolution in the same tank. The slugs are to be dumped into the tank; their positions with respect to one another are uncontrolled. How many 1 per cent slugs may safely be dissolved at one time?

First disregard the presence of natural uranium-slugs. Then the problem is: what is the minimum critical mass of 1 per cent uranium in a water system? The system may be a uniform solution; it may be a solution of uranium in water in a roughly spherical shape surrounded by a full-water reflector; it may be an array of slugs with any diameter up to 1.36 in. surrounded by full-water reflector; or it may be any mixture of the above three possible configurations.

Calculations show that, for this degree of enrichment, the inhomogeneous system consisting of a lattice of slugs in water will have a higher reactivity than a homogeneous solution. This results from the larger value of the resonance escape probability for a lattice. We thus reduce the problem to finding the highest reactivity or buckling possible in a water-uranium lattice of rods in which the lattice spacing and the rod diameter are variable (the rods up to 1.36 in.). Experimental measurements on lattices of this type are available.[28,29] From these it is found that the maximum buckling obtainable with 1 per cent uranium is about 3600×10^{-6} cm^{-2} with a rod diameter of about 0.75 in. in a lattice with a water-to-uranium volume ratio of 2:1. Since the experiments were done with uranium clad in aluminum jackets, it is necessary to raise the value of the buckling to about 4100×10^{-6} cm^{-2} for a pure uranium-water system.

With this number, we are in a position to specify safe numbers of slugs. A simple calculation shows that 3490 lb of uranium will go critical if the lattice has near spherical shape and is fully reflected by water. This is equivalent to 435 slugs, each 8 in. long. If the possibility of double batching in the dissolver cannot be excluded, then this number should be halved. It is thus concluded that a safe batch size is about 200 slugs. Some additional safety factor is present since this specification is based on charging slugs of 1.36 in. in diameter. By the time the slugs are dissolved down to the optimum diameter, some of the uranium is in solution and some in slugs. This is a less reactive situation than if this total amount of uranium were all in the form of slugs of the optimum size.

We have not yet considered the effects which may be caused by a natural-uranium reflector that may be present in the dissolver. Experiments with aluminum-uranium alloy slugs reflected with closely packed natural-uranium slugs in a water system show that the critical mass is approximately halved.[30] Calculations on the present type slugs give about the same result. Thus, if natural uranium is also present in large amounts in the dissolver, the safe batch size for enriched slugs should be reduced to 100. If the natural-uranium slugs can assume some optimized latticed arrangement, thereby contributing substantially to the over-all reactivity, the critical number of enriched slugs may be reduced still further. If this extreme situation is considered likely, the batch size should be set at about 70 slugs.

An alternate method of ensuring safety in this dissolver would be to introduce a geometric constraint on the slugs. A cylinder with porous walls might be inserted to maintain a fixed radius for the configuration of the slugs and yet permit free circulation of the dissolving solution. According to the maximum buckling quoted above, the radius of this cylinder would be 11 in. Here, only water reflector is allowed for. So long as this radius could be maintained, no restriction on the number of slugs is necessary.

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REFERENCES

1. C. K. Beck, A. D. Callihan, and R. L. Murray, Critical Mass Studies, Part I, Report A-4716, June 1947.
2. C. K. Beck, A. D. Callihan, J. W. Morfitt, and R. L. Murray, Critical Mass Studies, Part III, Report K-343, April 1949.
3. J. R. Brown, B. N. Noordhoff, and W. O. Bateson, Critical Experiments on a Highly Enriched Homogeneous Reactor, Report WAPD-128, May 1955. (Classified.)
4. A. D. Callihan, Nuclear Safety in Processing Reactor Fuel Solutions, Nucleonics, 14(7): 39 (July 1956).
5. J. K. Fox, L. W. Gilley, and D. Callihan, Critical Mass Studies, Part IX, Aqueous U^{235} Solutions, Report ORNL-2367, February 1958.
6. H. C. Paxton, Critical Masses of Fissionable Metal as Basic Nuclear Safety Data, Report LA-1958, January 1955.
7. F. E. Kruesi, J. O. Erkman, and D. D. Lanning, Critical Mass Studies of Plutonium Solutions, Report HW-24514, May 1952. (Classified.)
8. G. Safonov, Survey of Reacting Mixtures Employing U^{235}, Pu^{239}, and U^{233} for Fuel and H_2O, D_2O, Carbon, Beryllium, and BeO for Moderator, Report R-259, January 1954. (Classified.)
9. A. D. Callihan, J. W. Morfitt, and J. T. Thomas, Small Thermal Homogeneous Critical Assemblies, Paper UN-834, International Conference on the Uses of Atomic Energy, June 1955.
10. J. K. Fox, L. W. Gilley, and E. R. Rohrer, Critical Mass Studies, Part VIII, Aqueous Solutions of U^{233}, Report ORNL-2143, August 1956.
11. J. K. Fox, L. W. Gilley, and J. H. Marable, Critical Parameters of a Proton Moderated and Proton Reflected Slab of U^{235}, Report ORNL-2389, October 1957, p. 87.
12. F. F. Hart, Safety Tests for Melting and Casting Oralloy, Report LA-1623, December 1953.
13. A. D. Callihan, D. F. Cronin, J. K. Fox, and J. W. Morfitt, Critical Mass Studies, Part V, Report K-643, June 1950.
14. J. T. Thomas, Limiting Concentrations for Fissile Isotopes, Report ORNL-2081, November 1956, p. 78.
15. H. C. Paxton, Estimated Critical Masses of Diluted Oralloy, Report N-2-263, July 1956.
16. H. F. Henry, J. R. Knight, and C. W. Newlon, General Application of a Theory of Neutron Interaction, Report K-1309, November 1956.
17. H. F. Henry, C. E. Newlon, and J. R. Knight, Self-consistent Criteria for Evaluation of Neutron Interaction, Report K-1317, December 1956.
18. H. F. Henry, C. E. Newlon, and J. R. Knight, Application of Interaction Crtieria to Heterogeneous Systems, Report K-1335, June 1957. (Classified.)
19. J. A. Pond, Critical Geometries for Bare Cylinders, Report GAT-189, July 1956.
20. J. K. Fox and L. W. Gilley, Applied Nuclear Physics Division Annual Report for Period Ending Sept. 10, 1956, Report ORNL-2081, November 1956, p. 63.
21. J. K. Fox and L. W. Gilley, Applied Nuclear Physics Division Annual Progress Report for Period Ending Sept. 1, 1957, Report ORNL-2389, October 1957, p. 77.
22. C. L. Schuske, M. G. Arthur, and D. F. Smith, Rocky Flats Plant Report, CD56-869, July 1956. (Classified.)
23. C. L. Schuske, Rocky Flats Plant Report, RFP-59, February 1956. (Classified.)
24. J. K. Fox and L. W. Gilley, Physics Division Semiannual Progress Report for Period Ending Mar. 10, 1955, Report ORNL-1926, September 1955, p. 2.
25. C. L. Schuske, An Empirical Method for Calculating Subcritical Pipe Intersections, Rocky Flats Plant Report, TID-5451, July 1956. (Classified.)
26. J. D. McLendon and J. W. Morfitt, Critcal Mass Tests on U^{235} Machine Turnings, Report Y-A2-71(Del.), February 1952.

27. H. F. Henry, A. J. Mallett, and C. E. Newlon, Basic Critical Mass Information and Its Application to K-25 Design and Operation, Report K-1019, Fourth Revision, August 1957. (Classified.)
28. E. D. Clayton, Physics Research Quarterly Report, Report HW-42183.
29. H. Kouts, G. Price, K. Downes, R. Sher, and V. Walsh, Exponential Experiments with Slightly Enriched Rods in Ordinary Water, Paper UN-600, International Conference on Peaceful Uses of Atomic Energy, June 1955.
30. A. D. Callihan, D. F. Cronin, J. K. Fox, J. W. Morfitt, E. R. Rohrer, and D. V. P. Williams, Critical Mass Studies, Part VI, Report Y-801, August 1951. (Classified.)

Selected Reading List

Included are documents giving background information but to which specific reference is not made in the text. For completeness it has been necessary to include in this List a number of classified references and a few which received limited distribution. The authors regret that all the information may not be available to every reader.

C. K. Beck, A. D. Callihan, and R. L. Murray, Critical Mass Studies, Part II, Report K-126, January 1948.

A. D. Callihan, D. F. Cronin, J. K. Fox, R. L. Macklin, and J. W. Morfitt, Critical Mass Studies, Part IV, Report K-406, November 1949.

A. D. Callihan and D. F. Cronin, Critical Experiments with Uranium of Intermediate U^{235} Content, Report ORNL-55-10-97, October 1955. (Classified.)

L. W. Gilley and A. D. Callihan, Nuclear Safety Tests on a Proposed Ball Mill, Report ORNL-54-9-89, September 1954.

R. Gwin and W. T. Mee, Critical Assemblies of U^{235}, Report Y-A2-124(Del.), September 1953.

E. C. Mallary, H. C. Paxton, and R. H. White, Safety Tests for the Storage of Fissile Units, Report LA-1875, February 1955. (Classified.)

J. J. Neuer and C. B. Stewart, Preliminary Survey of Uranium Metal Exponential Columns, Report LA-2023, January 1956.

C. L. Schuske, Rocky Flats Plant Report, RFP-51, June 1955. (Classified.)

C. L. Schuske, M. G. Arthur, and D. F. Smith, Rocky Flats Plant Report, RFP-58, January 1956. (Classified.)

C. L. Schuske, M. G. Arthur, and D. F. Smith, Rocky Flats Plant Report, RFP-63, April 1956. (Classified.)

C. L. Schuske, M. G. Arthur, and D. F. Smith, Rocky Flats Plant Report, RFP-66, August 1956. (Classified.)

C. L. Schuske and J. W. Morfitt, An Empirical Study of Some Critical Mass Data, Report Y-533, December 1949.

C. L. Schuske and J. W. Morfitt, Empirical Studies of Critical Mass Data, Part II, Report Y-829, December 1951.

C. L. Schuske and J. W. Morfitt, Empirical Studies of Critical Mass Data, Part III, Report Y-839, January 1952. (Classified.)

D. Callihan et al., Physics Division Semiannual Progress Report for Period Ending Mar. 10, 1954, Report ORNL-1715, July 1954, p. 11. (Classified.)

C. L. Schuske, M. G. Arthur, and D. F. Smith, Rocky Flats Plant Report, RFP-69, October 1956. (Classified.)

H. C. Paxton, Critical Masses of Oralloy Lattices Immersed in Water, Report LA-2026, November 1955. (Classified.)

J. J. Neuer, Critical Assembly of Uranium Metal at an Average U^{235} Concentration of $16\frac{1}{4}\%$, Report LA-2085, October 1956. (Classified.)

C. E. Newlon, Extension of the Safe Geometric Parameters to Slightly Enriched Uranium, Report K-1370, January 1958.

G. A. Graves and H. C. Paxton, Critical Masses of Oralloy Assemblies, Nucleonics, 15(6): 90-92 (June 1957).

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nuclear safety guide

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FOREWORD

The Nuclear Safety Guide was first issued in 1956 as a classified AEC report (LA-2063). Since it can now be more widely distributed with no significant changes, it is appropriate to restate the intended purposes of the information it contains and to emphasize the caution with which it must be used.

The recommendations in the Guide are intentionally conservative, and they may, therefore, be applied directly and safely provided the appropriate restricting conditions are met. In this usage it is believed that the Guide will be of value to organizations whose activities with fissionable materials are not extensive. The Guide is also expected to be a point of departure for members of established nuclear safety teams, experienced in the field, who can judiciously extend the specifications to their particular problems. The references in this report will be of especial value to them since reference to the experimental results will aid in guided extrapolations.

Particular reference is made to the recommendations of the Guide relating to arrays of individually subcritical units that may be applied to storage conditions and, a priori, to the arrangement of materials in shipment. A note of caution is added to the arrangement of materials in shipment. Recognition must be made of the continually increasing frequency of shipments of fissionable materials and of the necessity of exercising some control prohibiting risks which could arise if two or more individually nonhazardous shipments met in transit. In many instances such occurrences are not probable because the container arrangements are controlled by their escort or by the exclusive use of the carrier. The preparation of shipments by common carriers, where controls of this type will not, in general, be exercised, must be very carefully planned.

Recently published reports of importance to the subject material have been included in the reference section.

PREFACE

The Nuclear Safety Guide was conceived by a group that met at the Rocky Flats Plant, October 1955, to discuss industrial nuclear safety problems. A committee was selected to prepare a draft for consideration by the group during the following meeting at the Hanford Atomic Products Operation, June 1956. Although the resulting Guide remains controversial in form and general content, differences of opinion concerning specific regulations have been resolved (quite generally in favor of the more restrictive versions). In addition to the committee of authors, the following are members of the nuclear safety group who reviewed drafts of the Guide and contributed suggestions.

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It is recognized that the Guide is neither handbook (too ambitious for a start) nor manual (a separate problem for each installation). It is hoped, however, that it serves immediate needs for guidance and that it encourages continuing, more comprehensive efforts toward organizing nuclear safety information.

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PART I

THE NUCLEAR SAFETY PROBLEM

INTRODUCTION

The general question considered in this Guide is: How can the neutron chain reaction be prevented in fissionable materials being processed, stored, or transported on an industrial scale? For the discussion this question may be divided into several parts.

There are the purely scientific problems connected with the conditions needed for the chain reaction. These problems can be exactly stated and permit of precise solutions. The solution consists in a number, known as the critical or chain reacting mass, giving the quantity of fissionable material which is just critical in the conditions stated. In principle, if accurate cross section and other nuclear data were available, it would be possible to calculate critical masses. However, at the present time, the data are not sufficient and the theoretical methods are not well enough understood to permit calculation of critical masses to an accuracy of better than about 15 or 20 per cent. It is necessary, then, to depend on experimental measurements of critical mass and extensions of these by theory.

Second, there are the problems of an engineering type. These depend on the detailed circumstances of the situation being considered. Thus, in some process, it is necessary to determine in detail not only the exact physical configuration of the fissionable and other materials involved in the normal course of events in the process, but also, and more important, it is necessary to know those off-standard conditions and configurations which are physically possible in the process equipment and, at the same time, the most favorable for the chain reaction. It is not possible to exactly state and solve general problems here. Rather, each situation must be considered in detail by itself.

Finally, a third type of problem is considered, described as administrative. Work on an industrial scale involves men and equipment. In considering the possible events which may lead to dangerous configurations of fissionable material, it is necessary to know the rules under which the men operate the process equipment, what violations, intentional or not, are possible, and what physical controls exist to minimize violations. It is only with such knowledge that a careful administrative system of routine checks can be set up and carried out effectively.

In summary, the nuclear safety problems of an industrial plant can be described as follows. With a list of known (by experiment) critical masses as a guide, a detailed study is made of the equipment and conditions in which the fissionable material is processed and a safe distribution of mass throughout the plant is determined. Finally, nuclear safety operating rules are formulated in detail, and an administrative system is set up to enforce these rigorously. In this way it is possible to have a high degree of assurance that chain reactions will not occur.

In this Guide we deal in varying emphasis with all three aspects of the nuclear safety problem. In succeeding sections is given a discussion of the factors that govern the critical condition. In Part II is the main content of the Guide which is a compilation of known safe configurations of the three fissionable isotopes U^{233}, U^{235}, and Pu^{239}. These are based on ex-

isting experimental data and extrapolations thereof. In Part III there is a description of a few methods and examples illustrating applications to actual industrial equipment.

In concluding these introductory remarks, it seems appropriate to say that this Guide is by no means to be considered as an authoritative "last word" on the subject. It is rather a preliminary compilation based on experimental data for use in industrial nuclear safety work. At the present time a systematic and thorough treatment is not possible. As mentioned before, we do not know how to calculate critical masses accurately, even in simple idealized geometries. Further, we do not have the necessary data on the nuclear cross sections and other constants. Thus much experimentation remains to be done before definitive theoretical methods can be developed and a systematic and complete treatment of critical masses can be given. Meanwhile, it is hoped that this preliminary Guide will assist those whose purpose and responsibility it is to achieve nuclear safety in industrial plants.

CRITICAL PARAMETERS

As a background for criteria applicable to the problems of nuclear safety, it is appropriate to review the factors which govern the critical condition of an assembly of fissionable material and to discuss some other aspects including the origin of the criteria and their administration.

For an accumulation to be chain-reacting, there is required, of course, a quantity of the fissionable isotope, referred to as the critical mass, which is not single valued but depends very strongly on a number of factors which will be described briefly.

One factor of importance is the leakage, from the system, of neutrons which would otherwise produce fissions. The leakage depends on the shape of the fissionable system and on the neutron-reflecting properties of surrounding materials. It is possible, for example, to specify solution container dimensions, such as pipe diameters, which give a sufficiently unfavorable surface area to volume ratio to prevent a chain reaction regardless of the quantity of material contained. If the pipe is encased in a cooling jacket, or is near other process equipment or structural materials, its dimensions must be less than it would be if there were no neutron reflector proximate. In the treatment presented here, it is assumed that water, concrete, graphite, and stainless steel are typical reflector materials. Although more effective reflectors are known—heavy water and beryllium as examples—they are uncommon in processing plants. Consideration is given, therefore, to reflectors of three thicknesses in an attempt to make the specifications more generally applicable. The equipment may be nominally unreflected, i.e., the only neutron reflector is the container itself, the wall of the stainless-steel pipe, for example; it may be completely reflected by a surrounding layer of water at least 6 in. thick; the third reflector considered is a "thin" one consisting of a 1-in.-thick layer of water (or the equivalent) exemplified by the water in a cooling jacket.

The value of the critical mass is extremely sensitive to the presence of hydrogen, or other neutron moderating elements, intimately mixed with the fissionable isotope. In nuclear physics considerations the hydrogen concentration is usually expressed as the ratio of the number of hydrogen atoms to the number of fissionable atoms and may range from zero for metal or a dry unhydrated salt to several thousand for dilute aqueous solutions. Over this concentration range the critical mass may vary from a few tens of kilograms, through a minimum of a few hundred grams, to infinity in very dilute solutions where the neutron absorption by hydrogen makes chain reactions impossible. In this latter limit nuclear safety is assured by the chemical concentration alone. The following recommendations are based on homogeneous and uniform distributions of the fissionable materials in the moderator.

The critical mass of any process material varies inversely as its density in a manner depending on other characteristics of the assembly; it depends, in a somewhat similar manner, on the isotopic concentration of the fissionable element.

Strong neutron absorbers have not been generally used to increase capacities because they must be homogeneously mixed with the process materials for effects to be predictable, thereby presenting subsequent purification problems. Coating a thin-wall, otherwise unreflected, vessel with cadmium, for example, actually increases the reactivity since additional neutron reflection is provided by the cadmium. If the vessel were submerged in water, the reactivity would

be significantly less with the cadmium than without it. The presence of nitrogen in the nitrate solutions often used in chemical processing, or of Pu^{240} as an impurity in plutonium solutions, increases the margin of safety.

Most homogeneous accumulations of fissionable materials have negative temperature coefficients of reactivity which are due to density changes, including the formation of vapors in liquid systems, and the change in neutron energy distributions. Although this property is important in reactor designs where it facilitates shutdown in case of a power excursion, it does not contribute to the prevention of such excursions. Much damage can occur before the temperature effect begins to control a reaction initiated at a low temperature. The values of the temperature coefficient depend on the material, the geometry of the system, and the temperature range. The presence of resonances in the energy distribution of cross sections may alter the relative importance of the density and neutron energy contributions to the over-all coefficient.

The preceding comments have referred to single volumes. In most plant problems the effect of the exchange of neutrons between individual components of an array of vessels must be considered in order to assure safety in the whole system.

DESIGN CRITERIA

It is possible to avoid nuclear hazards by designing into a process one or more of the full limitations outlined above, but it is equally apparent that the result probably would be very inefficient and uneconomic. The practical approach to design problems has been through a combination of partial limitations whereby each one of several contributes some safety and none is sufficiently stringent to greatly impair the over-all economy.

As mentioned in the Introduction, the bases for the design of equipment and processes for the fissionable isotopes are almost entirely predicated on results from necessarily restricted critical experiments or on interpolations or extrapolations of these results. Many experiments have also been performed which show that particular situations were not critical—important results but of limited application. In spite of an impressive accumulation of background data, many gaps exist which must be covered by extremely conservative estimates. Thus the recommendations given in the succeeding sections are, in some cases, probably overly conservative; it is hoped that none errs in the other direction. Further, in practice, it has been customary to assume operating conditions to be more severe than they probably will be. Most piping, for example, has been designed on the assumption that it may become surrounded by a thick layer of water—perhaps it will because of the rupture of a water main and the stoppage of drains—but a more important reason for such conservative designs is the unknown neutron-reflecting properties of nearby concrete walls, floors, neighboring water lines, and process vessels and of personnel. The recommendations presented below for partial or "nominal" reflectors are truly applicable in borderline cases if the user can assure to his satisfaction that the stated conditions will not be violated. As more confidence is gained, not only in the bases for nuclear safety but also in the predictability of operating conditions, more liberal approaches to the problems will evolve.

INSTRUMENTATION

Radiation-detecting instrumentation is not useful in indicating margins of safety in operations except, possibly, in a few special instances. Any approach to a critical condition is manifested by the multiplication of the ambient neutron field by the fissionable nuclei so some supply of neutrons is necessary in order to detect the multiplying medium. Spontaneous fissions occur in subcritical arrays, frequently at an almost undetectable rate, and the product neutrons produce more fissions, establishing a low-level steady-state activity. In some special cases neutrons may be produced in reactions between the constituents of some process materials—in aqueous solutions of plutonium salts, for example, where the neutrons arise from the interaction of plutonium alpha particles with oxygen. These neutrons can also be multiplied and can establish an activity level which may be detected adequately. As more fissionable material is added to the system, this level increases but usually does not reach

a significant value until the system becomes supercritical. Then, the time rate of change of radiation level increases rapidly. To have observed the changes in the subcritical neutron multiplication would have been practically impossible in most instances because of the low initial level and because it is the rate of change in this level that is indicative of the approach to criticality. A possible solution to this difficulty is the inclusion of a strong neutron source in the system and the observation of changes in the level as material is added. This is the way critical experiments are performed, and experience has shown that the neutron source, the detector, and the fissioning material must be carefully located with respect to each other in order to achieve results which yield meaningful values of the so-called neutron multiplication. To equip process operations in the necessary elaborate manner is generally not practical. Instrumentation has, however, been installed in many operations to indicate the radiation hazard which would exist after a radiation accident had occurred, and reference is made to standard Health Physics procedures for the description of recommended equipment. The utility of other than very specially installed detectors can be summarized by saying they are important after an accident, not in predicting that one is imminent.

CONSEQUENCES OF A NUCLEAR ACCIDENT

It is obviously impossible to predict the results of an accidental accumulation of a supercritical quantity of fissionable material because the neutron background, rate of assembly, type of material, excess mass over that required to be critical, and degree of confinement are among the factors which determine the magnitude of the occurrence. Several supercritical assemblies have occurred, however, in the programs of critical experiments, which perhaps set lower limits on the damage to be expected. These experiments have, for the most part, resulted from the accidental achievement of an effective neutron-reproduction factor only 2 or 3 per cent greater than unity, the value required for the system to be chain-reacting. This condition has resulted from the addition of the order of a few per cent excess mass in experiments where water was present as a neutron moderator. A decrease in the density of the water, due to vaporization and dissociation, was, no doubt, a significant factor in limiting the extent of the excursions. The energy released in each of these accidents has originated in about 10^{17} fissions and amounted to about 1 kw-hr. The containing vessels were open to the atmosphere so no explosion occurred, although vessel deformations were observed. Monitoring equipment has shown the excursions to have been accompanied by neutron and gamma radiation of sufficient intensity to have produced lethal exposures at distances up to a few feet from the source.

It is of interest to consider an example of the margin between a subcritical, "safe" system, and one which is prompt critical, i.e., chain-reacting on prompt neutrons only. The latter is completely out of control. A mass of 2.2 kg U^{235} in an aqueous solution of U^{235} at a concentration of 459 g/liter contained in a cylinder 10 in. in diameter and 3.8 in. high has an effective neutron-reproduction factor of 0.9 when surrounded by a neutron reflector. As increment of 900 g U^{235} will make the reproduction factor unity; i.e., the cylinder will be delayed critical at a height of 5.3 in.; only 67 g additional is now required to make the vessel prompt critical. If the reproduction factor should be made greater than unity by even an infinitesimal amount, the activity would increase with the ultimate release of lethal quantities of radiation. This condition would be reached immediately if the cylinder became prompt critical. It is pointed out that this is a randomly selected example, and there are probably combinations of parameters, certainly with plutonium solutions, where the reactivity is even more sensitive to mass additions.

ADMINISTRATION OF NUCLEAR SAFETY

The administration of nuclear safety practices is determined in detail by the functions of the organization. Those installations having continuing problems as a consequence of their inventory of fissionable materials, or because of frequent alterations in their process, have, in the past, assigned to staff groups the responsibility for advising design and operating personnel in these matters. The infrequent problems of facilities processing only small amounts of material have often been referred to qualified persons in other organizations. A representative

example of the administrative practices in an organization of the former class is described here. It is recognized that modification will be necessary to meet the needs of others.

The responsibility for nuclear safety in the plant considered is placed on line organization. Individuals directing activities of such a nature as to involve nuclear hazards are responsible for control in these activities to the same extent that they are responsible for research, design, maintenance, and operations. An approvals committee, reporting to the plant manager and composed of personnel familiar with the potential hazards and methods of their control, approves the procedures and equipment to be used on the operational processes and in storage and shipment procedures.

In the administration of the safety practice, line supervision responsible for any design or operations obtains approval of those parts which involve nuclear safety. Necessary information is furnished to the approvals committee, including the type, quantity, and chemical composition of the material; its concentrations and density; the dimensions and geometric shapes of the containers; and a flow sheet of the process. The committee investigates each problem, advises the originating group on the hazards which may be incurred, and approves the final design and procedure. In general, such approval specifies necessary operating restrictions.

The nuclear safety of any process will be assured, wherever possible, by the dimensions of the components, such as pipe sizes and container capacities, including spacing between individual components of the same or adjacent systems. Where safety based on geometry alone is precluded, designs may be predicated on batch sizes and/or chemical concentrations, or combinations of them with geometry, and such designs will be considered satisfactory only if two or more simultaneous and independent contingencies must occur to promote a chain reaction. In the use of these nongeometric safety criteria, operational supervision is responsible for accuracy in sampling and analytical procedures.

PART II

BASIC NUCLEAR SAFETY RULES

RULES FOR INDIVIDUAL SYSTEMS

From the discussion of Part I, it is clear that the potential hazard of a system of fissionable material may be influenced by a multitude of factors that defy generalization. Special equipment may be crowded between vessels for emergency repairs; a large bucket may be placed under a leaking geometry-safe column; a janitor may stack spaced cans into a neat pile. A container volume that is safe for all foreseen external conditions may be unsafe with re-entrant water-filled passages. These are examples of the factors not included in the following rules that may lead to difficulty unless margins of safety are generous.

Basic Rules for Individual Systems

Basic regulations for simple, homogeneous, individual systems are stated alternatively as mass limits in Table 1 (kilograms of fissionable isotope), as container capacity limits in Table 2, and as dimensional limits in Tables 3 and 4. References in the tables give critical parameters on which the limits are based and include some supporting calculations. The mass limits include factors of safety of slightly more than 2 as a safeguard against double batching. Capacity limits include factors of safety of at least $1\frac{1}{3}$, and the equivalent margins appear in dimensional limits (even with unspecified dimensions infinite).* Added to normal safety factors are allowances for uncertainties in critical data on which the limits are based.

Specifications are given for various ranges of H/X atomic ratio (X ≡ U^{235}, Pu^{239}, or U^{233}) and for limited types of reflector. Although thick beryllium, D_2O, uranium, or tungsten reflectors are more efficient than thick water,[6] the latter is considered the most effective reflector that is likely to be encountered in ordinary processing or handling operations. "Nominal reflector" refers to water no more than 1 in. thick. Surrounding fissionable metal systems, $1\frac{1}{2}$-in.-thick graphite (or $1\frac{1}{2}$-in.-thick steel) is equivalent in effect to 1-in.-thick water (in small thicknesses water is one of the more effective reflectors). For solutions, equal thicknesses of steel and water are nearly equivalent.[13] "Minimal reflector" refers to no more than $\frac{1}{8}$-in.-thick stainless steel, or the same thickness of other common metal including iron, copper, aluminum, nickel, or titanium. Unless conditions are rigidly controlled, the appropriate limit for thick water reflector should be used for all applications, and for solutions the limit also should be the most restrictive of those given for the various H/X ranges.

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*Upper limits for values in Tables 3 and 4 were obtained from constant-buckling conversions of capacities in Table 2 (for metals, Table 1 volumes increased 50 per cent). Extrapolation lengths used were: 5.5 cm for solutions, 4.1 cm for U^{235} metal, 2.8 cm for Pu^{239} metal, 3.1 cm for U^{233} metal in thick water reflector; 3.5 cm for solutions, 3.2 cm for U^{235} metal, 2.3 cm for Pu^{239} metal, 2.5 cm for U^{233} metal in nominal reflector; 2.4 cm for solutions, 2.2 cm for U^{235} metal, 1.7 cm for Pu^{239} metal, 1.8 cm for U^{233} metal in minimal reflector.

Table 1—MASS LIMITS FOR INDIVIDUAL SYSTEMS

(Maximum mass in kg of X ≡ U^{235}, Pu^{239}, or U^{233})

	Metal, low H mixtures, compounds	Principally hydrogenous compounds, mixtures	Principally solutions	
	0 ≤ H/X ≤ 2	H/X ≤ 20	H/X ≤ 100	H/X unlimited*
U^{235} (Refs. 1–6)				
Thick water reflector	11.0	2.5	0.80	0.35
Nominal reflector (≤ 1 in. water)	15.0	3.5	1.04	0.43
Minimal reflector (≤ 1/8 in. S.S.)	22.0	5.0	1.40	0.55
Pu^{239} (Refs. 4, 6–8)				
Thick water reflector	2.6†	2.2	0.50	0.25
Nominal reflector (≤ 1 in. water)	3.3†	3.2	0.70	0.32
Minimal reflector (≤ 1/8 in. S.S.)	4.4†	4.8	1.00	0.43
U^{233} (Refs. 4, 6, 8–10)				
Thick water reflector	3.0	1.3	0.48	0.25
Nominal reflector (≤ 1 in. water)	4.1	1.7	0.69	0.33
Minimal reflector (≤ 1/8 in. S.S.)	6.0	2.3	0.90	0.45

* See p. 9 for values of H/X beyond which no limit is required.

† These limits apply to Pu metal at ρ = 19.6 g/cm^3; for alloy at ρ = 15.8 g/cm^3, the corresponding limits are 3.5 kg with thick water reflector, 4.8 kg with nominal reflector, and 7.0 kg with minimal reflector.

Table 2—CONTAINER CAPACITY LIMITS FOR INDIVIDUAL SYSTEMS

(Maximum volume in liters)

	Principally solutions		
	20 ≤ H/X	400 ≤ H/X	800 ≤ H/X
U^{235} (Refs. 2–5)			
Thick water reflector	4.8	9.5	20.0
Nominal reflector (≤ 1 in. water)	6.0	11.3	24.0
Minimal reflector (≤ 1/8 in. S.S.)	8.0	14.0	30.0
Pu^{239} (Refs. 4, 7, 8)			
Thick water reflector	3.3	6.8	11.4
Nominal reflector (≤ 1 in. water)	5.0	9.3	14.7
Minimal reflector (≤ 1/8 in. S.S.)	6.6	13.0	19.7
U^{233} (Refs. 4, 9, 10)			
Thick water reflector	2.0	6.0	12.0
Nominal reflector (≤ 1 in. water)	3.0	8.4	14.4
Minimal reflector (≤ 1/8 in. S.S.)	4.0	12.0	18.0

Table 3—SAFE CYLINDER DIAMETERS FOR INDIVIDUAL SYSTEMS

(Maximum diameter of cylinder of fissionable material in inches; for solution, ID of containing cylinder)

	Metal at full density	Principally solutions		
		20 ≤ H/X	400 ≤ H/X	800 ≤ H/X
U^{235} (Refs. 2, 4–6)				
Thick water reflector	2.5	5.0	6.9	9.1
Nominal reflector (≤ 1 in. water)	3.0	5.8	7.7	10.2
Minimal reflector (≤ 1/8 in. S.S.)	3.8	6.7	8.5	11.0
Pu^{239} (Refs. 4, 6–8)				
Thick water reflector	1.4*	4.5	6.1	7.4
Nominal reflector (≤ 1 in. water)	1.7*	5.7	7.2	8.5
Minimal reflector (≤ 1/8 in. S.S.)	2.0*	6.8	8.3	9.6
U^{233} (Refs. 4, 6, 10)				
Thick water reflector	1.5	3.7	5.8	7.4
Nominal reflector (≤ 1 in. water)	1.9	4.7	6.9	8.4
Minimal reflector (≤ 1/8 in. S.S.)	2.3	5.7	8.1	9.4

* These limits apply to Pu metal at ρ = 19.6 g/cm^3; also to be used for alloy at reduced density.

Table 4—SAFE SLAB THICKNESSES FOR INDIVIDUAL SYSTEMS

(Maximum slab thickness in inches)

	Metal at full density	Principally solutions		
		20 ≤ H/X	400 ≤ H/X	800 ≤ H/X
U^{235} (Refs. 4, 6, 11, 12)				
Thick water reflector	0.7	1.4	2.5	4.0
Nominal reflector (≤ 1 in. water)	1.2	2.4	3.6	5.2
Minimal reflector (≤ 1/8 in. S.S.)	2.0	3.3	4.4	6.1
Pu^{239} (Refs. 4, 6–8)				
Thick water reflector	0.2*	1.5	2.5	3.3
Nominal reflector (≤ 1 in. water)	0.5*	2.6	3.7	4.6
Minimal reflector (≤ 1/8 in. S.S.)	0.9*	3.6	4.8	5.6
U^{233} (Refs. 4, 6, 10)				
Thick water reflector	0.2	0.5	1.9	2.9
Nominal reflector (≤ 1 in. water)	0.5	1.7	3.2	4.2
Minimal reflector (≤ 1/8 in. S.S.)	1.0	2.5	4.2	5.1

* These limits apply to Pu metal at ρ = 19.6 g/cm^3; also to be used for alloy at reduced density.

The type of limit most convenient for a given application may be chosen. Mass limits are particularly appropriate for handling of metal or compounds or for processing solution batches where there is no volume or dimensional control. Container capacity limits and "safe" cylinder diameters are best suited for solutions. The principal value of safe slab thicknesses is for the design of catch basins for solutions in case of leakage of the normal container and for the control of isolated metal sheet.

Conditions That Require Special Consideration

The basic rules do not apply to "reactor compositions" such as dilute fissionable material in heavy water, beryllium, or graphite (where D/X, Be/X, or C/X > ~100) or to systems with thick reflectors of these materials, normal uranium, or tungsten.

The rules also fail to apply in the cases in which the densities of fissionable material (vs. H/X) exceed the values[2,7] of Figs. 1 and 2. In the event that the density of fissionable material, ρ, is greater than the density, ρ_0, from Figs. 1 or 2, mass limits of Table 1 should be reduced by the ratio $(\rho_0/\rho)^2$, the container volume limits of Table 2 by $(\rho_0/\rho)^3$, and the container linear dimension of Tables 3 and 4 by (ρ_0/ρ). If ρ is less than ρ_0, limits must not be increased by these ratios.

Again, the rules for nominal or minimal reflector, or for solutions in a limited range of H/X, may be applied only if these conditions are rigidly controlled.

Conditions Under Which Basic Limits Are Not Required

For solutions or other homogeneous hydrogenous mixtures, no further restriction is required[14] if (1) for U^{235}: the atomic ratio $H/U^{235} \geq 2300$, which corresponds to the concentration $c(U^{235}) \leq$ g/liter in aqueous (light water) solution; (2) for Pu^{239}: $H/Pu^{239} \geq 3600$, which corresponds to $c(Pu^{239}) \leq 7.8$ g/liter in aqueous solution; and (3) for U^{233}: $H/U^{233} \geq 2300$, which corresponds to $c(U^{233}) \leq 11$ g/liter in aqueous solution. These values contain no factor of safety; in application a margin compatible with control errors should be maintained.

Any mass of natural or depleted uranium homogeneously distributed in light water is safe.

Uranium in which the atomic ratio U^{235}/U^{238} is equal to or less than 0.05 needs no further restriction provided it is (1) in the form of metal with no interspersed hydrogenous material, e.g., a single piece; (2) in a nonhydrogenous chemical compound; or (3) intimately mixed, either as metal or a nonhydrogenous compound, with any element of atomic number, Z, greater than 13 if the atomic ratio $Z/U^{235} \leq 100$ (Ref. 8).

Conditions Under Which Basic Limits May Be Increased

For certain intermediate shapes of fissionable system, such as elongated or squat cylinders, mass and container capacity limits may be increased by the appropriate factor[4,6,7] from Fig. 3.

For undiluted fissionable metal* at density less than normal (17.6 g/cm^3 for U^{235}, 19.6 g/cm^3 for Pu^{239}, and 18.3 g/cm^3 for U^{233}), such as metal turnings, the mass limit may be increased by the appropriate factor[6] from Fig. 4. Factors from this figure also may be applied to solutions with uniformly distributed voids ($\leq$ 1 in. in one dimension), for which $H/X \geq 100$, provided "fraction of total density" is interpreted as the ratio of average density of solution plus void to the solution density.[13] Figure 5 shows factors by which the mass limits in the first column of Table 1 may be increased if fissionable atoms are mixed uniformly with any of the listed elements either as physical mixtures or chemical compounds.[8,15] It is emphasized that no H_2, D_2, or beryllium can be present if these factors are applied. Although intended primarily for homogeneous systems, these factors may be used for similar units of X distributed uniformly in the diluent provided one dimension of the unit does not exceed $\frac{1}{8}$ in. for U^{235} or $\frac{1}{16}$ in. for

* Uranium metal enriched in U^{235} is sometimes referred to as "Oralloy," abbreviated Oy, with a suffix designating the U^{235} enrichment. For example, Oy(93) indicates uranium that is 93 wt. % U^{235}.

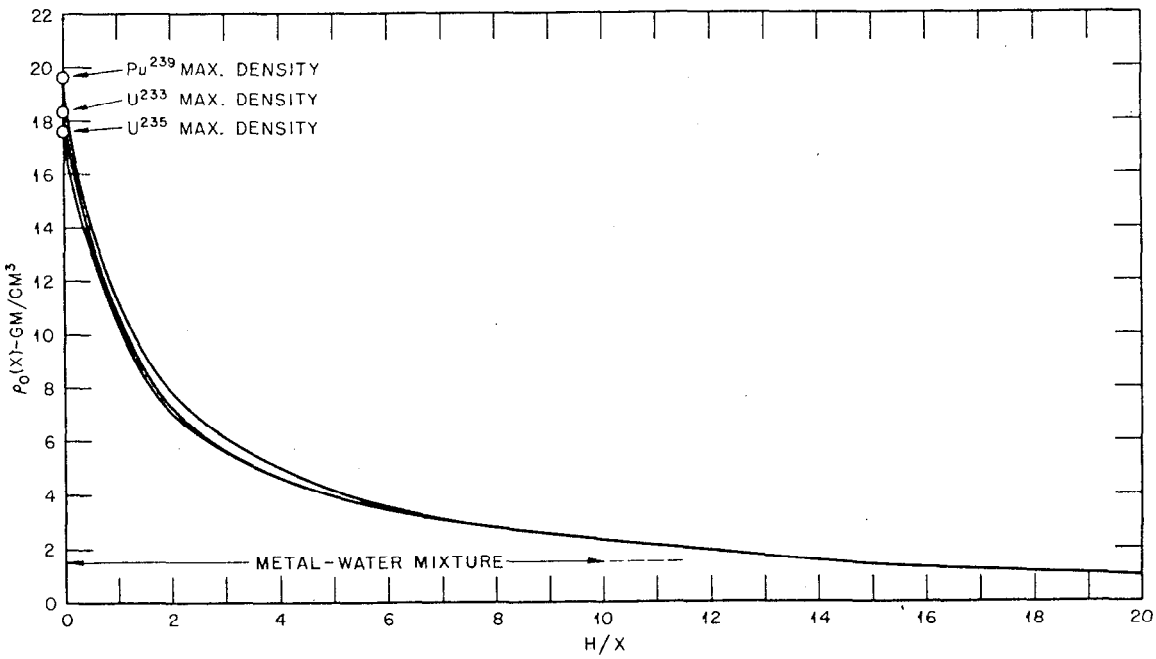


Fig. 1—Assumed densities of U^{235}, Pu^{239}, or U^{233} at $H/X \leq 20$. (If a density exceeds the indicated value by the ratio n, reduce mass limits by the factor $1/n^2$, volume limits by $1/n^3$, and linear dimension limits by 1/n.)

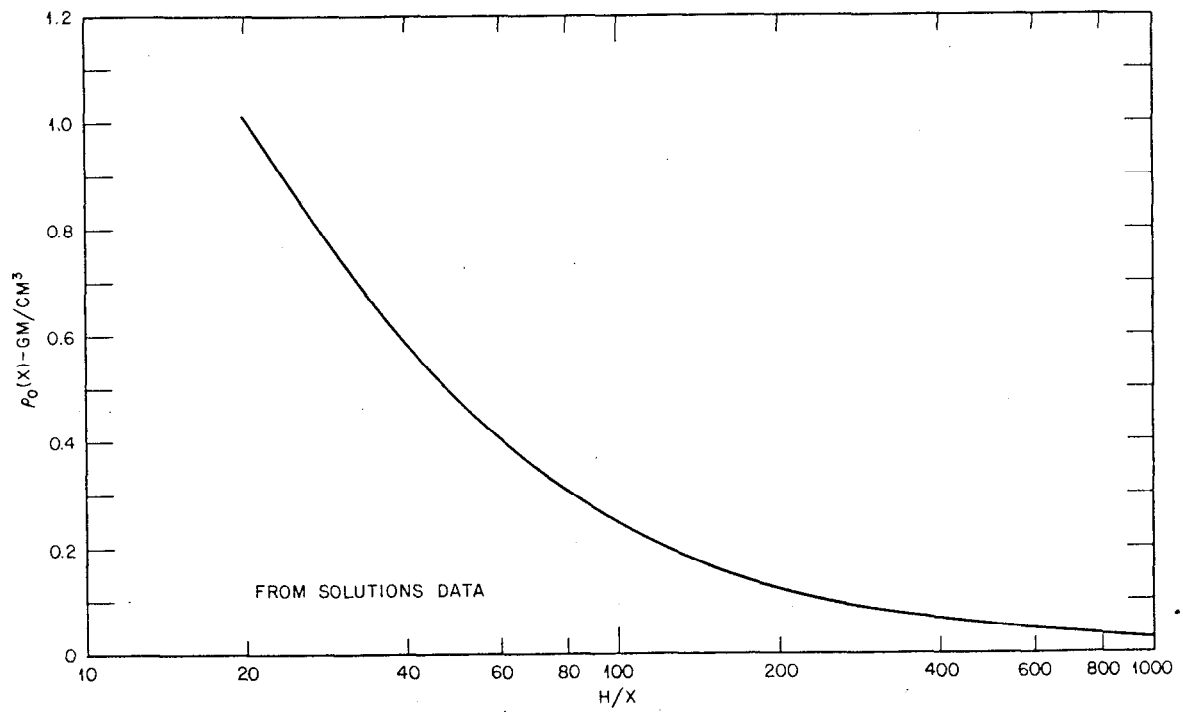


Fig. 2—Assumed densities of U^{235}, Pu^{239}, or U^{233} at $H/X \geq 20$. (If a density exceeds the indicated value by the ratio n, reduce mass limits by the factor $1/n^2$, volume limits by $1/n^3$, and linear dimension limits by 1/n.)

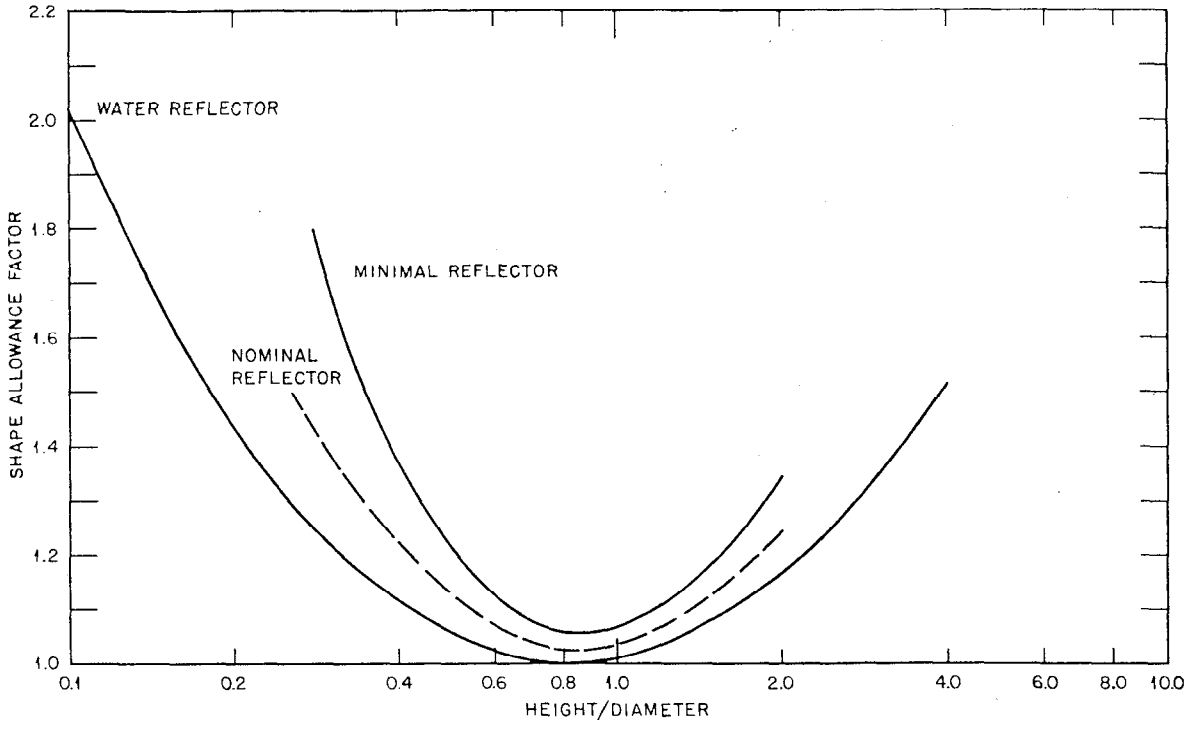


Fig. 3—Shape allowance factors for cylinders (factor by which mass and volume limits may be increased for elongated or squat cylinders).

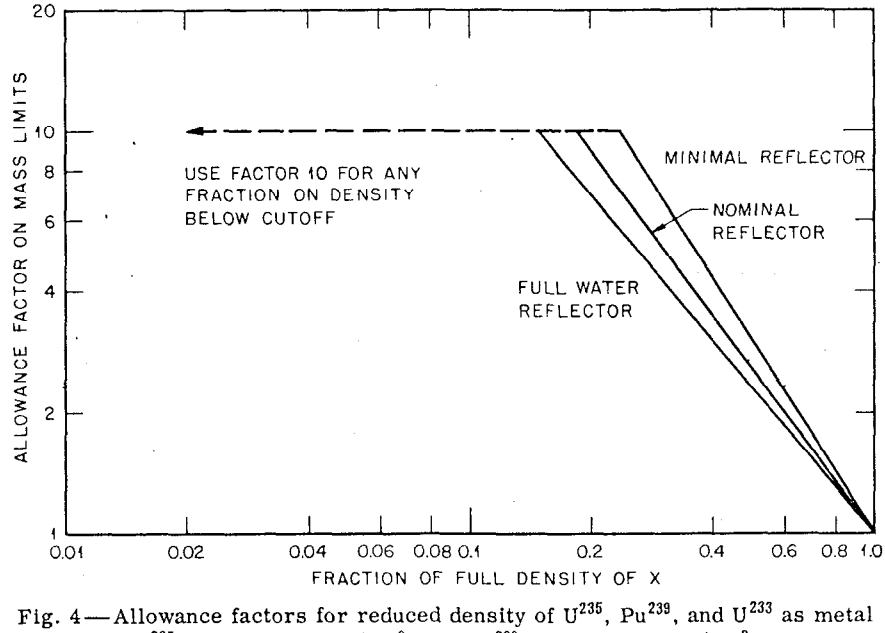


Fig. 4—Allowance factors for reduced density of U^{235}, Pu^{239}, and U^{233} as metal only. Full U^{235} density = 17.6 g/cm^3, full Pu^{239} density = 19.6 g/cm^3, and full U^{233} density = 18.3 g/cm^3.

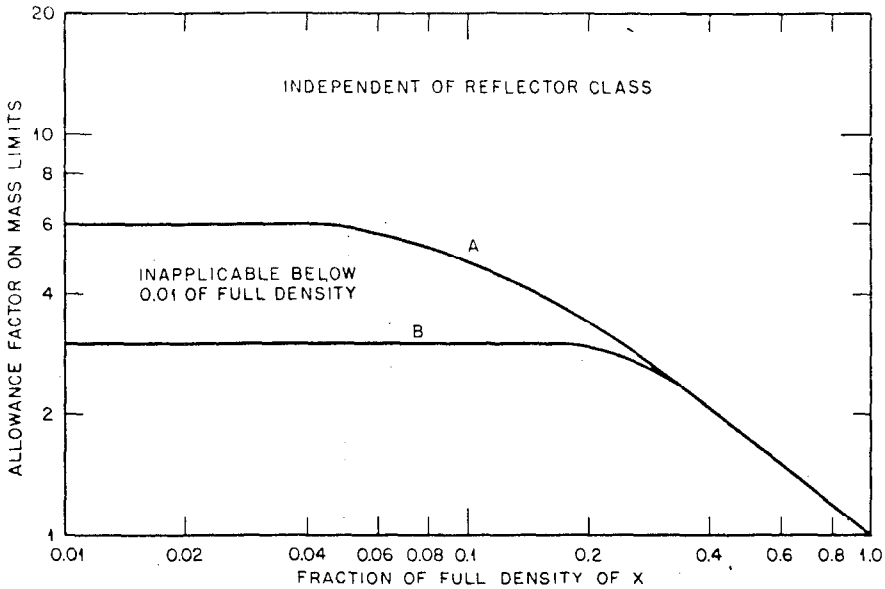


Fig. 5—Allowance factors for reduced density of U^{235}, Pu^{239}, or U^{233} mixed homogeneously with elements listed (H, D, and Be excluded). Curve A: any element for which $11 \leq Z \leq 83$ (from Na to Bi). Curve B: compounds of X and C, N, O, F, and elements $11 \leq Z \leq 83$, with at least 1 atom of X per 7 others, e.g., UC, UO_2, U_3O_8, UO_3, UO_2F_2, UF_4, and UF_6). Full U^{235} density = 17.6 g/cm^3, full Pu^{239} density = 19.6 g/cm^3, and full U^{233} density = 18.3 g/cm^3.

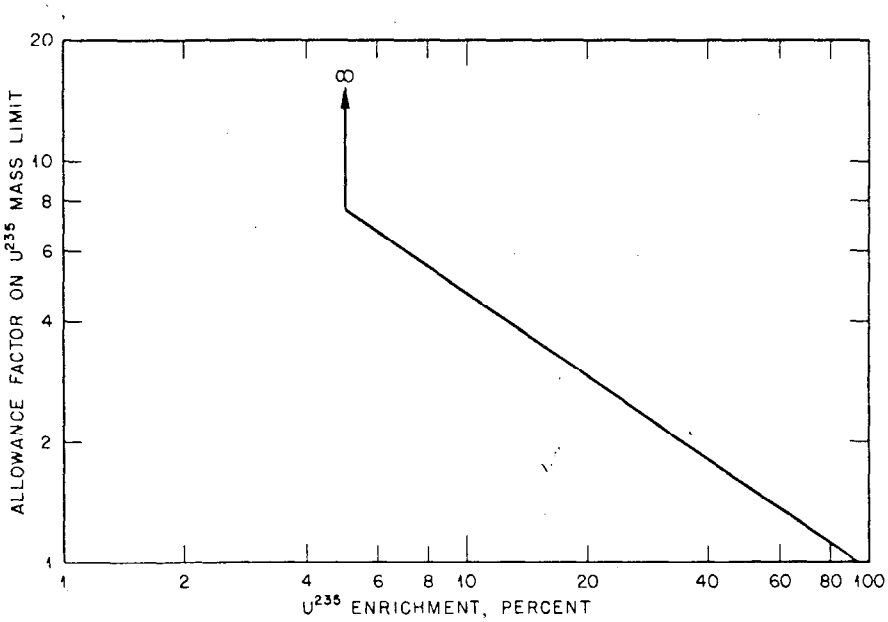


Fig. 6—Allowance factors on U^{235} mass limits for uranium metal at intermediate U^{235} enrichments.

Pu^{239} or U^{233}. (The factors are not applicable to mixtures having X densities less than 1 per cent of the full density in order to guard against moderation by relatively large proportions of nuclei of intermediate atomic number.)

In the special case of undiluted uranium metal in which the U^{235} content is less than 93 per cent, the U^{235} mass limit may be increased by the appropriate factor[6] from Fig. 6. A factor for reduced density of total uranium (not U^{235}), from Fig. 4, may be applied in addition to this enrichment factor.

As stated before, the mass limits of Table 1 contain a factor of safety of slightly more than 2 as protection against a double-batching error. (The capacity limits have a somewhat smaller safety factor.) Where the possibility of over-batching is excluded, the basic mass limit may be increased by the factor 1.5.

RULES FOR INTERACTING UNITS

General Criteria

Empirically formulated specifications for the spacing of individually subcritical units in an array which is also subcritical have been established.[16–19] These specifications are predicated on the assumptions that the over-all neutron multiplication factor, k, of several vessels is determined by the values of k of the individual components and by some probability that neutrons leaking from one vessel will be intercepted by another. This probability, in turn, is related to a geometric parameter which is a simplified expression for the total solid angle subtended at the most centrally located unit by the other components of the array. In the method referred to here this solid angle is calculated by a "point-to-plane" method where the point is on the most centrally located unit and the planes either define the boundaries of the other units or are appropriate projections of the boundaries. Examples of this calculation are given in Fig. 7. The total solid angle is, of course, the sum of the angles subtended by the individual units.

Currently applicable specifications for unit spacings are determined by a method, detailed in the above references, in which the reactivity of each unit is estimated by a two-group diffusion theory and the total solid angle then set by an empirical relation. This method is strongly supported by extensive experimental measures of the critical conditions of a large assortment of arrays of various shaped vessels containing U^{235} in a variety of forms.[5,20,21]

For the purposes of this Guide a total solid angle of one steradian is selected as a conservative limit on the solid angle, calculated by the method described above, subtended at the unit which "sees" the others to the greatest extent. The units referred to here are those described in Tables 1 to 4, including appropriate allowance factors. In calculating the total solid angle, fully shielded units may be ignored; e.g., the first and fifth of five identical cylinders with axes coplanar do not contribute to the solid angle at the center one. In those instances where flooding of the array by water is a possibility, a concomitant specification is the requirement that each vessel be spaced from its nearest neighbor by at least 12 in. or by 8 in. if there are only two units. This specification is based on the observation that these thicknesses of water or materials of comparable hydrogen density effectively isolate the unit.[20,22]

Storage and Transportation Rules for Special Units

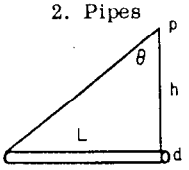
Consideration, based on experiments to establish storage and transportation rules, is given here to arrays of units of relatively small volume and possibly high density. It is assumed that the control of the size of individual units is more stringent than in the production operations of a process, thereby allowing a relaxation of the double-batching safety factors imposed above. It is further assumed that the units are either bare or are in relatively light containers (nominal reflectors) and are spaced by birdcages, compartments, or specifically located anchorages. Table 5 specified maximum units of this class. These units may be-in-

A. Formulae

1. General

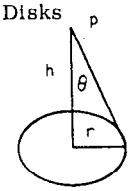
$$\Omega = \frac{\text{Cross Sectional Area}}{(\text{Separation Distance})^2}$$

2. Pipes



$$\Omega = \frac{d}{h} \sin \Theta$$

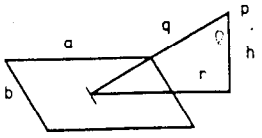
3. Disks



$$\Omega = 2\pi (1 - \cos \Theta)$$

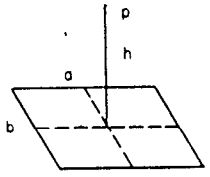
4. Planes

a.



$$\Omega = \frac{ab \cos \Theta}{q^2}$$

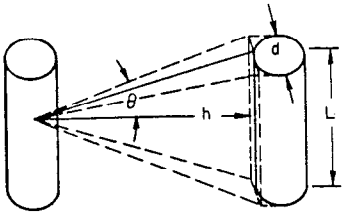
b.



$$\Omega = 4 \sin^{-1} \frac{\left(\frac{a}{2}\right) \left(\frac{b}{2}\right)}{\sqrt{\left(\frac{a}{2}\right)^2 + h^2} \sqrt{\left(\frac{b}{2}\right)^2 + h^2}}$$

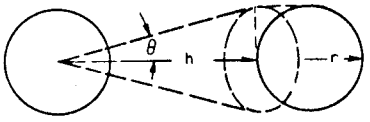
B. Applied Methods

1. Cylinders



$$\Omega = \frac{2d}{h} \sin \Theta$$

2. Spheres



$$\Omega = 2\pi (1 - \cos \Theta)$$

Fig. 7—Solid angle calculations.

Table 5 — MAXIMUM SIZES OF UNITS TO WHICH TABLES 6 AND 7 APPLY

	Maximum unit*		
	U^{235}	Pu^{239}	U^{233}
Metal, compounds, or mixtures, H/X ≤ 2; mass limits, kg†	18.5‡	4.5§	4.5
Hydrogenous compounds or mixtures, 2 < H/X < 20; mass limits, kg†	4.5	4.5	2.5
Solutions, or hydrogenous mixtures, H/X ≥ 20, in non-safe containers;¶ volume limits, liters	4.0	4.0	2.0

* If density (ρ) is greater than the reference value (ρ_0) in Fig. 1 or 2, reduce mass limits by the factor $(\rho_0/\rho)^2$, volume limits by $(\rho_0/\rho)^3$.

† Material volume of unit is not to exceed 4.5 liters.

‡ This corresponds to 20 kg of uranium enriched to about 93 per cent in U^{235}.

§ This limit holds for Pu metal at ρ = 19.6 g/cm^3; for the alloy at ρ = 15.8 g/cm^3, the corresponding limit is 6.0 kg.

¶ For safe containers defined in Table 3, there is no mass or volume limit for stable solutions (H/X ≥ 20).

creased by the shape allowance factors of Fig. 3 and the metal density and U^{235} enrichment factors of Figs. 4 to 6 but not, of course, by the allowance for perfect batch control.

Again, certain reactor compositions, as dilute mixtures with D_2, beryllium, or carbon, must be treated as special cases.

Storage

The storage rules of Table 6 allow a factor of safety greater than 2 (in number of units) for arrays in a concrete vault that is not less than 9 ft in smallest dimension. Arrays that are safe in a concrete vault also will be safe in vaults of other materials such as steel, wood, or earth. For convenience the storage rules are given in terms of number of maximum units at a given center-to-center spacing between units. A maximum unit may consist of a close-packed group of smaller units provided the total quantity specified for a maximum unit is not exceeded. Storage arrays defined in Tables 5 and 6 will be safe if fully flooded by water provided the edge-to-edge separation between maximum units is at least 12 in. and not more than 10 per cent of the volume of composite units can be occupied by water.

Isolated and associated arrays referred to in Table 6 are described in the following manner. Two arrays are effectively isolated from one another if they are completely separated by concrete at least 8 in. thick.[22] Two plane (i.e., items with centers coplanar) or cubic (i.e., items with centers in three dimensions) arrays are also isolated if the separation (minimum edge-to-edge spacing between any unit in one array and any unit in the other) is the larger of the following quantities: (1) the maximum dimension of one array and (2) 12 ft (Ref. 23). Two linear arrays are isolated regardless of length if the separation is at least 12 ft. Nonisolated plane arrays are associated if the minimum edge-to-edge spacing between units in the two arrays is at least 7½ ft.

Transportation

Table 7 is a set of rules for shipment of units of fissionable materials defined in Table 5. "Maximum density established by birdcage or shipping case" is based on a unit packaged in a 20-in. birdcage.

Table 6 — LIMITS FOR STORAGE ARRAYS OR UNITS DEFINED IN TABLE 5

Type of array	Minimum center-to-center spacing of units within array, in.*	Storage limit per array (No. of max. storage units)†
Isolated linear or plane array	≥ 16	No limit
Isolated cubic array	36	200
	30	120
	24	80
	20	50
Two associated plane arrays	30	120/array, 240 total‡
	24	90/array, 180 total‡
	20	50/array, 100 total‡

* Edge-to-edge separation of units must be at least 12 in.

† In the case of safe containers for solution ($H/X \geq 20$) defined in Table 3, there is no limit for a parallel in-line array at a minimum axis-to-axis spacing of 24 in. or for two associated in-line arrays where the spacing in each array is 24 in.

‡ The same total storage limit applies to more than two associated arrays.

Table 7 — LIMITS FOR SHIPMENTS OF UNITS DEFINED IN TABLE 5

	Max. density established by birdcage or shipping case*			Normal carload limit (50 max. shipping units except for safe cylinders)†		
	U^{235}	Pu^{239}	U^{233}	U^{235}	Pu^{239}	U^{233}
Metal, compounds or mixtures, $H/X \leq 2$; mass limits	4 kg/ft^3	1 kg/ft^3	1 kg/ft^3	925 kg/car	225 kg/car	225 kg/car
Hydrogenous compounds or mixtures, $2 < H/X \leq 20$; mass limits	1 kg/ft^3	1 kg/ft^3	0.5 kg/ft^3	225 kg/car	225 kg/car	125 kg/car
Solutions, or hydrogenous mixtures, $H/X \geq 20$, in non-safe containers‡	0.8 liter/ft^3	0.8 liter/ft^3	0.4 liter/ft^3	225 liters/car	225 liters/car	100 liters/car

* This density is (mass of unit)/birdcage volume; birdcages or cases shall define at least 1 ft edge-to-edge separation between units; unit container shall be sealed against inleakage of water.

† For combined shipping (excluding safe cylinders), the carload limit is any combination of 50 appropriate maximum shipping units (or the equivalent in smaller units); the listed mass limits increase if allowance factors are applied to the shipping units of Table 5.

‡ For the safe solution cylinders of Table 5, the storage conditions of Table 6 may be used for transportation provided spacings are expected to be maintained in case of accident.

The assumption underlying these rules is that the integrity of birdcages or shipping cases and of the sealed container will be preserved, but the possibility of accidental flooding or the combination of the contents of two carriers is admitted. "Carload limits" in Table 7 allow a normal factor of safety of at least 4, of which a factor of 2 is for the combination of two carloads. If flooded, individual units will be less than 80 per cent of the critical mass, and requirements are such that units will not interact through the intervening water.

PART III

APPLICATION OF PROCESSING PLANTS

GENERAL DISCUSSION

It should be emphasized again that the typical process plant contains a crowded arrangement of tanks, pipes, and columns with interconnections and nearby structures instead of the simple, isolated units of Part II. Because of the complexity of some process layouts, nuclear measurements on portions of the system mocked up in a critical assembly laboratory may be necessary to utilize, in the most advantageous manner, available plant floor area and equipment. In some cases where this procedure is impractical, it may be desirable to make controlled *in situ* measurements within a plant. The latter method has been used effectively.

Generally, however, safe, but perhaps overconservative, restrictions for plant equipment can be established in terms of the rules stated above for simple systems. For example, an isolated cylinder of rectangular cross section will obviously be safe if the diagonal dimension does not exceed the diameter of a safe circular cylinder. For the evaluations of multiple unit systems, Rules For Interacting Systems, Part II, may be applied.

Incidental Reflectors

A wall of concrete, steel, or wood (or the equivalent in columns, etc.) within six volume-average radii of the center of a vessel increases minimal inherent reflection to nominal effective reflection, or nominal inherent reflection to the equivalent of full-water reflection.[24] It does not influence a system with the equivalent of a full-water reflector. Beyond six volume-average radii the effect of such a structure may be ignored. For nominally or fully water reflected systems, the effect of extraneous human body reflection may be neglected provided the bodies in question are not in gross contact with the systems.

Minimal reflector conditions rarely occur in a chemical processing plant. A system which by itself has this type of reflector is quite sensitive to interaction with other process vessels containing fissionable material and to the effects of incidental (or accidental) reflectors.

Adaptation to Standard Volumes and Pipe Sizes

In principle, the limits of Tables 1 to 4 might be represented as a series of curves as a function of H/X atomic ratios. In view, however, of gaps in experimental data on which tables are based (and of the relative ease of scanning compact tables), it is believed that finer subdivisions than afforded by these tables are not presently justified. In applications to plant equipment there will be situations where the appropriate limit of Table 2 will fall just below the volume of a convenient standard vessel or where the safe dimensional limit of Table 3 is slightly smaller than a standard pipe or tubing diameter. In such a case it is suggested that a nuclear safety specialist help determine whether there may be safe adjustment to the size of

standard equipment. It should be emphasized that linear interpolation between some of the tabulated limits in Part II will be unsafe.

RULES FOR SPECIAL SYSTEMS

This section contains rules for a few specific situations occurring in plants that are not covered by the generalizations of Part II.

Pipe Intersections

Table 8 describes conservative uniform pipe intersections for aqueous solutions of U^{235}, Pu^{239}, and U^{233} salts.[25] These data do not apply to metals. The examples may be extended to nonuniform intersections by the method outlined in the reference.

Table 8—CONSERVATIVE INSIDE PIPE DIAMETERS (IN INCHES) FOR UNIFORM 90-DEG INTERSECTIONS CONTAINING FISSIONABLE SOLUTIONS ($H/X \geq 20$)

	U^{235}	Pu^{239}	U^{233}
Tees:			
Full water reflector	3.5	3.2	2.6
Nominal reflector (≤ 1 in. water)	4.1	4.0	3.3
Minimal reflector (≤ 1/8 in. S.S.)	4.7	4.8	4.0
Crosses:			
Full water reflector	2.9*	2.6	2.1
Nominal reflector (≤ 1 in. water)	3.3	3.3	2.7
Minimal reflector (≤ 1/8 in. S.S.)	3.9*	3.9	3.3

* Experiments indicate that these values are highly conservative.

If a pipe is to contain multiple intersections, no two intersections may occur within 18 in. (axis-to-axis) of one another.

Metal Machine Turnings

Machine turnings immersed in a hydrogenous moderator should be handled in the same manner as aqueous solutions of the metal salts. Table 1 applies if densities are consistent with Fig. 2 (Ref. 26).

Compounds and Solutions of U^{235}

Safety specifications applicable to chemical compounds and aqueous solutions of U^{235} have been published.[27]* These limits, applicable to dry compounds in which the uranium density is no greater than 3.2 g/cm^3 and to solutions and mixtures with water having uranium densities characterized by typical solubility relations, can be used extensively by uranium processing plants. Tables 9 and 10 are typical examples, in condensed form, of the nuclear safety limits presented in this reference.

* This document, which undergoes revision as new basic data become available, provides an excellent illustration of nuclear safety regulations for a specific class of operations.

Table 9—MASS LIMITS FOR MIXTURES OF U^{235} AS UF_6 AND HYDROGENOUS MATERIAL, $H/U^{235} \geq 10$
(For any reflector class)

Max. uranium density, g/cm^3	H/U^{235} atomic ratio	Safe mass kg U^{235}
1.8	10	5.0
2.3	5	9.4
2.6	3	14.3
2.8	2	20.0
3.0	1	28.5
3.2	0.1	39.8
3.2	0.01	43.0

Table 10—DEPENDENCE OF SAFE MASS, VOLUME, AND CYLINDER DIAMETER ON U^{235} CONTENT OF URANIUM
(For total uranium densities that do not exceed 1.07 times the values for U^{235} in Figs. 1 and 2, any H/U^{235} ratio, and thick water reflector)

U^{235} content of uranium, wt.%	Mass, kg U^{235}	Volume, liters	Cylinder I.D., in.
40	0.41	6.7	6.0
20	0.48	9.5	6.9
10	0.60	14.0	8.2
5	0.80	27.0	10.2
2	2.00	27.0	10.2
0.8	36.00	27.0	10.2
$\leq 0.7_1$	Infinite	Infinite	Infinite

Table 11—BATCH LIMITS FOR URANIUM METAL IN WATER
(U^{235} Enrichment = 1.03 per cent)

Solid rod diameter, in.	U^{235} batch limit, kg
0.39	8.1
0.60	6.9
0.75	7.1
0.93	8.1
1.66	13.1

Uranium Metal, Low U^{235} Content

The critical mass of uranium metal rods only slightly enriched in U^{235} and dispersed in water depends on the dimensions of the units and the manner in which they are arranged. Permissible batch sizes of solid metal rods, enriched to 1.03 per cent in U^{235}, of several diameters, and latticed in water in the manner giving the greatest reactivity, are listed in Table 11. It is emphasized that these values refer to solid rods. Annular pieces of uranium metal have smaller critical masses than do solid pieces having the same outside diameter.

EXAMPLES OF PLANT APPLICATION

This section contains several problems typical of those arising in chemical or metallurgical plants processing sizable quantities of fissionable materials.

Pouring Crucible and Mold Limits for 40 Per Cent Enriched-uranium Metal

The problem is to suggest the weight of a safe charge of uranium containing 40 wt.% U^{235} and 60 wt.% U^{238} in a large pouring crucible and mold having no safety features imposed by their shape. Graphite crucible and mold walls plus insulation and heating coils are sufficiently thin to be classed as nominal reflector, and there is no possibility of internal flooding.

The basic mass limit from Table 1 is 15.0 kg U^{235} for nominal reflector. Figure 6 then gives an allowance factor of 1.8 for reduction of U^{235} concentration from ~93 to 40 per cent. This leads to an allowable charge of 27 kg U^{235} which corresponds to 67 kg of uranium of this enrichment.

Pouring Crucible and Mold Limits for a 10 Wt.% U^{235} – 90 Wt.% Aluminum Alloy

The problem is to suggest a safe charge weight of a 10 wt.% U^{235}–90 wt.% aluminum alloy for a melting crucible and mold with compact shapes. As crucible and mold walls, etc., exceed 2 in. in thickness, the equivalent of full-water reflection must be assumed. Charge is to be introduced as the alloy, and melting and casting conditions are controlled to avoid segregation. There is no possibility of flooding within the furnace.

The volume fraction of U^{235} in this alloy (or the fraction of full U^{235} density) is about 0.016. From Table 1 the basic mass limit is 11 kg U^{235}, and Fig. 5 gives an allowance factor of 6 for aluminum dilution. Thus the limit is 66 kg U^{235} which corresponds to about 660 kg of alloy. [*Note:* If the alloy were to be compounded during melting, the allowance factor would be disregarded and the limit would be 11 kg U^{235} (thick aluminum reflector is less extreme than thick water)].

Pulse Column (Infinite Pipe System)

The problem is to choose a safe diameter for a pulse column given the following pertinent data:

1. The column, $^3/_{32}$-in.-thick stainless steel, is to be mounted against a concrete wall at a distance of six column radii (column is not to be recessed into a cavity).
2. There are no other interacting columns or tanks, and the possibility of flooding is excluded.
3. The concentration of U^{235} occurring in the column is not to exceed 150 g U^{235} per liter of solution.
4. The column length is 5 ft or more and must be considered effectively infinite.

The safe diameter is 6.7 in., from Table 3 and Fig. 2.

CAUTION: It is common practice to design a pulse column with phase separation units at the top and bottom of the column, which are of larger diameter than the column proper. It is to be understood that the 6.7 in. diameter is the maximum safe diameter for all parts of the system.

Determination of a Safe Batch Size for Enriched-uranium Slugs in a Chemical Plant Dissolver

This final example illustrates both the relatively sophisticated approach that some nuclear safety problems require and a method by which the recommendations in Table 11 were derived.

It is known that natural uranium containing 0.71 wt.% U^{235} cannot be made critical when homogeneously distributed in a water moderator; thus a chemical plant may be designed for processing this kind of uranium with no concern for critical mass problems. Sometimes it is desirable to use slightly enriched uranium in reactors, and the question then arises of how enriched slugs may be safely processed. The following problem is considered. Slugs of 1.36 in. in diameter and containing 1 wt.% U^{235} are to be dissolved in a large tank. Large numbers of natural-uranium slugs may also be undergoing dissolution in the same tank. The slugs are to be dumped into the tank; their positions with respect to one another are uncontrolled. How many 1 per cent slugs may safely be dissolved at one time?

First disregard the presence of natural uranium-slugs. Then the problem is: what is the minimum critical mass of 1 per cent uranium in a water system? The system may be a uniform solution; it may be a solution of uranium in water in a roughly spherical shape surrounded by a full-water reflector; it may be an array of slugs with any diameter up to 1.36 in. surrounded by full-water reflector; or it may be any mixture of the above three possible configurations.

Calculations show that, for this degree of enrichment, the inhomogeneous system consisting of a lattice of slugs in water will have a higher reactivity than a homogeneous solution. This results from the larger value of the resonance escape probability for a lattice. We thus reduce the problem to finding the highest reactivity or buckling possible in a water-uranium lattice of rods in which the lattice spacing and the rod diameter are variable (the rods up to 1.36 in.). Experimental measurements on lattices of this type are available.[28,29] From these it is found that the maximum buckling obtainable with 1 per cent uranium is about 3600×10^{-6} cm^{-2} with a rod diameter of about 0.75 in. in a lattice with a water-to-uranium volume ratio of 2:1. Since the experiments were done with uranium clad in aluminum jackets, it is necessary to raise the value of the buckling to about 4100×10^{-6} cm^{-2} for a pure uranium-water system.

With this number, we are in a position to specify safe numbers of slugs. A simple calculation shows that 3490 lb of uranium will go critical if the lattice has near spherical shape and is fully reflected by water. This is equivalent to 435 slugs, each 8 in. long. If the possibility of double batching in the dissolver cannot be excluded, then this number should be halved. It is thus concluded that a safe batch size is about 200 slugs. Some additional safety factor is present since this specification is based on charging slugs of 1.36 in. in diameter. By the time the slugs are dissolved down to the optimum diameter, some of the uranium is in solution and some in slugs. This is a less reactive situation than if this total amount of uranium were all in the form of slugs of the optimum size.

We have not yet considered the effects which may be caused by a natural-uranium reflector that may be present in the dissolver. Experiments with aluminum-uranium alloy slugs reflected with closely packed natural-uranium slugs in a water system show that the critical mass is approximately halved.[30] Calculations on the present type slugs give about the same result. Thus, if natural uranium is also present in large amounts in the dissolver, the safe batch size for enriched slugs should be reduced to 100. If the natural-uranium slugs can assume some optimized latticed arrangement, thereby contributing substantially to the over-all reactivity, the critical number of enriched slugs may be reduced still further. If this extreme situation is considered likely, the batch size should be set at about 70 slugs.

An alternate method of ensuring safety in this dissolver would be to introduce a geometric constraint on the slugs. A cylinder with porous walls might be inserted to maintain a fixed radius for the configuration of the slugs and yet permit free circulation of the dissolving solution. According to the maximum buckling quoted above, the radius of this cylinder would be 11 in. Here, only water reflector is allowed for. So long as this radius could be maintained, no restriction on the number of slugs is necessary.

REFERENCES

1. C. K. Beck, A. D. Callihan, and R. L. Murray, Critical Mass Studies, Part I, Report A-4716, June 1947.
2. C. K. Beck, A. D. Callihan, J. W. Morfitt, and R. L. Murray, Critical Mass Studies, Part III, Report K-343, April 1949.
3. J. R. Brown, B. N. Noordhoff, and W. O. Bateson, Critical Experiments on a Highly Enriched Homogeneous Reactor, Report WAPD-128, May 1955. (Classified.)
4. A. D. Callihan, Nuclear Safety in Processing Reactor Fuel Solutions, Nucleonics, 14(7): 39 (July 1956).
5. J. K. Fox, L. W. Gilley, and D. Callihan, Critical Mass Studies, Part IX, Aqueous U^{235} Solutions, Report ORNL-2367, February 1958.
6. H. C. Paxton, Critical Masses of Fissionable Metal as Basic Nuclear Safety Data, Report LA-1958, January 1955.
7. F. E. Kruesi, J. O. Erkman, and D. D. Lanning, Critical Mass Studies of Plutonium Solutions, Report HW-24514, May 1952. (Classified.)
8. G. Safonov, Survey of Reacting Mixtures Employing U^{235}, Pu^{239}, and U^{233} for Fuel and H_2O, D_2O, Carbon, Beryllium, and BeO for Moderator, Report R-259, January 1954. (Classified.)
9. A. D. Callihan, J. W. Morfitt, and J. T. Thomas, Small Thermal Homogeneous Critical Assemblies, Paper UN-834, International Conference on the Uses of Atomic Energy, June 1955.
10. J. K. Fox, L. W. Gilley, and E. R. Rohrer, Critical Mass Studies, Part VIII, Aqueous Solutions of U^{233}, Report ORNL-2143, August 1956.
11. J. K. Fox, L. W. Gilley, and J. H. Marable, Critical Parameters of a Proton Moderated and Proton Reflected Slab of U^{235}, Report ORNL-2389, October 1957, p. 87.
12. F. F. Hart, Safety Tests for Melting and Casting Oralloy, Report LA-1623, December 1953.
13. A. D. Callihan, D. F. Cronin, J. K. Fox, and J. W. Morfitt, Critical Mass Studies, Part V, Report K-643, June 1950.
14. J. T. Thomas, Limiting Concentrations for Fissile Isotopes, Report ORNL-2081, November 1956, p. 78.
15. H. C. Paxton, Estimated Critical Masses of Diluted Oralloy, Report N-2-263, July 1956.
16. H. F. Henry, J. R. Knight, and C. W. Newlon, General Application of a Theory of Neutron Interaction, Report K-1309, November 1956.
17. H. F. Henry, C. E. Newlon, and J. R. Knight, Self-consistent Criteria for Evaluation of Neutron Interaction, Report K-1317, December 1956.
18. H. F. Henry, C. E. Newlon, and J. R. Knight, Application of Interaction Crtieria to Heterogeneous Systems, Report K-1335, June 1957. (Classified.)
19. J. A. Pond, Critical Geometries for Bare Cylinders, Report GAT-189, July 1956.
20. J. K. Fox and L. W. Gilley, Applied Nuclear Physics Division Annual Report for Period Ending Sept. 10, 1956, Report ORNL-2081, November 1956, p. 63.
21. J. K. Fox and L. W. Gilley, Applied Nuclear Physics Division Annual Progress Report for Period Ending Sept. 1, 1957, Report ORNL-2389, October 1957, p. 77.
22. C. L. Schuske, M. G. Arthur, and D. F. Smith, Rocky Flats Plant Report, CD56-869, July 1956. (Classified.)
23. C. L. Schuske, Rocky Flats Plant Report, RFP-59, February 1956. (Classified.)
24. J. K. Fox and L. W. Gilley, Physics Division Semiannual Progress Report for Period Ending Mar. 10, 1955, Report ORNL-1926, September 1955, p. 2.
25. C. L. Schuske, An Empirical Method for Calculating Subcritical Pipe Intersections, Rocky Flats Plant Report, TID-5451, July 1956. (Classified.)
26. J. D. McLendon and J. W. Morfitt, Critcal Mass Tests on U^{235} Machine Turnings, Report Y-A2-71(Del.), February 1952.

27. H. F. Henry, A. J. Mallett, and C. E. Newlon, Basic Critical Mass Information and Its Application to K-25 Design and Operation. Report K-1019, Fourth Revision, August 1957. (Classified.)
28. E. D. Clayton, Physics Research Quarterly Report, Report HW-42183.
29. H. Kouts, G. Price, K. Downes, R. Sher, and V. Walsh, Exponential Experiments with Slightly Enriched Rods in Ordinary Water, Paper UN-600, International Conference on Peaceful Uses of Atomic Energy, June 1955.
30. A. D. Callihan, D. F. Cronin, J. K. Fox, J. W. Morfitt, E. R. Rohrer, and D. V. P. Williams, Critical Mass Studies, Part VI, Report Y-801, August 1951. (Classified.)

Selected Reading List

Included are documents giving background information but to which specific reference is not made in the text. For completeness it has been necessary to include in this List a number of classified references and a few which received limited distribution. The authors regret that all the information may not be available to every reader.

C. K. Beck, A. D. Callihan, and R. L. Murray, Critical Mass Studies, Part II, Report K-126, January 1948.

A. D. Callihan, D. F. Cronin, J. K. Fox, R. L. Macklin, and J. W. Morfitt, Critical Mass Studies, Part IV, Report K-406, November 1949.

A. D. Callihan and D. F. Cronin, Critical Experiments with Uranium of Intermediate U^{235} Content, Report ORNL-55-10-97, October 1955. (Classified.)

L. W. Gilley and A. D. Callihan, Nuclear Safety Tests on a Proposed Ball Mill, Report ORNL-54-9-89, September 1954.

R. Gwin and W. T. Mee, Critical Assemblies of U^{235}, Report Y-A2-124(Del.), September 1953.

E. C. Mallary, H. C. Paxton, and R. H. White, Safety Tests for the Storage of Fissile Units, Report LA-1875, February 1955. (Classified.)

J. J. Neuer and C. B. Stewart, Preliminary Survey of Uranium Metal Exponential Columns, Report LA-2023, January 1956.

C. L. Schuske, Rocky Flats Plant Report, RFP-51, June 1955. (Classified.)

C. L. Schuske, M. G. Arthur, and D. F. Smith, Rocky Flats Plant Report, RFP-58, January 1956. (Classified.)

C. L. Schuske, M. G. Arthur, and D. F. Smith, Rocky Flats Plant Report, RFP-63, April 1956. (Classified.)

C. L. Schuske, M. G. Arthur, and D. F. Smith, Rocky Flats Plant Report, RFP-66, August 1956. (Classified.)

C. L. Schuske and J. W. Morfitt, An Empirical Study of Some Critical Mass Data, Report Y-533, December 1949.

C. L. Schuske and J. W. Morfitt, Empirical Studies of Critical Mass Data, Part II, Report Y-829, December 1951.

C. L. Schuske and J. W. Morfitt, Empirical Studies of Critical Mass Data, Part III, Report Y-839, January 1952. (Classified.)

D. Callihan et al., Physics Division Semiannual Progress Report for Period Ending Mar. 10, 1954, Report ORNL-1715, July 1954, p. 11. (Classified.)

C. L. Schuske, M. G. Arthur, and D. F. Smith, Rocky Flats Plant Report, RFP-69, October 1956. (Classified.)

H. C. Paxton, Critical Masses of Oralloy Lattices Immersed in Water, Report LA-2026, November 1955. (Classified.)

J. J. Neuer, Critical Assembly of Uranium Metal at an Average U^{235} Concentration of 16¼%, Report LA-2085, October 1956. (Classified.)

C. E. Newlon, Extension of the Safe Geometric Parameters to Slightly Enriched Uranium, Report K-1370, January 1958.

G. A. Graves and H. C. Paxton, Critical Masses of Oralloy Assemblies, Nucleonics, 15(6): 90-92 (June 1957).

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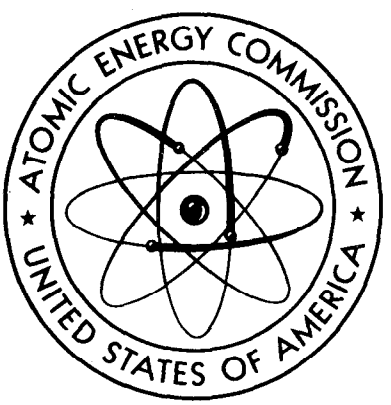

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LOS ALAMOS SCIENTIFIC LABORATORY
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FOREWORD

The Nuclear Safety Guide was first issued in 1956 as a classified AEC report (LA-2063). Since it can now be more widely distributed with no significant changes, it is appropriate to restate the intended purposes of the information it contains and to emphasize the caution with which it must be used.

The recommendations in the Guide are intentionally conservative, and they may, therefore, be applied directly and safely provided the appropriate restricting conditions are met. In this usage it is believed that the Guide will be of value to organizations whose activities with fissionable materials are not extensive. The Guide is also expected to be a point of departure for members of established nuclear safety teams, experienced in the field, who can judiciously extend the specifications to their particular problems. The references in this report will be of especial value to them as reference to the experimental results will aid in guided extrapolations.

Particular attention is called to the recommendations of the Guide relating to arrays of individually subcritical units that may be applied to storage conditions and, a priori, to the arrangement of materials in shipment. A note of caution should be added to the arrangement of materials in shipment. Recognition must be made of the continually increasing frequency of shipments of fissionable materials and of the necessity of exercising some control prohibiting risks which could arise if a number of individually nonhazardous shipments met in transit. In many instances such occurrences are not probable because the container arrangements are controlled by their escort or by the exclusive use of the carrier. The preparation of shipments by common carriers, where controls of this type will not, in general, be exercised, must be very carefully planned.

Recently published reports of importance to the subject material have been included in the reference section.

Preface to first revision

PREFACE

The Nuclear Safety Guide was conceived by a group that met at the Rocky Flats Plant, October 1955, to discuss industrial nuclear safety problems. A committee was selected to prepare a draft for consideration by the group during the following meeting at the Hanford Atomic Products Operation, June 1956. Although the resulting Guide remains controversial in form and general content, differences of opinion concerning specific regulations have been resolved (quite generally in favor of the more restrictive versions). In addition to the committee of authors, the following are members of the nuclear safety group who reviewed drafts of the Guide and contributed suggestions.

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General Electric Company (ANPD): F. G. Boyle
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Los Alamos Scientific Laboratory: J. A. Grundl
Phillips Petroleum Co. (NRTS): R. B. Lemon
Union Carbide Nuclear Company (K-25): H. F. Henry, A. J. Mallett, and C. E. Newlon
Union Carbide Nuclear Company (ORNL): R. Gwin and J. T. Thomas
Union Carbide Nuclear Company (Y-12): J. D. McLendon and J. W. Wachter
University of California Radiation Laboratory (Livermore): C. G. Andre and F. A. Kloverstrom

It is recognized that the Guide is neither handbook (too ambitious for a start) nor manual (a separate problem for each installation). It is hoped, however, that it serves immediate needs for guidance and that it encourages continuing, more comprehensive efforts toward organizing nuclear safety information.

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PART I

THE NUCLEAR SAFETY PROBLEM

INTRODUCTION

The general question considered in this Guide is: How can the neutron chain reaction be prevented in fissionable materials being processed, stored, or transported on an industrial scale? For the discussion this question may be divided into several parts.

There are the purely scientific problems connected with the conditions needed for the chain reaction. These problems can be exactly stated and permit of precise solutions. The solution consists in a number, known as the critical or chain reacting mass, giving the quantity of fissionable material which is just critical in the conditions stated. In principle, if accurate cross section and other nuclear data were available, it would be possible to calculate critical masses. However, at the present time, the data are not sufficient and the theoretical methods are not well enough understood to permit calculation of critical masses to an accuracy of better than about 15 or 20 per cent. It is necessary, then, to depend on experimental measurements of critical mass and extensions of these by theory.

Second, there are the problems of an engineering type. These depend on the detailed circumstances of the situation being considered. Thus, in some process, it is necessary to determine in detail not only the exact physical configuration of the fissionable and other materials involved in the normal course of events in the process, but also, and more important, it is necessary to know those off-standard conditions and configurations which are physically possible in the process equipment and, at the same time, the most favorable for the chain reaction. It is not possible to exactly state and solve general problems here. Rather, each situation must be considered in detail by itself.

Finally, a third type of problem is considered, described as administrative. Work on an industrial scale involves men and equipment. In considering the possible events which may lead to dangerous configurations of fissionable material, it is necessary to know the rules under which the men operate the process equipment, what violations, intentional or not, are possible, and what physical controls exist to minimize violations. It is only with such knowledge that a careful administrative system of routine checks can be set up and carried out effectively.

In summary, the nuclear safety problems of an industrial plant can be described as follows. With a list of known (by experiment) critical masses as a guide, a detailed study is made of the equipment and conditions in which the fissionable material is processed and a safe distribution of mass throughout the plant is determined. Finally, nuclear safety operating rules are formulated in detail, and an administrative system is set up to enforce these rigorously. In this way it is possible to have a high degree of assurance that chain reactions will not occur.

In this Guide we deal in varying emphasis with all three aspects of the nuclear safety problem. In succeeding sections is given a discussion of the factors that govern the critical condition. In Part II is the main content of the Guide which is a compilation of known safe configurations of the three fissionable isotopes U^{233}, U^{235}, and Pu^{239}. These are based on ex-

isting experimental data and extrapolations thereof. In Part III there is a description of a few methods and examples illustrating applications to actual industrial equipment.

In concluding these introductory remarks, it seems appropriate to say that this Guide is by no means to be considered as an authoritative "last word" on the subject. It is rather a preliminary compilation based on experimental data for use in industrial nuclear safety work. At the present time a systematic and thorough treatment is not possible. As mentioned before, we do not know how to calculate critical masses accurately, even in simple idealized geometries. Further, we do not have the necessary data on the nuclear cross sections and other constants. Thus much experimentation remains to be done before definitive theoretical methods can be developed and a systematic and complete treatment of critical masses can be given. Meanwhile, it is hoped that this preliminary Guide will assist those whose purpose and responsibility it is to achieve nuclear safety in industrial plants.

CRITICAL PARAMETERS

As a background for criteria applicable to the problems of nuclear safety, it is appropriate to review the factors which govern the critical condition of an assembly of fissionable material and to discuss some other aspects including the origin of the criteria and their administration.

For an accumulation to be chain-reacting, there is required, of course, a quantity of the fissionable isotope, referred to as the critical mass, which is not single valued but depends very strongly on a number of factors which will be described briefly.

One factor of importance is the leakage, from the system, of neutrons which would otherwise produce fissions. The leakage depends on the shape of the fissionable system and on the neutron-reflecting properties of surrounding materials. It is possible, for example, to specify solution container dimensions, such as pipe diameters, which give a sufficiently unfavorable surface area to volume ratio to prevent a chain reaction regardless of the quantity of material contained. If the pipe is encased in a cooling jacket, or is near other process equipment or structural materials, its dimensions must be less than it would be if there were no neutron reflector proximate. In the treatment presented here, it is assumed that water, concrete, graphite, and stainless steel are typical reflector materials. Although more effective reflectors are known—heavy water and beryllium as examples—they are uncommon in processing plants. Consideration is given, therefore, to reflectors of three thicknesses in an attempt to make the specifications more generally applicable. The equipment may be nominally unreflected, i.e., the only neutron reflector is the container itself, the wall of the stainless-steel pipe, for example; it may be completely reflected by a surrounding layer of water at least 6 in. thick; the third reflector considered is a "thin" one consisting of a 1-in.-thick layer of water (or the equivalent) exemplified by the water in a cooling jacket.

The value of the critical mass is extremely sensitive to the presence of hydrogen, or other neutron moderating elements, intimately mixed with the fissionable isotope. In nuclear physics considerations the hydrogen concentration is usually expressed as the ratio of the number of hydrogen atoms to the number of fissionable atoms and may range from zero for metal or a dry unhydrated salt to several thousand for dilute aqueous solutions. Over this concentration range the critical mass may vary from a few tens of kilograms, through a minimum of a few hundred grams, to infinity in very dilute solutions where the neutron absorption by hydrogen makes chain reactions impossible. In this latter limit nuclear safety is assured by the chemical concentration alone. The ~~following~~ recommendations in the following sections are based on homogeneous and uniform distributions of the fissionable materials in the moderator.

The critical mass of any process material varies inversely as its density in a manner depending on other characteristics of the assembly; it depends, in a somewhat similar manner, on the isotopic concentration of the fissionable element.

Strong neutron absorbers in solution have not been generally used to increase capacities because they ~~must be homo~~geneously mixed with the process materials for effects to be predictable, ~~thereby presenting subsequent purification problems~~. Coating a thin-wall, otherwise unreflected, vessel with cadmium, for example, actually increases the reactivity since additional neutron reflection is provided by the cadmium. If the vessel were submerged in water, the reactivity would

be significantly less with the cadmium than without it. The presence of nitrogen in the nitrate solutions often used in chemical processing, or of Pu^{240} as an impurity in plutonium solutions, increases the margin of safety.

Most homogeneous accumulations of fissionable materials have negative temperature coefficients of reactivity which are due to density changes, including the formation of vapors in liquid systems, and the change in neutron energy distributions. Although this property is important in reactor designs where it facilitates shutdown in case of a power excursion, it does not contribute to the prevention of such excursions. Much damage can occur before the temperature effect begins to control a reaction initiated at a low temperature. The values of the temperature coefficient depend on the material, the geometry of the system, and the temperature range. The presence of resonances in the energy distribution of cross sections may alter the relative importance of the density and neutron energy contributions to the over-all coefficient.

The preceding comments have referred to single volumes. In most plant problems the effect of the exchange of neutrons between individual components of an array of vessels must be considered in order to assure safety in the whole system.

DESIGN CRITERIA

It is possible to avoid nuclear hazards by designing into a process one or more of the full limitations outlined above, but it is equally apparent that the result probably would be very inefficient and uneconomic. The practical approach to design problems has been through a combination of partial limitations whereby each one of several contributes some safety and none is sufficiently stringent to greatly impair the over-all economy.

As mentioned in the Introduction, the bases for the design of equipment and processes for the fissionable isotopes are almost entirely predicated on results from necessarily restricted critical experiments or on interpolations or extrapolations of these results. Many experiments have also been performed which show that particular situations were not critical—important results but of limited application. In spite of an impressive accumulation of background data, many gaps exist which must be covered by extremely conservative estimates. Thus the recommendations given in the succeeding sections are, in some cases, probably overly conservative; it is hoped that none errs in the other direction. Further, in practice, it has been customary to assume operating conditions to be more severe than they probably will be. Most piping, for example, has been designed on the assumption that it may become surrounded by a thick layer of water—perhaps it will because of the rupture of a water main and the stoppage of drains—but a more important reason for such conservative designs is the unknown neutron-reflecting properties of nearby concrete walls, floors, neighboring water lines, and process vessels and of personnel. The recommendations presented below for partial or "nominal" reflectors are truly applicable in borderline cases if the user can assure to his satisfaction that the stated conditions will not be violated. As more confidence is gained, not only in the bases for nuclear safety but also in the predictability of operating conditions, more liberal approaches to the problems will evolve.

INSTRUMENTATION

Radiation-detecting instrumentation is not useful in indicating margins of safety in operations except, possibly, in a few special instances. Any approach to a critical condition is manifested by the multiplication of the ambient neutron field by the fissionable nuclei so some supply of neutrons is necessary in order to detect the multiplying medium. Spontaneous fissions occur in subcritical arrays, frequently at an almost undetectable rate, and the product neutrons produce more fissions, establishing a low-level steady-state activity. In some special cases neutrons may be produced in reactions between the constituents of some process materials—in aqueous solutions of plutonium salts, for example, where the neutrons arise from the interaction of plutonium alpha particles with oxygen. These neutrons can also be multiplied and can establish an activity level which may be detected adequately. As more fissionable material is added to the system, this level increases but usually does not reach

a significant value until the system becomes supercritical. Then, the time rate of change of radiation level increases rapidly. To have observed the changes in the subcritical neutron multiplication would have been practically impossible in most instances because of the low initial level and because it is the rate of change in this level that is indicative of the approach to criticality. A possible solution to this difficulty is the inclusion of a strong neutron source in the system and the observation of changes in the level as material is added. This is the way critical experiments are performed, and experience has shown that the neutron source, the detector, and the fissioning material must be carefully located with respect to each other in order to achieve results which yield meaningful values of the so-called neutron multiplication. To equip process operations in the necessary elaborate manner is generally not practical. Instrumentation has, however, been installed in many operations to indicate the radiation hazard which would exist after a radiation accident had occurred, and reference is made to standard Health Physics procedures for the description of recommended equipment. The utility of other than very specially installed detectors can be summarized by saying they are important after an accident, not in predicting that one is imminent.

CONSEQUENCES OF A NUCLEAR ACCIDENT

It is obviously impossible to predict the results of an accidental accumulation of a supercritical quantity of fissionable material because the neutron background, rate of assembly, type of material, excess mass over that required to be critical, and degree of confinement are among the factors which determine the magnitude of the occurrence. Several supercritical assemblies have occurred, however, in the programs of critical experiments, which perhaps set lower limits on the damage to be expected. These experiments have, for the most part, resulted from the accidental achievement of an effective neutron-reproduction factor only 2 or 3 per cent greater than unity, the value required for the system to be chain-reacting. This condition has resulted from the addition of the order of a few per cent excess mass in experiments where water was present as a neutron moderator. A decrease in the density of the water, due to vaporization and dissociation, was, no doubt, a significant factor in limiting the extent of the excursions. The energy released in each of these accidents has originated in about 10^{17} fissions and amounted to about 1 kw-hr. The containing vessels were open to the atmosphere so no explosion occurred, although vessel deformations were observed. Monitoring equipment has shown the excursions to have been accompanied by neutron and gamma radiation of sufficient intensity to have produced lethal exposures at distances up to a few feet from the source.

It is of interest to consider an example of the margin between a subcritical, "safe" system, and one which is prompt critical, i.e., chain-reacting on prompt neutrons only. The latter is completely out of control. A mass of 2.2 kg U^{235} in an aqueous solution of U^{235} at a concentration of 459 g/liter contained in a cylinder 10 in. in diameter and 3.8 in. high has an effective neutron-reproduction factor of 0.9 when surrounded by a neutron reflector. As increment of 900 g U^{235} will make the reproduction factor unity; i.e., the cylinder will be delayed critical at a height of 5.3 in.; only 67 g additional is now required to make the vessel prompt critical. If the reproduction factor should be made greater than unity by even an infinitesimal amount, the activity would increase with the ultimate release of lethal quantities of radiation. This condition would be reached immediately if the cylinder became prompt critical. It is pointed out that this is a randomly selected example, and there are probably combinations of parameters, certainly with plutonium solutions, where the reactivity is even more sensitive to mass additions.

ADMINISTRATION OF NUCLEAR SAFETY

The administration of nuclear safety practices is determined in detail by the functions of the organization. Those installations having continuing problems as a consequence of their inventory of fissionable materials, or because of frequent alterations in their process, have, in the past, assigned to staff groups the responsibility for advising design and operating personnel in these matters. The infrequent problems of facilities processing only small amounts of material have often been referred to qualified persons in other organizations. A representative

example of the administrative practices in an organization of the former class is described here. It is recognized that modification will be necessary to meet the needs of others.

The responsibility for nuclear safety in the plant considered is placed on line organization. Individuals directing activities of such a nature as to involve nuclear hazards are responsible for control in these activities to the same extent that they are responsible for research, design, maintenance, and operations. ~~An approvals~~ committee, reporting to the plant manager and composed of personnel familiar with the potential hazards and methods of their control, approves the procedures and equipment to be used on the operational processes and in storage and shipment procedures.

In the administration of the safety practice, line supervision responsible for any design or operations obtains approval of those parts which involve nuclear safety. Necessary information is furnished to the ~~approvals~~ committee, including the type, quantity, and chemical composition of the material; its concentrations and density; the dimensions and geometric shapes of the containers; and a flow sheet of the process. The committee investigates each problem, advises the originating group on the hazards which may be incurred, and approves the final design and procedure. In general, such approval specifies necessary operating restrictions.

The nuclear safety of any process ~~will~~ should be assured, wherever possible, by the dimensions of the components, such as pipe sizes and container capacities, including spacing between individual components of the same or adjacent systems, or by the presence of fixed poisons such as borosilicate glass. Where safety based on geometry alone is precluded, designs may be predicated on batch sizes and/or chemical concentrations, ~~or~~ combinations of them with geometry, and such designs will not be considered satisfactory ~~only if~~ unless two or more simultaneous and independent contingencies must occur to promote a chain reaction. In the use of these nongeometric safety criteria, operational supervision is responsible for accuracy in sampling and analytical procedures.

relocate to design criteria

Poison Basic safe numbers

reflector	shape	U^{235} solution	U^{235} metal	Pu^{239} solution	Pu^{239} metal	U^{233} solution	U^{233} metal
thick water	sphere	5.9	4.1	5.7	2.55	5.1	2.95
"	cylinder	6.35	4.3	6.15	2.65	5.5	3.1
"	slab	6.6	4.55	6.4	2.8	5.7	3.3
nominal	sphere	4.35	3.3	4.25	2.15	3.95	2.6
"	cylinder	4.7	3.6	4.6	2.3	4.25	2.7
"	slab	4.9	3.7	4.75	2.4	4.4	2.85
minimal	sphere	2.45	2.3	2.45	1.64	2.45	1.9
"	cylinder	2.55	2.7	2.55	2.05	2.55	2.3
"	slab	3.05	2.7	3.05	2.05	3.05	2.3

PART II

BASIC NUCLEAR SAFETY RULES

RULES FOR INDIVIDUAL SYSTEMS

From the discussion of Part I, it is clear that the potential hazard of a system of fissionable material may be influenced by a multitude of factors that defy generalization. Special equipment may be crowded between vessels for emergency repairs; a large bucket may be placed under a leaking geometry-safe column; a janitor may stack spaced cans into a neat pile. A container volume that is safe for all foreseen external conditions may be unsafe with re-entrant water-filled passages. These are examples of the factors not included in the following rules that may lead to difficulty unless margins of safety are generous.

Basic Rules for Individual Systems

Basic regulations for simple, homogeneous, individual systems are stated alternatively as mass limits in ~~Table 1~~ (kilograms of fissionable isotope), as container capacity limits in ~~Table 2~~, and as dimensional limits in ~~Tables 3 and 4~~. References in the ~~tables~~ give critical parameters on which the limits are based and include some supporting calculations. The mass limits include factors of safety of ~~slightly more than 2~~ as a safeguard against double batching. Capacity limits include factors of safety of ~~at least~~ $1\frac{1}{3}$, and the equivalent margins appear in dimensional limits (even with unspecified dimensions infinite).* Added to normal safety factors are allowances for uncertainties in critical data on which the limits are based.

Specifications are given for various ranges of H/X atomic ratio ($X \equiv U^{235}$, Pu^{239}, or U^{233}) and for limited types of reflector. Although thick beryllium, D_2O, uranium, or tungsten reflectors are more efficient than thick water,[6] the latter is considered the most effective reflector that is likely to be encountered in ordinary processing or handling operations. "Nominal reflector" refers to water no more than 1 in. thick. Surrounding fissionable metal systems, $1\frac{1}{2}$-in.-thick graphite (or $1\frac{1}{2}$-in.-thick steel) is equivalent in effect to 1-in.-thick water (in small thicknesses water is one of the more effective reflectors). For solutions, equal thicknesses of steel and water are nearly equivalent.[13] "Minimal reflector" refers to no more than $\frac{1}{8}$-in.-thick stainless steel, or the same thickness of other common metal including iron, copper, aluminum, nickel, or titanium. Unless conditions are rigidly controlled, the appropriate limit for thick water reflector should be used for all applications, ~~and for solutions the limit also should be the most restrictive of those given for the various H/X ranges~~.

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*Upper limits for ~~values in Tables 3 and 4~~ were obtained from constant-buckling conversions of capacities in ~~Table 2 (for metals, Table 1 volumes increased 50 per cent)~~. Extrapolation lengths used ~~were: 5.5 cm for solutions, 4.1 cm for U^{235} metal, 2.8 cm for Pu^{239} metal, 3.1 cm for U^{233} metal in thick water reflector; 3.5 cm for solutions, 3.2 cm for U^{235} metal, 2.3 cm for Pu^{239} metal, 2.5 cm for U^{233} metal in nominal reflector; 2.4 cm for solutions, 2.2 cm for U^{235} metal, 1.7 cm for Pu^{239} metal, 1.8 cm for U^{233} metal in minimal reflector.~~ appear in the following table. Volume interpolation between solution and metal values was applied for effective densities greater than 1 g/liter.

Table 1—MASS LIMITS FOR INDIVIDUAL SYSTEMS

(Maximum mass in kg of X ≡ U^{235}, Pu^{239}, or U^{233})

	Metal, low H mixtures, compounds	Principally hydrogenous compounds, mixtures	Principally solutions	
	0 ≤ H/X ≤ 2	H/X ≤ 20	H/X ≤ 100	H/X unlimited*
U^{235} (Refs. 1–6)				
Thick water reflector	11.0	2.5	0.80	0.35
Nominal reflector (≤ 1 in. water)	15.0	3.5	1.04	0.43
Minimal reflector (≤ 1/8 in. S.S.)	22.0	5.0	1.40	0.55
Pu^{239} (Refs. 4, 6–8)				
Thick water reflector	2.6†	2.2	0.50	0.25
Nominal reflector (≤ 1 in. water)	3.3†	3.2	0.70	0.32
Minimal reflector (≤ 1/8 in. S.S.)	4.4†	4.8	1.00	0.43
U^{233} (Refs. 4, 6, 8–10)				
Thick water reflector	3.0	1.3	0.48	0.25
Nominal reflector (≤ 1 in. water)	4.1	1.7	0.69	0.33
Minimal reflector (≤ 1/8 in. S.S.)	6.0	2.3	0.90	0.45

*See p. 9 for values of H/X beyond which no limit is required.

†These limits apply to Pu metal at ρ = 19.6 g/cm^3; for alloy at ρ = 15.8 g/cm^3, the corresponding limits are 3.5 kg with thick water reflector, 4.8 kg with nominal reflector, and 7.0 kg with minimal reflector.

Table 2—CONTAINER CAPACITY LIMITS FOR INDIVIDUAL SYSTEMS

(Maximum volume in liters)

	Principally solutions		
	20 ≤ H/X	400 ≤ H/X	800 ≤ H/X
U^{235} (Refs. 2–5)			
Thick water reflector	4.8	9.5	20.0
Nominal reflector (≤ 1 in. water)	6.0	11.3	24.0
Minimal reflector (≤ 1/8 in. S.S.)	8.0	14.0	30.0
Pu^{239} (Refs. 4, 7, 8)			
Thick water reflector	3.3	6.8	11.4
Nominal reflector (≤ 1 in. water)	5.0	9.3	14.7
Minimal reflector (≤ 1/8 in. S.S.)	6.6	13.0	19.7
U^{233} (Refs. 4, 9, 10)			
Thick water reflector	2.0	6.0	12.0
Nominal reflector (≤ 1 in. water)	3.0	8.4	14.4
Minimal reflector (≤ 1/8 in. S.S.)	4.0	12.0	18.0

Table 3—SAFE CYLINDER DIAMETERS FOR INDIVIDUAL SYSTEMS

(Maximum diameter of cylinder of fissionable material in inches; for solution, ID of containing cylinder)

	Metal at full density	Principally solutions		
		20 ≤ H/X	400 ≤ H/X	800 ≤ H/X
U^{235} (Refs. 2, 4–6)				
Thick water reflector	2.5	5.0	6.9	9.1
Nominal reflector (≤ 1 in. water)	3.0	5.8	7.7	10.2
Minimal reflector (≤ 1/8 in. S.S.)	3.8	6.7	8.5	11.0
Pu^{239} (Refs. 4, 6–8)				
Thick water reflector	1.4*	4.5	6.1	7.4
Nominal reflector (≤ 1 in. water)	1.7*	5.7	7.2	8.5
Minimal reflector (≤ 1/8 in. S.S.)	2.0*	6.8	8.3	9.6
U^{233} (Refs. 4, 6, 10)				
Thick water reflector	1.5	3.7	5.8	7.4
Nominal reflector (≤ 1 in. water)	1.9	4.7	6.9	8.4
Minimal reflector (≤ 1/8 in. S.S.)	2.3	5.7	8.1	9.4

* These limits apply to Pu metal at ρ = 19.6 g/cm^3; also to be used for alloy at reduced density.

Table 4—SAFE SLAB THICKNESSES FOR INDIVIDUAL SYSTEMS

(Maximum slab thickness in inches)

	Metal at full density	Principally solutions		
		20 ≤ H/X	400 ≤ H/X	800 ≤ H/X
U^{235} (Refs. 4, 6, 11, 12)				
Thick water reflector	0.7	1.4	2.5	4.0
Nominal reflector (≤ 1 in. water)	1.2	2.4	3.6	5.2
Minimal reflector (≤ 1/8 in. S.S.)	2.0	3.3	4.4	6.1
Pu^{239} (Refs. 4, 6–8)				
Thick water reflector	0.2*	1.5	2.5	3.3
Nominal reflector (≤ 1 in. water)	0.5*	2.6	3.7	4.6
Minimal reflector (≤ 1/8 in. S.S.)	0.9*	3.6	4.8	5.6
U^{233} (Refs. 4, 6, 10)				
Thick water reflector	0.2	0.5	1.9	2.9
Nominal reflector (≤ 1 in. water)	0.5	1.7	3.2	4.2
Minimal reflector (≤ 1/8 in. S.S.)	1.0	2.5	4.2	5.1

* These limits apply to Pu metal at ρ = 19.6 g/cm^3; also to be used for alloy at reduced density.

The type of limit ~~most convenient for a given~~ application ~~may be chosen~~. Mass limits are particularly appropriate for handling of metal or compounds or for processing solution batches where there is no volume or dimensional control. Container capacity limits and "safe" cylinder diameters are best suited for solutions. ~~The~~ principal value of safe slab thicknesses is ~~for~~ the design of catch basins for solutions in case of leakage of the normal container and for the control of isolated metal sheet.

Conditions That Require Special Consideration

The basic rules do not apply to "reactor compositions" such as dilute fissionable material in heavy water, beryllium, or graphite (where D/X, Be/X, or C/X > ~100) or to systems with thick reflectors of these materials, normal uranium, or tungsten.

The rules also fail to apply in the cases in which ~~the densities of fissionable material (vs. H/X)~~ exceed the values[2,7] of Figs. 1 and 2. In the event that the density of fissionable material, ρ, is greater than the density, ρ_0, from Figs. 1 or 2, mass limits of Table 1 should be reduced by the ratio $(\rho_0/\rho)^2$, the container volume limits of Table 2 by $(\rho_0/\rho)^3$, and the container linear dimension of Tables 3 and 4 by (ρ_0/ρ). If ρ is less than ρ_0, limits must not be increased by these ratios.

Again, the rules for nominal or minimal reflector, or for solutions in a limited range of ~~H/X,~~ may be applied only if these conditions are rigidly controlled.

Conditions Under Which Basic Limits Are Not Required

For solutions or other homogeneous hydrogenous mixtures, no further restriction is required[14] if (1) for U^{235}: the atomic ratio $H/U^{235} \geq 2300$, which corresponds to the ~~concentration~~ $\rho(U^{235}) \leq$ g/liter in aqueous (light water) solution; (2) for Pu^{239}: $H/Pu^{239} \geq 3600$, which corresponds to $\rho(Pu^{239}) \leq 7.8$ g/liter in aqueous solution; and (3) for U^{233}: $H/U^{233} \geq 2300$, which corresponds to $\rho(U^{233}) \leq 11$ g/liter in aqueous solution. These values contain no factor of safety; in application a margin compatible with control errors should be maintained.

Any mass of ~~natural or depleted~~ uranium homogeneously distributed in light water is safe.

Uranium in which the atomic ratio U^{235}/U^{238} is equal to or less than 0.05 needs no further restriction provided it is (1) in the form of metal with no interspersed hydrogenous material, e.g., a single piece; (2) in a nonhydrogenous chemical compound; or (3) intimately mixed, either as metal or a nonhydrogenous compound, with any element of atomic number, Z, greater than 13 if the atomic ratio $Z/U^{235} \leq 100$ (Ref. 8).

Conditions Under Which Basic Limits May Be Increased

For certain intermediate shapes of fissionable system, such as elongated or squat cylinders, mass and container capacity limits may be increased by the appropriate factor[4,6,7] from Fig. 3.

For undiluted fissionable metal* at density less than normal (17.6 g/cm^3 for U^{235}, 19.6 g/cm^3 for Pu^{239}, and 18.3 g/cm^3 for U^{233}), such as metal turnings, the mass limit may be increased by the appropriate factor[6] from Fig. 4. Factors from this figure also may be applied to solutions with uniformly distributed voids (≤ 1 in. in one dimension), ~~for which H/X ≥ 100,~~ provided "fraction of total density" is interpreted as the ratio of average density of solution plus void to the solution density.[13] Figure 5 shows factors by which the mass limits ~~in the first column of Table 1~~ may be increased if fissionable atoms are mixed uniformly with any of the listed elements either as physical mixtures or chemical compounds.[8,15] It is emphasized that no H_2, D_2, or beryllium can be present if these factors are applied. Although intended primarily for homogeneous systems, these factors may be used for similar units of X distributed uniformly in the diluent provided one dimension of the unit does not exceed 1/8 in. for U^{235} or 1/16 in. for

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*Uranium metal enriched in U^{235} is sometimes referred to as "Oralloy," abbreviated Oy, with a suffix designating the U^{235} enrichment. For example, Oy(93) indicates uranium that is 93 wt. % U^{235}.

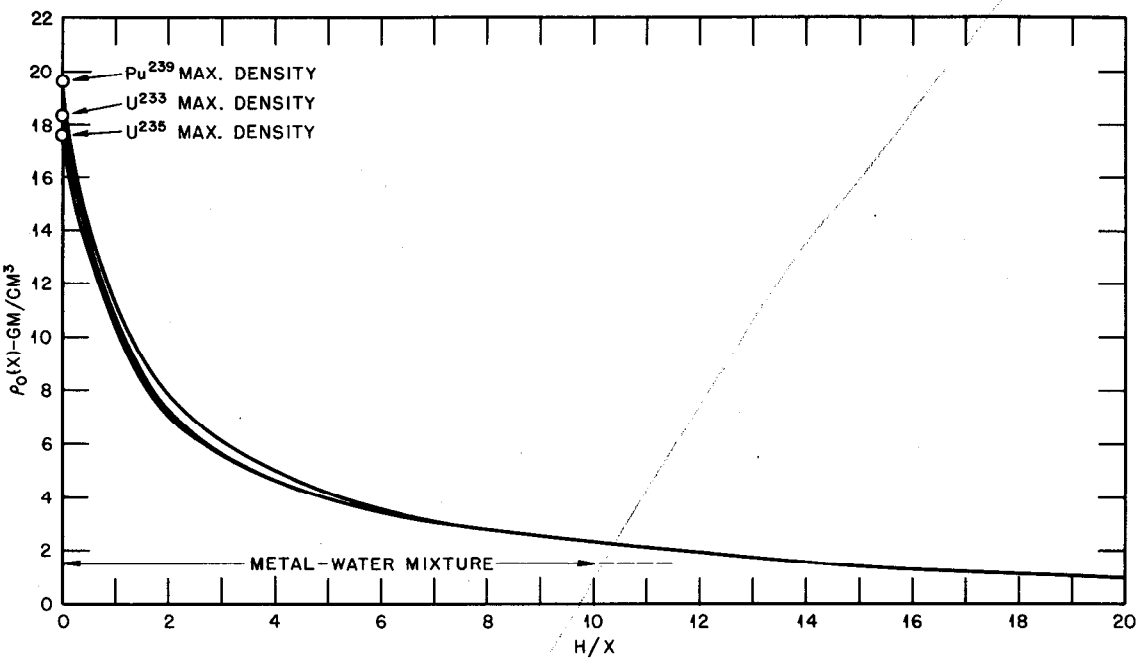


Fig. 1—Assumed densities of U^{235}, Pu^{239}, or U^{233} at $H/X \leq 20$. (If a density exceeds the indicated value by the ratio n, reduce mass limits by the factor $1/n^2$, volume limits by $1/n^3$, and linear dimension limits by $1/n$.)

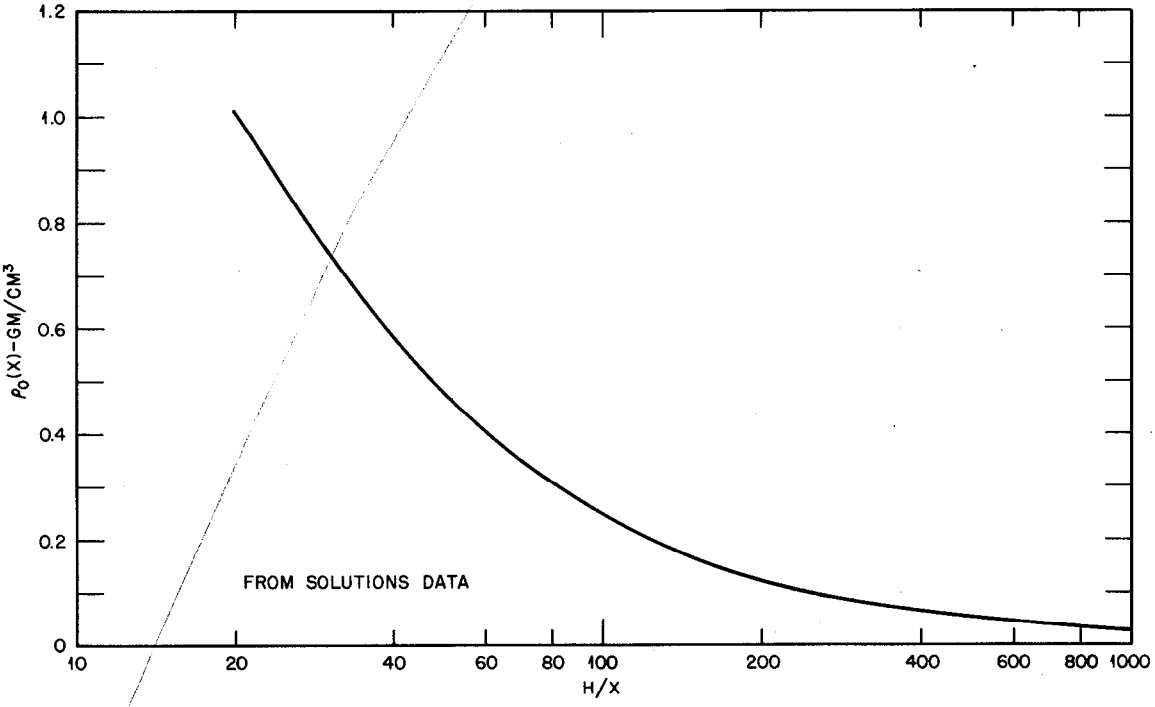


Fig. 2—Assumed densities of U^{235}, Pu^{239}, or U^{233} at $H/X \geq 20$. (If a density exceeds the indicated value by the ratio n, reduce mass limits by the factor $1/n^2$, volume limits by $1/n^3$, and linear dimension limits by $1/n$.)

Reider

Expansion by factor of two

consequences of nuclear accidents

administration of nuclear safety training, evacuation, practices

Tables more widely used than curves, but tables are fuller.

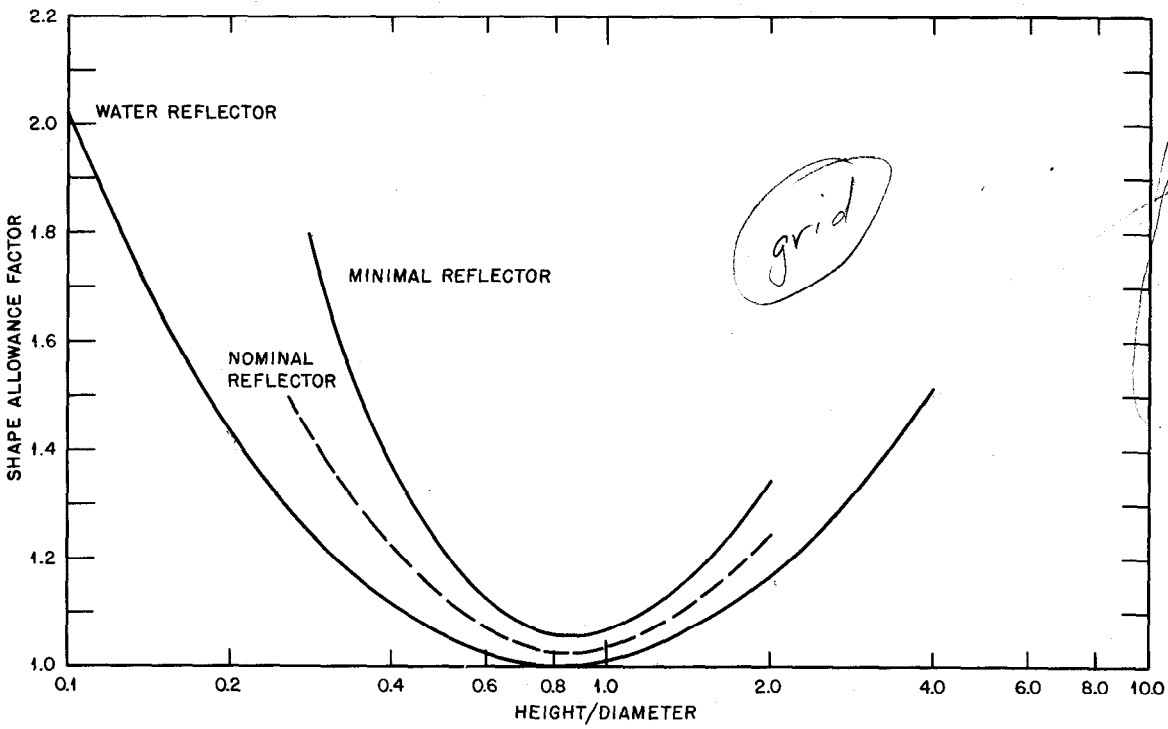


Fig. 13—Shape allowance factors for cylinders (factor by which mass and volume limits may be increased for elongated or squat cylinders).

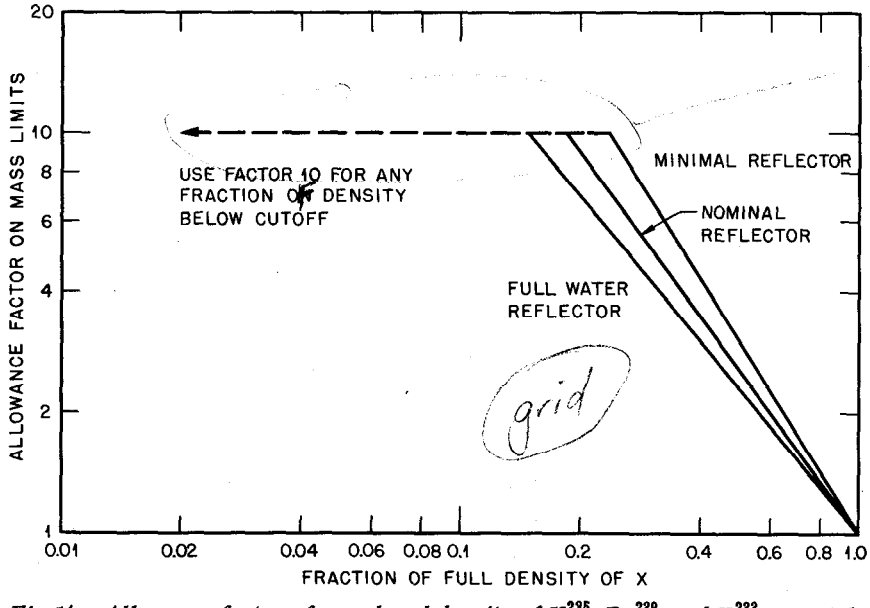


Fig. 14—Allowance factors for reduced density of U^{235}, Pu^{239}, and U^{233} as metal only. Full U^{235} density = 17.6 g/cm^3, full Pu^{239} density = 19.6 g/cm^3, and full U^{233} density = 18.3 g/cm^3.

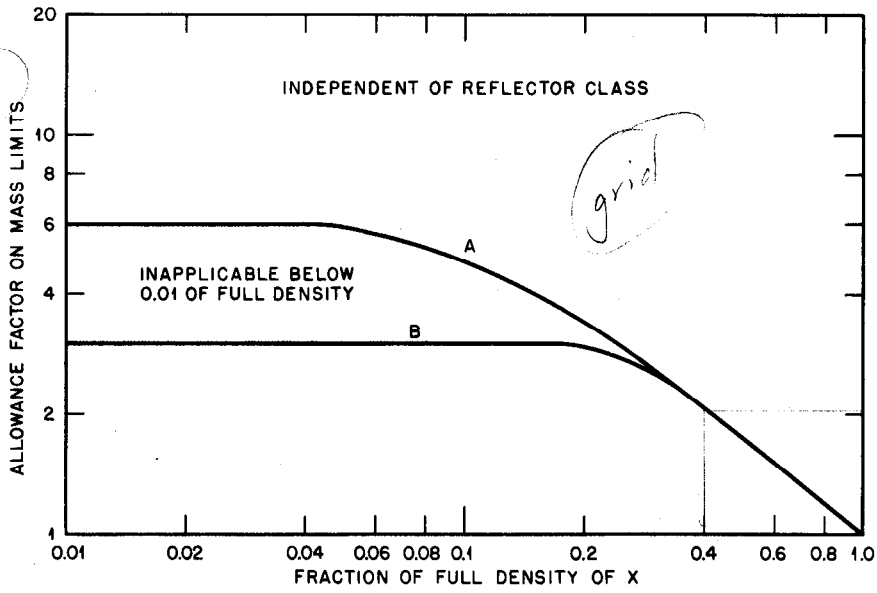


Fig. 5 — Allowance factors for reduced density of U^{235}, Pu^{239}, or U^{233} mixed homogeneously with elements listed (H, D, and Be excluded). Curve A: any element for which $11 \leq Z \leq 83$ (from Na to Bi). Curve B: compounds of X and C, N, O, F, and elements $11 \leq Z \leq 83$, with at least 1 atom of X per 7 others, e.g., UC, UO_2, U_3O_8, UO_3, UO_2F_2, UF_4, and UF_6). Full U^{235} density = 17.6 g/cm^3, full Pu^{239} density = 19.6 g/cm^3, and full U^{233} density = 18.3 g/cm^3.

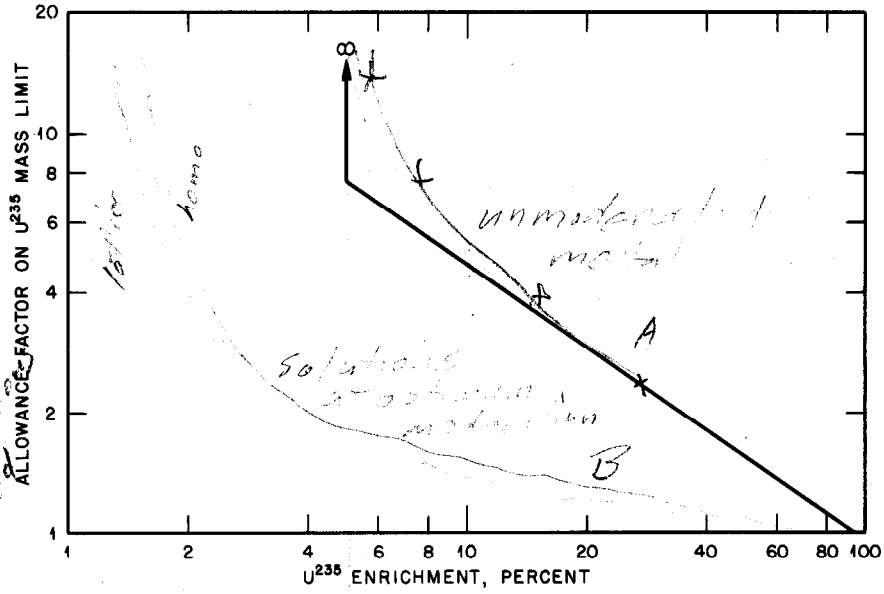


Fig. 6 — Allowance factors on U^{235} mass limits for uranium ~~metal~~ at intermediate U^{235} enrichments.

Pu^{239} or U^{233}. (The factors are not applicable to mixtures having X densities less than 1 per cent of the full density in order to guard against moderation by relatively large proportions of nuclei of intermediate atomic number.)

In the special case of undiluted uranium metal in which the U^{235} content is less than 93 per cent, the U^{235} mass limit may be increased by the appropriate factor[6] from Fig. 16. A factor for reduced density of total uranium (not U^{235}), from Fig. 14, may be applied in addition to this enrichment factor.

As stated before, the mass limits of Tables 1 contain a factor of safety of ~~slightly more~~ than ~~2~~ as protection against a double-batching error. (The capacity limits have a ~~somewhat~~ smaller safety factor.) Where the possibility of over-batching is excluded, the basic mass limit may be increased by the factor 1.7.

RULES FOR INTERACTING UNITS

General Criteria

Empirically formulated specifications for the spacing of individually subcritical units in an array which is also subcritical have been established.[16–19] These specifications are predicated on the assumptions that the over-all neutron multiplication factor, k, of several vessels is determined by the values of k of the individual components and by some probability that neutrons leaking from one vessel will be intercepted by another. This probability, in turn, is related to a geometric parameter which is a simplified expression for the total solid angle subtended at the most centrally located unit by the other components of the array. In the method referred to here this solid angle is calculated by a "point-to-plane" method where the point is on the most centrally located unit and the planes either define the boundaries of the other units or are appropriate projections of the boundaries. Examples of this calculation are given in Fig. 17. The total solid angle is, of course, the sum of the angles subtended by the individual units.

~~Currently applicable~~ specifications for unit spacings are determined by a method, detailed in the above references, in which the reactivity of each unit is estimated by a two-group diffusion theory and the total solid angle then set by an empirical relation. This method is strongly supported by extensive experimental measures of the critical conditions of a large assortment of arrays of various shaped vessels containing U^{235} in a variety of forms.[5,20,21]

For the purposes of this Guide a total solid angle of one steradian is selected as a conservative limit on the solid angle, calculated by the method described above, subtended at the unit which "sees" the others to the greatest extent. The units referred to here are those described in ~~Tables 1 to 4~~, including appropriate allowance factors. In calculating the total solid angle, fully shielded units may be ignored; e.g., the first and fifth of five identical cylinders with axes coplanar do not contribute to the solid angle at the center one. In those instances where flooding of the array by water is a possibility, a concomitant specification is the requirement that each vessel be spaced from its nearest neighbor by at least 12 in. or by 8 in. if there are only two units. This specification is based on the observation that these thicknesses of water or materials of comparable hydrogen density effectively isolate the unit.[20,22]

Storage and Transportation Rules ~~for Special Units~~

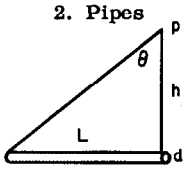
Consideration, based on experiments to establish storage and transportation rules, is given here to arrays of units ~~of relatively~~ small volume and ~~possibly~~ high density. It is assumed that the control of the size of individual units is more stringent than in the production operations of a process, thereby allowing a relaxation of the double-batching safety factors imposed above. It is further assumed that the units are either bare or are in relatively light containers (nominal reflectors) and are spaced by birdcages, compartments, or specifically located anchorages. Table 5 specifies maximum units of this class. These units may be in-

A. Formulae

1. General

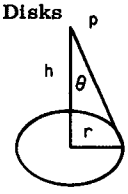
$$\Omega = \frac{\text{Cross Sectional Area}}{(\text{Separation Distance})^2}$$

2. Pipes



$$\Omega = \frac{d}{h} \sin \Theta$$

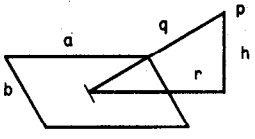
3. Disks



$$\Omega = 2\pi (1 - \cos \Theta)$$

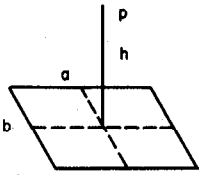
4. Planes

a.



$$\Omega = \frac{ab \cos \Theta}{q^2}$$

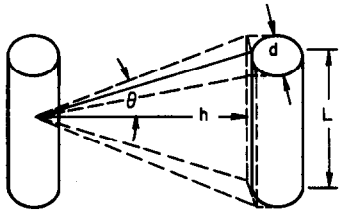
b.



$$\Omega = 4 \sin^{-1} \frac{\left(\frac{a}{2}\right) \left(\frac{b}{2}\right)}{\sqrt{\left(\frac{a}{2}\right)^2 + h^2} \sqrt{\left(\frac{b}{2}\right)^2 + h^2}}$$

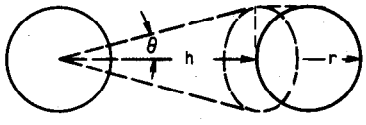
B. Applied Methods

1. Cylinders



$$\Omega = \frac{2d}{h} \sin \Theta$$

2. Spheres



$$\Omega = 2\pi (1 - \cos \Theta)$$

Fig. 7—Solid angle calculations.

Table 6—MAXIMUM SIZES OF UNITS TO WHICH TABLES 6 AND 7 APPLY

	Maximum unit*		
	U^{235}	Pu^{239}	U^{233}
Metal, compounds, or mixtures, H/X ≤ 2; mass limits, kg	18.5‡	4.5§	4.5
Hydrogenous compounds or mixtures, 2 < H/X < 20; mass limits, kg†	3.6	2.4	2.0
Solutions, or hydrogenous mixtures, H/X ≥ 20, in non-safe containers;¶ volume limits, liters	3.6	2.4	2.0

* If density (ρ) is greater than the reference value (ρ_0) in Fig. 1 or 2, reduce mass limits by the factor $(\rho_0/\rho)^2$, volume limits by $(\rho_0/\rho)^3$.

† Material volume of unit is not to exceed 4.5 liters.

‡ This corresponds to 20 kg of uranium enriched to about 98 per cent in U^{235}.

§ This limit holds for Pu metal at ρ = 19.6 g/cm^3; for the alloy at ρ = 15.8 g/cm^3, the corresponding limit is 6.0 kg.

¶ For safe containers defined in Table 3, there is no mass or volume limit for stable solutions (H/X ≥ 20).

creased by the shape allowance factors of Fig. 3 and the metal density and U^{235} enrichment factors of Figs. 4 to 6 but not, of course, by the allowance for perfect batch control.

Again, certain reactor compositions, as dilute mixtures with D_2, beryllium, or carbon, must be treated as special cases.

Storage

The storage rules of Table 6 allow a factor of safety greater than 2 (in number of units) for arrays in a concrete vault that is not less than 9 ft in smallest dimension. Arrays that are safe in a concrete vault also will be safe in vaults of other materials such as steel, wood, or earth. For convenience the storage rules are given in terms of number of maximum units at a given center-to-center spacing between units. A maximum unit may consist of a close-packed group of smaller units provided the total quantity specified for a maximum unit is not exceeded. Storage arrays defined in Tables 5 and 6 will be safe if fully flooded by water provided the edge-to-edge separation between maximum units is at least 12 in. and not more than 10 per cent of the volume of composite units can be occupied by water.

Isolated and associated arrays referred to in Table 6 are described in the following manner. Two arrays are effectively isolated from one another if they are completely separated by concrete at least 8 in. thick.[22] Two plane (i.e., items with centers coplanar) or cubic (i.e., items with centers in three dimensions) arrays are also isolated if the separation (minimum edge-to-edge spacing between any unit in one array and any unit in the other) is the larger of the following quantities: (1) the maximum dimension of one array and (2) 12 ft (Ref. 23). Two linear arrays are isolated regardless of length if the separation is at least 12 ft. Nonisolated plane arrays are associated if the minimum edge-to-edge spacing between units in the two arrays is at least 7½ ft; if the separation is less, they are to be regarded as a single array.

Transportation

Table 7 is a set of rules for shipment of units of fissionable materials defined in Table 5. "Maximum density established by birdcage or shipping case" is based on a unit packaged in a 20-in. birdcage.

Table 6 — LIMITS FOR STORAGE ARRAYS OF UNITS DEFINED IN TABLE 5

Type of array	Minimum center-to-center spacing of units within array, in.*	Storage limit per array (No. of max. storage units)†
Isolated linear or plane array	≥16	No limit
Isolated cubic array	36	200
	30	120
	24	80
	20	50
Two associated plane arrays	30	120/array, 240 total‡
	24	90/array, 180 total‡
	20	50/array, 100 total‡

* Edge-to-edge separation of units must be at least 12 in.

† In the case of safe containers for solution (H/X ≥ 20) defined in Table 3, there is no limit for a parallel in-line array at a minimum axis-to-axis spacing of 24 in. or for two associated in-line arrays where the spacing in each array is 24 in.

‡ The same total storage limit applies to more than two associated arrays.

Table 7 — LIMITS FOR SHIPMENTS OF UNITS DEFINED IN TABLE 5

	Max. density established by birdcage or shipping case*			Normal carload limit (50 max. shipping units except for safe cylinders)†		
	U^{235}	Pu^{239}	U^{233}	U^{235}	Pu^{239}	U^{233}
Metal, compounds or mixtures, H/X ≤ 2; mass limits	4 kg/ft³	1 kg/ft³	1 kg/ft³	925 kg/car	225 kg/car	225 kg/car
Hydrogenous compounds or mixtures, 2 < H/X ≤ 20; mass limits	1 kg/ft³	1 kg/ft³	0.5 kg/ft³	225 kg/car	225 kg/car	125 kg/car
Solutions, or hydrogenous mixtures, H/X ≥ 20, in non-safe containers‡	0.8 liter/ft³	0.8 liter/ft³	0.4 liter/ft³	225 liters/car	225 liters/car	100 liters/car

* This density is (mass of unit)/(birdcage volume); birdcages or cases shall define at least 1 ft edge-to-edge separation between units; unit container shall be sealed against inleakage of water.

† For combined shipping (excluding safe cylinders), the carload limit is any combination of 50 appropriate maximum shipping units (or the equivalent in smaller units); the listed mass limits increase if allowance factors are applied to the shipping units of Table 5.

‡ For the safe solution cylinders of Table 5, the storage conditions of Table 6 may be used for transportation provided spacings are expected to be maintained in case of accident.

The assumption underlying these rules is that the integrity of birdcages or shipping cases and of the sealed container will be preserved, but the possibility of accidental flooding or the combination of the contents of two carriers is admitted. "Carload limits" in Table 7 allow a normal factor of safety of at least 4, of which a factor of 2 is for the combination of two carloads. If flooded, individual units will be less than 80 per cent of the critical mass, and requirements are such that units will not interact through the intervening water.

PART III

APPLICATIONS TO PROCESSING PLANTS

GENERAL DISCUSSION

It should be emphasized again that the typical process plant contains a crowded arrangement of tanks, pipes, and columns with interconnections and nearby structures instead of the simple, isolated units of Part II. Because of the complexity of some process layouts, nuclear measurements on portions of the system mocked up in a critical assembly laboratory may be necessary to utilize, in the most advantageous manner, available plant floor area and equipment. In some cases where this procedure is impractical, it may be desirable to make controlled *in situ* measurements within a plant. The latter method has been used effectively.

Generally, however, safe, but perhaps overconservative, restrictions for plant equipment can be established in terms of the rules stated above for simple systems. For example, an isolated cylinder of rectangular cross section will obviously be safe if the diagonal dimension does not exceed the diameter of a safe circular cylinder. For the evaluations of multiple-unit systems, Rules For Interacting Systems, Part II, may be applied.

Incidental Reflectors

A wall of concrete, steel, or wood (or the equivalent in columns, etc.) within six volume-average radii of the center of a vessel increases minimal inherent reflection to nominal effective reflection, or nominal inherent reflection to the equivalent of full-water reflection.[24] It does not influence a system with the equivalent of a full-water reflector. Beyond six volume-average radii the effect of such a structure may be ignored. For nominally or fully water-reflected systems, the effect of extraneous human body reflection may be neglected provided the bodies in question are not in gross contact with the systems.

Minimal reflector conditions rarely occur in a chemical processing plant. A system which by itself has this type of reflector is quite sensitive to interaction with other process vessels containing fissionable material and to the effects of incidental (or accidental) reflectors.

Adaptation to Standard Volumes and Pipe Sizes

In principle, the limits of Tables 1 to 4 might be represented as a series of curves as a function of H/X atomic ratios. In view, however, of gaps in experimental data on which tables are based (and of the relative ease of scanning compact tables), it is believed that finer subdivisions than afforded by these tables are not presently justified. In applications to plant equipment there will be situations where the appropriate limit of Table 2 will fall just below the volume of a convenient standard vessel or where the safe dimensional limit of Table 3 is slightly smaller than a standard pipe or tubing diameter. In such a case it is suggested that a nuclear safety specialist help determine whether there may be safe adjustment to the size of

standard equipment. It should be emphasized that linear interpolation between some of the tabulated limits in Part II will be unsafe.

RULES FOR SPECIAL SYSTEMS

This section contains rules for a few specific situations occurring in plants that are not covered by the generalizations of Part II.

Pipe Intersections

Table 8 describes conservative uniform pipe intersections for aqueous solutions of U^{235}, Pu^{239}, and U^{233} salts.[25] These data do not apply to metals. The examples may be extended to nonuniform intersections by the method outlined in the reference.

Table 8—CONSERVATIVE INSIDE PIPE DIAMETERS (IN INCHES) FOR UNIFORM 90-DEG INTERSECTIONS CONTAINING FISSIONABLE SOLUTIONS (H/X ≥ 20)

	U^{235}	Pu^{239}	U^{233}
Tees:			
Full water reflector	~~3.5~~ 4.2	3.2 3.8	~~2.6~~ 3.2
Nominal reflector (≤ 1 in. water)	~~4.1~~ 5.1	4.0 4.6	~~3.5~~ 3.7
Minimal reflector (≤ ⅛ in. S.S.)	~~4.7~~ 6.0	4.8 5.4	~~4.0~~ 4.2
Crosses:			
Full water reflector	~~2.9*~~ 3.8	2.8 3.4	~~2.1~~ 2.8
Nominal reflector (≤ 1 in. water)	~~3.3~~ 4.9	3.3 4.4	~~2.7~~ 3.5
Minimal reflector (≤ ⅛ in. S.S.)	~~3.9*~~ 6.0	3.9 5.4	~~3.3~~ 4.2

~~*Experiments indicate that these values are highly conservative.~~

Full water refl 4.6 4.0 3.4
Nominal 5.3 4.7 3.8
Minimal 6.0 5.4 4.2

If a pipe is to contain multiple intersections, no two intersections may occur within 18 in. (axis-to-axis) of one another.

Metal Machine Turnings

Machine turnings immersed in a hydrogenous moderator should be handled in the same manner as aqueous solutions of the metal salts. ~~Table I applies if densities are consistent with Fig. 2 (Ref. 20).~~ Figs 1, 5 and 9 apply (Ref. 26).

Compounds and Solutions of U^{235}

Safety specifications applicable to chemical compounds and aqueous solutions of U^{235} have been published.[27*] These limits, applicable to dry compounds in which the uranium density is no greater than 3.2 g/cm³ and to solutions and mixtures with water having uranium densities characterized by typical solubility relations, can be used extensively by uranium processing plants. Tables ~~9 and 10 are~~ typical examples, in condensed form, of the nuclear safety limits presented in this reference.

Small table - Joe Thomas

* This document, which undergoes revision as new basic data become available, provides an excellent illustration of nuclear safety regulations for a specific class of operations.

Table 5—MASS LIMITS FOR MIXTURES OF U^{235} AS UF_6 AND HYDROGENOUS MATERIAL, $H/U^{235} \leq 10$
(For any reflector class)

Max. uranium density, g/cm^3	H/U^{235} atomic ratio	Safe mass kg U^{235}
1.8	10	5.0
2.3	5	9.4
2.6	3	14.3
2.8	2	20.0
3.0	1	28.5
3.2	0.1	39.8
3.2	0.01	43.0

Table 6—DEPENDENCE OF SAFE MASS, VOLUME, AND CYLINDER DIAMETER ON U^{235} CONTENT OF URANIUM
(For total uranium densities that do not exceed 1.07 times the values for U^{235} in Figs. 1 and 2, any H/U^{235} ratio, and thick water reflector)

U^{235} content of uranium, wt.%	Mass, kg U^{235}	Volume, liters	Cylinder I.D., in.
40	0.41	6.7	6.0
20	0.48	9.5	6.9
10	0.60	14.0	8.2
5	0.80	27.0	10.2
2	2.00	27.0	10.2
0.8	36.00	27.0	10.2
$\leq 0.7_1$	Infinite	Infinite	Infinite

Table 7—BATCH LIMITS FOR URANIUM METAL IN WATER
(U^{235} Enrichment = 1.03 per cent)

Solid rod diameter, in.	U^{235} batch limit, kg
0.39	8.1
0.60	6.9
0.75	7.1
0.93	8.1
1.66	13.1

Uranium Metal, Low U^{235} Content

The critical mass of uranium metal rods only slightly enriched in U^{235} and dispersed in water depends on the dimensions of the units and the manner in which they are arranged. Permissible batch sizes of solid metal rods, enriched to 1.03 per cent in U^{235}, of several diameters, and latticed in water in the manner giving the greatest reactivity, are listed in Table 11. It is emphasized that these values refer to solid rods. Annular pieces of uranium metal have smaller critical masses than do solid pieces having the same outside diameter.

EXAMPLES OF PLANT APPLICATION

This section contains several problems typical of those arising in chemical or metallurgical plants processing sizable quantities of fissionable materials.

Pouring Crucible and Mold Limits for 40 Per Cent Enriched-uranium Metal

The problem is to suggest the weight of a safe charge of uranium containing 40 wt.% U^{235} and 60 wt.% U^{238} in a large pouring crucible and mold having no safety features imposed by their shape. Graphite crucible and mold walls plus insulation and heating coils are sufficiently thin to be classed as nominal reflector, and there is no possibility of internal flooding.

The basic mass limit from Table 1 is 15.0 kg U^{235} for nominal reflector. Figure 6 then gives an allowance factor of 1.8 for reduction of U^{235} concentration from ~93 to 40 per cent. This leads to an allowable charge of 27 kg U^{235} which corresponds to 67 kg of uranium of this enrichment.

Pouring Crucible and Mold Limits for a 10 Wt.% U^{235} – 90 Wt.% Aluminum Alloy

The problem is to suggest a safe charge weight of a 10 wt.% U^{235} – 90 wt.% aluminum alloy for a melting crucible and mold with compact shapes. As crucible and mold walls, etc., exceed 2 in. in thickness, the equivalent of full-water reflection must be assumed. Charge is to be introduced as the alloy, and melting and casting conditions are controlled to avoid segregation. There is no possibility of flooding within the furnace.

The volume fraction of U^{235} in this alloy (or the fraction of full U^{235} density) is about 0.016. From Table 1 the basic mass limit is 11 kg U^{235}, and Fig. 5 gives an allowance factor of 6 for aluminum dilution. Thus the limit is 66 kg U^{235} which corresponds to about 660 kg of alloy. [*Note:* If the alloy were to be compounded during melting, the allowance factor would be disregarded and the limit would be 11 kg U^{235} (thick aluminum reflector is less extreme than thick water)].

Pulse Column (Infinite Pipe System)

The problem is to choose a safe diameter for a pulse column given the following pertinent data:

1. The column, $^3/_{32}$-in.-thick stainless steel, is to be mounted against a concrete wall at a distance of six column radii (column is not to be recessed into a cavity).
2. There are no other interacting columns or tanks, and the possibility of flooding is excluded.
3. The concentration of U^{235} occurring in the column is not to exceed 150 g U^{235} per liter of solution.
4. The column length is 5 ft or more and must be considered effectively infinite.

The safe diameter is 6.7 in., from Table 3 and Fig. 2.

CAUTION: It is common practice to design a pulse column with phase separation units at the top and bottom of the column, which are of larger diameter than the column proper. It is to be understood that the 6.7 in. diameter is the maximum safe diameter for all parts of the system, provided concentration control is maintained.

Determination of a Safe Batch Size for Enriched-uranium Slugs in a Chemical Plant Dissolver

This final example illustrates both the relatively sophisticated approach that some nuclear safety problems require and a method by which the recommendations in Table 11 were derived.

It is known that natural uranium containing 0.71 wt.% U^{235} cannot be made critical when homogeneously distributed in a water moderator; thus a chemical plant may be designed for processing this kind of uranium with no concern for critical mass problems. Sometimes it is desirable to use slightly enriched uranium in reactors, and the question then arises of how enriched slugs may be safely processed. The following problem is considered. Slugs of 1.36 in. in diameter and containing 1 wt.% U^{235} are to be dissolved in a large tank. Large numbers of natural-uranium slugs may also be undergoing dissolution in the same tank. The slugs are to be dumped into the tank; their positions with respect to one another are uncontrolled. How many 1 per cent slugs may safely be dissolved at one time?

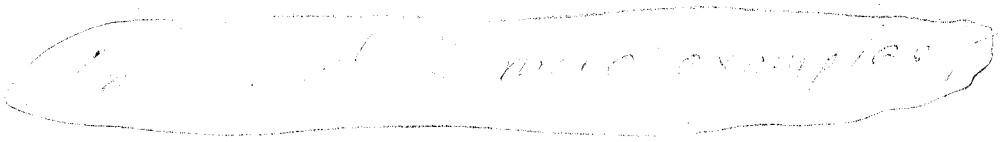
First disregard the presence of natural-uranium slugs. Then the problem is: what is the minimum critical mass of 1 per cent uranium in a water system? The system may be a uniform solution; it may be a solution of uranium in water in a roughly spherical shape surrounded by a full-water reflector; it may be an array of slugs with any diameter up to 1.36 in. surrounded by full-water reflector; or it may be any mixture of the above three possible configurations.

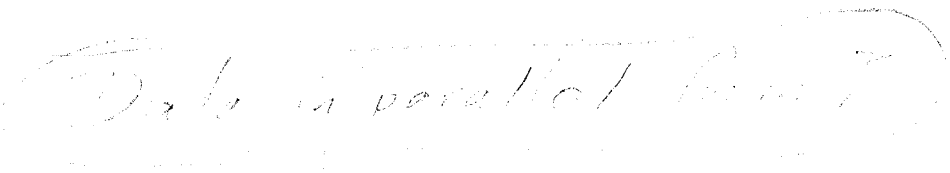
Calculations show that, for this degree of enrichment, the inhomogeneous system consisting of a lattice of slugs in water will have a higher reactivity than a homogeneous solution. This results from the larger value of the resonance escape probability for a lattice. We thus reduce the problem to finding the highest reactivity or buckling possible in a water-uranium lattice of rods in which the lattice spacing and the rod diameter are variable (the rods up to 1.36 in.). Experimental measurements on lattices of this type are available.[28,29] From these it is found that the maximum buckling obtainable with 1 per cent uranium is about 3600×10^{-6} cm^{-2} with a rod diameter of about 0.75 in. in a lattice with a water-to-uranium volume ratio of 2:1. Since the experiments were done with uranium clad in aluminum jackets, it is necessary to raise the value of the buckling to about 4100×10^{-6} cm^{-2} for a pure uranium-water system.

With this number, we are in a position to specify safe numbers of slugs. A simple calculation shows that 3490 lb of uranium will go critical if the lattice has near spherical shape and is fully reflected by water. This is equivalent to 435 slugs, each 8 in. long. If the possibility of double batching in the dissolver cannot be excluded, then this number should be halved. It is thus concluded that a safe batch size is about 200 slugs. Some additional safety factor is present since this specification is based on charging slugs of 1.36 in. in diameter. By the time the slugs are dissolved down to the optimum diameter, some of the uranium is in solution and some in slugs. This is a less reactive situation than if this total amount of uranium were all in the form of slugs of the optimum size.

We have not yet considered the effects which may be caused by a natural-uranium reflector that may be present in the dissolver. Experiments with aluminum-uranium alloy slugs reflected with closely packed natural-uranium slugs in a water system show that the critical mass is approximately halved.[30] Calculations on the present type slugs give about the same result. Thus, if natural uranium is also present in large amounts in the dissolver, the safe batch size for enriched slugs should be reduced to 100. If the natural-uranium slugs can assume some optimized latticed arrangement, thereby contributing substantially to the over-all reactivity, the critical number of enriched slugs may be reduced still further. If this extreme situation is considered likely, the batch size should be set at about 70 slugs.

An alternate method of ensuring safety in this dissolver would be to introduce a geometric constraint on the slugs. A cylinder with porous walls might be inserted to maintain a fixed radius for the configuration of the slugs and yet permit free circulation of the dissolving solution. According to the maximum buckling quoted above, the radius of this cylinder would be 11 in. Here, only water reflector is allowed for. So long as this radius could be maintained, no restriction on the number of slugs is necessary.





REFERENCES

1. C. K. Beck, A. D. Callihan, and R. L. Murray, Critical Mass Studies, Part I, Report A-4716, June 1947.
2. C. K. Beck, A. D. Callihan, J. W. Morfitt, and R. L. Murray, Critical Mass Studies, Part III, Report K-343, April 1949.
3. J. R. Brown, B. N. Noordhoff, and W. O. Bateson, Critical Experiments on a Highly Enriched Homogeneous Reactor, Report WAPD-128, May 1955. (Classified.)
4. A. D. Callihan, Nuclear Safety in Processing Reactor Fuel Solutions, Nucleonics, 14(7): 39 (July 1956).
5. J. K. Fox, L. W. Gilley, and D. Callihan, Critical Mass Studies, Part IX, Aqueous U^{235} Solutions, Report ORNL-2367, February 1958.
6. H. C. Paxton, Critical Masses of Fissionable Metal as Basic Nuclear Safety Data, Report LA-1958, January 1955.
7. F. E. Kruesi, J. O. Erkman, and D. D. Lanning, Critical Mass Studies of Plutonium Solutions, Report HW-24514, May 1952. (Classified.)
8. G. Safonov, Survey of Reacting Mixtures Employing U^{235}, Pu^{239}, and U^{233} for Fuel and H_2O, D_2O, Carbon, Beryllium, and BeO for Moderator, Report R-259, January 1954. (Classified.)
9. A. D. Callihan, J. W. Morfitt, and J. T. Thomas, Small Thermal Homogeneous Critical Assemblies, Paper UN-834, International Conference on the Uses of Atomic Energy, June 1955. 5, 145-155 (1955)
10. J. K. Fox, L. W. Gilley, and E. R. Rohrer, Critical Mass Studies, Part VIII, Aqueous Solutions of U^{233}, Report ORNL-2143, August 1956.
11. J. K. Fox, L. W. Gilley, and J. H. Marable, Critical Parameters of a Proton Moderated and Proton Reflected Slab of U^{235}, Report ORNL-2389, October 1957, p. 87.
12. F. F. Hart, Safety Tests for Melting and Casting Oralloy, Report LA-1623, December 1953.
13. A. D. Callihan, D. F. Cronin, J. K. Fox, and J. W. Morfitt, Critical Mass Studies, Part V, Report K-643, June 1950.
14. J. T. Thomas, Limiting Concentrations for Fissile Isotopes, Report ORNL-2081, November 1956, p. 78.
15. H. C. Paxton, Estimated Critical Masses of Diluted Oralloy, Report N-2-263, July 1956.
16. H. F. Henry, J. R. Knight, and C. W. Newlon, General Application of a Theory of Neutron Interaction, Report K-1309, November 1956.
17. H. F. Henry, C. E. Newlon, and J. R. Knight, Self-consistent Criteria for Evaluation of Neutron Interaction, Report K-1317, December 1956.
18. H. F. Henry, C. E. Newlon, and J. R. Knight, Application of Interaction Crtieria to Heterogeneous Systems, Report K-1335, June 1957. (Classified.)
19. J. A. Pond, Critical Geometries for Bare Cylinders, Report GAT-189, July 1956.
20. J. K. Fox and L. W. Gilley, Applied Nuclear Physics Division Annual Report for Period Ending Sept. 10, 1956, Report ORNL-2081, November 1956, p. 63.
21. J. K. Fox and L. W. Gilley, Applied Nuclear Physics Division Annual Progress Report for Period Ending Sept. 1, 1957, Report ORNL-2389, October 1957, p. 77.
22. C. L. Schuske, M. G. Arthur, and D. F. Smith, Rocky Flats Plant Report, CD56-869, July 1956. (Classified.)
23. C. L. Schuske, Rocky Flats Plant Report, RFP-59, February 1956. (Classified.)
24. J. K. Fox and L. W. Gilley, Physics Division Semiannual Progress Report for Period Ending Mar. 10, 1955, Report ORNL-1926, September 1955, p. 2.
25. C. L. Schuske, An Empirical Method for Calculating Subcritical Pipe Intersections, Rocky Flats Plant Report, TID-5451, July 1956. (Classified.)
26. J. D. McLendon and J. W. Morfitt, Critcal Mass Tests on U^{235} Machine Turnings, Report Y-A2-71(Del.), February 1952.

27. H. F. Henry, A. J. Mallett, and C. E. Newlon, Basic Critical Mass Information and Its Application to K-25 Design and Operation, Report K-1019, Fourth Revision, August 1957. (Classified.)
28. E. D. Clayton, Physics Research Quarterly Report, Report HW-42183.
29. H. Kouts, G. Price, K. Downes, R. Sher, and V. Walsh, Exponential Experiments with Slightly Enriched Rods in Ordinary Water, Paper UN-600, International Conference on Peaceful Uses of Atomic Energy, June 1955.
30. A. D. Callihan, D. F. Cronin, J. K. Fox, J. W. Morfitt, E. R. Rohrer, and D. V. P. Williams, Critical Mass Studies, Part VI, Report Y-801, August 1951. (Classified.)

Selected Reading List

Included are documents giving background information but to which specific reference is not made in the text. For completeness it has been necessary to include in this List a number of classified references and a few which received limited distribution. The authors regret that all the information may not be available to every reader.

C. K. Beck, A. D. Callihan, and R. L. Murray, Critical Mass Studies, Part II, Report K-126, January 1948.

A. D. Callihan, D. F. Cronin, J. K. Fox, R. L. Macklin, and J. W. Morfitt, Critical Mass Studies, Part IV, Report K-406, November 1949.

A. D. Callihan and D. F. Cronin, Critical Experiments with Uranium of Intermediate U^{235} Content, Report ORNL-55-10-97, October 1955. (Classified.)

L. W. Gilley and A. D. Callihan, Nuclear Safety Tests on a Proposed Ball Mill, Report ORNL-54-9-89, September 1954.

R. Gwin and W. T. Mee, Critical Assemblies of U^{235}, Report Y-A2-124(Del.), September 1953.

E. C. Mallary, H. C. Paxton, and R. H. White, Safety Tests for the Storage of Fissile Units, Report LA-1875, February 1955. (Classified.)

J. J. Neuer and C. B. Stewart, Preliminary Survey of Uranium Metal Exponential Columns, Report LA-2023, January 1956.

C. L. Schuske, Rocky Flats Plant Report, RFP-51, June 1955. (Classified.)

C. L. Schuske, M. G. Arthur, and D. F. Smith, Rocky Flats Plant Report, RFP-58, January 1956. (Classified.)

C. L. Schuske, M. G. Arthur, and D. F. Smith, Rocky Flats Plant Report, RFP-63, April 1956. (Classified.)

C. L. Schuske, M. G. Arthur, and D. F. Smith, Rocky Flats Plant Report, RFP-66, August 1956. (Classified.)

C. L. Schuske and J. W. Morfitt, An Empirical Study of Some Critical Mass Data, Report Y-533, December 1949.

C. L. Schuske and J. W. Morfitt, Empirical Studies of Critical Mass Data, Part II, Report Y-829, December 1951.

C. L. Schuske and J. W. Morfitt, Empirical Studies of Critical Mass Data, Part III, Report Y-839, January 1952. (Classified.)

D. Callihan et al., Physics Division Semiannual Progress Report for Period Ending Mar. 10, 1954, Report ORNL-1715, July 1954, p. 11. (Classified.)

C. L. Schuske, M. G. Arthur, and D. F. Smith, Rocky Flats Plant Report, RFP-69, October 1956. (Classified.)

H. C. Paxton, Critical Masses of Oralloy Lattices Immersed in Water, Report LA-2026, November 1955. (Classified.)

J. J. Neuer, Critical Assembly of Uranium Metal at an Average U^{235} Concentration of $16\frac{1}{4}\%$, Report LA-2085, October 1956. (Classified.)

C. E. Newlon, Extension of the Safe Geometric Parameters to Slightly Enriched Uranium, Report K-1370, January 1958.

G. A. Graves and H. C. Paxton, Critical Masses of Oralloy Assemblies, Nucleonics, 15(6): 90-92 (June 1957).

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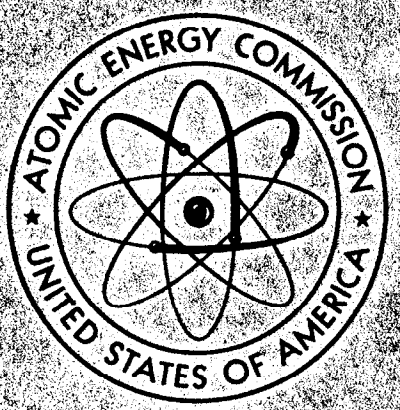

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