TID-7016
Rev. I

nuclear safety guide

1961

revised by Subcommittee 8 *of the*
AMERICAN STANDARDS ASSOCIATION SECTIONAL COMMITTEE N6

and

Project 8 *of the*
AMERICAN NUCLEAR SOCIETY STANDARDS COMMITTEE

Prepared Under Contract AT–(33–2)–1 for the
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by the
GOODYEAR ATOMIC CORPORATION
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ERRATA

Subsequent to the first printing of TID-7016, Rev. 1, errors were found. Although plans call for correction of the text at a later date when Revision 2 is issued, this second printing of Revision 1 presents the opportunity to provide a helpful listing of the errors found, to date. They are as follows:

Page 16 - In Figure 6, the dashed curve ("Pu^{239} only, full reflector") and the solid curve adjacent to it ("full reflector") have a common intercept of the latter on the rightmost ordinate (i.e., the ordinate for which the abscissa is 20 kg Pu/liter). This is accomplished arbitrarily by redrawing accordingly the last 1 to 1.5 cm of the dashed curve.

Page 22 - In column 2, paragraph 2, line 2 should be "...fissionable metal may be increased if fissionable..." instead of "...fissionable material may be increased if fissionable..."

Page 23 - In the title of Figure 19 insert the word "METALS" in the first line so that it will be "FIG. 19. ALLOWANCE FACTORS FOR U^{235}, Pu^{239}, OR U^{233} METALS MIXED HOMOGENEOUSLY WITH ELEMENTS..."

Page 23 - In column 1, paragraph 1, line 2 should read "...less than 5 weight percent needs no further restriction provided..." instead of "...less than 5 percent needs no further restriction provided..."

Page 23 - In column 1, paragraph 1, line 9 should read "...ratio N_Z/U^{235} is less than or equal[18] to 100, where N_Z is the number of atoms having the atomic number Z." instead of "...ratio Z/U^{235} is less than or equal to[8] 100."

Page 23 - In column 1, between paragraphs 2 and 3, insert the subtitle "Special Mass Limit"

Page 25 - In Figure 21, disregard the curves bearing the legends "Volume", "Slab" and "Cylinder". Only the "Mass" curve is to be generally used. However, all of the curves may be used in conjunction with Table I.

Page 27 - In Figure 23, the upper legend of the abscissa should be "Package Volume per Maximum Unit of Table IV, $ft.^3$/unit" instead of "Package Volume per Maximum Unit of Table V, $ft.^3$/unit". Also, the legend associated with the "Figure 23" should be followed by the additional words "Controlled Shipment".

Page 29 - In Figure 24, the upper legend of the abscissa should be "Package Volume per Maximum Unit of Table VII, $ft.^3$/unit" instead of "Package Volume per Maximum Unit of Table V, $ft.^3$/unit".

Page 29 - In column 2, paragraph 3, line 1 should read "In packages that are at least 20 inches in all dimensions,..." instead of "In packages that are at least 20 inches in any dimension,..."

Page 37 - Reference 1 should be: Stratton, W. R. "A Review of Criticality Accidents." Progress in Nuclear Energy. Series IV. Vol. 3. London, Pergamon Press, 1960

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FOREWORD

The Nuclear Safety Guide was first issued in 1956 as a classified AEC report (LA-2063). Since then it has been more widely distributed as an unclassified document with virtually no change in content. It is appropriate to restate the intended purposes of the contained information 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 restrictions 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 bibliography in this report will be of especial value since reference to the experimental results will aid in guided extrapolations.

The Guide contains recommendations for arrays of individually subcritical units that may be applied to processing plant layout, to storage, and to the arrangement of materials in shipment. A note of caution should be added, however, concerning materials in shipment. In view of the continually increasing frequency of shipments of fissionable materials, there must be sufficient control over fissionable materials in transit to prohibit 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. For the preparation of uncontrolled shipments and of those without exclusive use of the vehicle, the Guide makes special recommendations embodying a sufficiently greater safety factor than that for controlled shipments.

On comparing this revised edition to the first edition of TID-7016 it will be noted that in a few instances values that were originally thought to provide the stated factor of safety have been reduced. It is to be expected that as more information becomes available, or situations are better understood, the result will be a relaxation in some areas and a tightening of restrictions in others. There is evidence of both actions in the section on arrays of units. The reader is encouraged to search out those changes pertinent to his practice. In all cases, effort has been expended to ensure the validity of the safety factors given.

PREFACE TO TID-7016

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.

Dow Chemical Co. (Rocky Flats): M. G. Arthur and D. F. Smith
E. I. du Pont de Nemours and Co., Inc. (Savannah River): H. K. Clark
General Electric Company (ANPD): F. G. Boyle
General Electric Company (Hanford): G. W. Anthony, E. D. Clayton, D. E. Davenport, N. Ketzlach, D. D. Lanning, and G. W. Stuart
Goodyear Atomic Corporation: D. H. Francis and F. E. Woltz
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.

A. D. Callihan, ORNL
W. J. Ozeroff, Hanford Works
H. C. Paxton, LASL
C. L. Schuske, Rocky Flats

PREFACE TO TID-7016 REVISION 1

The Nuclear Safety Guide was conceived by a group that met at the Rocky Flats Plant of the Dow Chemical Company in October, 1955, to discuss industrial nuclear safety problems. The Guide was first issued in 1956 as classified document LA-2063, and subsequently reprinted, unclassified, in 1957 as TID-7016. The widespread acceptance of the Guide was gratifying to all who participated in its preparation.

The Group has contributed to the standardization of nuclear safety practices by organizing from its membership two committees charged with the responsibility of drafting an American Standard in the field. These are Subcommittee 8, Fissionable Material Outside Reactors, of the Nuclear Standards Board, Committee 6 on Reactor Safety, and the Subcommittee for Project 8 of the American Nuclear Society's Standards Committee. The membership of both of these are:

A. D. Callihan, Chairman
Union Carbide Nuclear Company
Oak Ridge National Laboratory
Oak Ridge, Tennessee

J. E. Carothers
Lawrence Radiation Laboratory
University of California
Livermore, California

H. K. Clark
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Dow Chemical Company
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Goodyear Atomic Corporation
Portsmouth, Ohio

A significant responsibility of these committees, in addition to the formulation of an American Standard, is the amplification and revision of the Nuclear Safety Guide which provides quantitative specifications, applicable to nuclear safety problems, and to which specific reference is made in the Standard. This first revision was inaugurated at a meeting of the Group in March, 1959, at the Savannah River Plant operated by the E. I. du Pont de Nemours and Company and has been effected by a committee staffed by members of the above Standards Subcommittee and other persons qualified in the field. The composition of this Committee on revision is:

F. E. Woltz, Chairman
Goodyear Atomic Corporation
Portsmouth, Ohio

O. C. Kolar
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Others who have actively participated in this project are:

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It is intended that the Guide will continue to serve immediate needs and will encourage continuing and more comprehensive efforts toward organizing nuclear safety information.

PART I

THE NUCLEAR SAFETY PROBLEM

INTRODUCTION

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

There are the purely scientific problems connected with the conditions needed for a chain reaction. These problems can be exactly stated, and in principle permit a precise solution. The solution yields a number, known as the critical or chain-reacting mass, being the quantity of fissionable material which is critical under the conditions stated. If accurate cross sections, other nuclear data, and better computational methods were available, it would be possible to calculate critical masses. At the present time, however, the data are not sufficient and the theoretical models are not well enough understood to permit calculation of critical masses to an accuracy better than the order of ten percent except in instances of simple materials, unencumbered with neutron absorbers, in simple geometry. It is necessary, then, to depend on experimental measures of critical mass and short extensions of these by theory.

Further, there are the problems of an engineering type. These depend on the particular circumstances of the situation being considered. Thus, in some processes, it is necessary to determine in detail not only the exact physical configuration of 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 which may be, at the same time, favorable for chain reactions. The intent here is not to exactly state and solve general problems; rather, each situation must be considered in detail by itself.

Finally a third type of problem, described as administrative, is considered. 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 of procedures, whether 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.

The solution of nuclear safety problems of an industrial plant can be described succinctly as follows. With guidance from experimentally determined critical parameters, 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 rules rigorously. In this way it is possible to have a high degree of assurance that chain reactions will not occur.

This Guide deals with varying emphasis in all three aspects of the nuclear safety problem. In succeeding sections of Part I a discussion is given of the factors that govern critical conditions. A compilation of recommended parameters of the three most readily fissionable isotopes, U^{233}, U^{235}, and Pu^{239}, constitutes Part II. These are based on existing experimental data and short extrapolations thereof. Part III is a description of a few methods and examples illustrating applications to actual industrial equipment.

In concluding these introductory remarks, it is appropriate to point out that revision of this Guide will be a continuing operation as more data are generated and as their applications are broadened. Although this edition contains significantly more information than did the previous one and presents it in more useful format, it still remains a guide in intent, but one step nearer a handbook. Much experimentation remains to be done before definitive theoretical models can be developed and a systematic and complete treatment of critical masses is possible. Meanwhile, nuclear safety in industrial plants must continue to be based upon empirical regulations of the kind presented here.

CRITICAL PARAMETERS

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

For a nuclear chain reaction 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 that 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, size, and composition of the system and on the neutron-reflecting properties of surrounding materials. For example, it is possible to specify solution container dimensions, such as pipe diameters, which give sufficient leakage, because of a large surface area-to-volume ratio, to prevent a chain reaction regardless of the quantity of material contained. If the container is encased in a cooling jacket, or is near other process equipment or

structural materials, its dimensions must be less than they could be were no neutron reflector proximate. In the treatment presented here, it is assumed that natural 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. Specifications are given in Part II for reflectors of three thicknesses in an attempt to make the information more generally applicable. The equipment may have a minimal reflector, i.e., the only neutron reflector is the container itself, the wall of a stainless-steel pipe, for example; the equipment may have a nominal reflector consisting of a 1-inch-thick layer of water (or its equivalent) exemplified by the water in a cooling jacket; or it may have a full reflector when surrounded by a layer of water or concrete at least 3 inches thick or their equivalent of other reflector material.

The value of the critical mass is also extremely sensitive to the presence of neutron-moderating elements, particularly hydrogen, mixed with the fissionable isotope. The specifications for individual units presented in this Guide apply exclusively to the conditions where hydrogen is the moderating material. Although 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, which may range from zero for metal or a dry unhydrated salt to several thousand for dilute aqueous solution, the specifications in Part II are also expressed in the more common unit of mass of fissionable material per unit volume of an aqueous solution or slurry. Over the above 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.

In general, the critical mass of a fissionable material when associated with a moderator is minimal when the two are intimately mixed as, for example, in an aqueous solution. Uranium containing a few percent U^{235} is an exception to this generalization. The critical mass of a lattice of slightly enriched uranium in water is less than the critical mass of uranium of that quality when mixed homogeneously with water in the same over-all proportion. This behavior is the consequence of the absorbing properties of U^{238} for neutrons having an energy of a few electron volts. This property is called resonance absorption. When the components are latticed, there is a greater probability of neutron energy degradation, in the water, from the high energy at which neutrons are produced to below that at which U^{238} is strongly absorbing. The neutrons therefore "escape" the U^{238} resonance absorption and the probability of the escape is a calculable and measurable property of such lattices. The maximum enrichment of the uranium at which latticing does reduce the critical mass is not exactly known although it is estimated to be between 3 and 5 weight percent U^{235}.

Consideration of a special case of the differences between latticed and homogeneous arrays of uranium of low U^{235} content illustrates a useful nuclear safety specification. Although rods of natural uranium metal of appropriate diameter can be carefully arranged in natural water with a lattice spacing chosen to make the array critical, the quantity required is large. Homogeneous mixtures of natural uranium and water in any proportion, however, cannot be made critical for the reasons stated previously. In fact, it has been shown that in order for such a mixture to be critical, the U^{235} content of the uranium must be about 1 percent.

The critical mass of the fissionable isotopes also depends upon their distribution in homogeneous mixtures with other materials, including air, in a manner which can be specified quantitatively only in special cases but which always increases as the mass per unit volume decreases, other parameters being constant. The critical mass of a sphere of Pu^{239} metal, for example, is less than that of a spherical volume of dry Pu^{239} sawdust, and the critical mass of U^{235} in an aqueous solution is greater than that of a homogeneous aqueous slurry of high density UO_2 of the same H/U^{235} ratio because the mass of U^{235} per unit volume is greater in the case of the slurry. A procedure for treating problems in which the density differs from that fixed by solutions is recommended in Part II.

The use of neutron-absorbing materials, such as cadmium and boron, distributed within the fissionable material can render equipment and processes safe within the requirement of nuclear safety, provided adequate experimental data confirm their suitability and their installation has assurance of permanency. Vigilance must be exercised to avoid unexpected loss of the poison or its prescribed distribution, e.g., by corrosion or thermal splintering. The inclusion of solid absorbers in the construction and assembly of equipment is recommended; the use of solutions of neutron absorbers as components of process streams is less acceptable because of the administrative control required to assure their presence. A word of caution is appropriate in any consideration of placing neutron-absorbing materials on the outside of vessels containing fissionable materials. If such vessels, surrounded, say, by a thin layer of cadmium are, in turn, surrounded by water, the cadmium is very effective in increasing the mass in the vessel required for criticality. In the absence of the external water, however, the cadmium will decrease the critical mass because the cadmium, being a scatterer as well as an absorber of neutrons, will serve as a partial neutron reflector.

The presence of nitrogen in the nitrate solutions often used in chemical processing, and of Pu^{240} as an impurity in plutonium solutions, increases the margin of safety of many operations. In processes with plutonium containing little or no hydrogen or other moderating nuclei, where the neutron population is essentially fast, Pu^{240} is not as effective a parasitic neutron absorber as it is at lower neutron energies. Little reliance should be put

upon it for additional safety under these conditions. Small amounts of Pu^{241}, an isotope readily fissionable by thermal neutrons, should not be ignored but should be treated as Pu^{239}.

Most homogeneous accumulations of fissionable materials have negative temperature coefficients of reactivity which are due to a density change, including the formation of vapors in liquid systems, and to a change in neutron energy distribution. Although this property is important in reactor design 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 value of the temperature coefficient depends on the material, the geometry of the system, and the range of the temperature change.

The preceding comments have referred to individual units. The effects, however, of the mutual exchange of neutrons between subcritical units in an array must be considered in order to assure the nuclear safety of the system as a whole. The establishment of adequate separation criteria for such units as well as the precautionary measures taken to ensure the integrity of the spacing are factors which should receive careful attention, both in the design of plant facilities and, particularly, in the storage and transportation of units. Compactness of storage and shipping arrays, often desired in normal industrial methods, is difficult to achieve safely in the handling of fissionable materials.

The probability of neutron interaction, and hence its effect on the over-all criticality of an array, is dependent upon such geometrical factors as the size, shape, and separation of the units, as well as the over-all size and shape of the array itself. It is also evident that the potential chain reacting properties of the units themselves are important in determining the safety of the array of units. The effects of materials which may be intermingled among the units of an interacting array or which may surround the array, as a concrete storage vault, are also important. A close-packed interacting array which is critical when flooded with water, may become subcritical if the water is removed. Conversely, a flooded subcritical array may actually become critical if the water is removed since the water, as a neutron absorber in the latter situation, may isolate the units from each other.

These, briefly, are some of the factors which necessarily must be recognized in establishing safe separation criteria for the handling of fissionable materials. The general approach to the problem to date has been essentially one of empiricism, and has suffered somewhat from a paucity of experimental data. Obviously, considerable work, both experimental and theoretical, remains to be done in order to develop a generally consistent body of knowledge of the effects of neutron interaction in arrays of fissionable materials.

MINIMAL SPECIFICATIONS

Tabulated in this section are two groups of quantities describing each of the fissionable isotopes both in aqueous solution and as metal which contains no internal neutron moderating material. In every case, however, a thick hydrogenous neutron reflector (or its equivalent) is present. The quantities in the columns designated "Recommended" are those suggested for application in the control of nuclear safety and are so selected that any one, applied singly, will assure safety regardless of other properties or quantities of the material in question within the over-all limitations of this Guide. Aggregates of solids, such as bundles of rods and accumulations of pellets, which may become submerged are specifically excluded. The best estimates of the minimum critical value of each of these controlling parameters, with all others optimized, are also tabulated and allow an approximate evaluation of the safety factors contained in the recommended values. The safety factors are somewhat dependent upon the uncertainties in the experimental data. The critical mass and volume of a solution are assumed contained in a sphere of natural water reflector of effectively infinite thickness. The two sets of values given for plutonium metal describe the α-phase, having a density of 19.6 g/cm^3, and the δ-phase, having a density of 15.65 g/cm^3, respectively. Additional safety factors appropriate to uncertainties in sampling, analysis, and environment should be applied to the recommended values of the chemical concentrations and of the U^{235} enrichment of homogeneous hydrogen-moderated uranium.

DESIGN CRITERIA

It is possible to avoid nuclear hazards by designing into a process one or more of the individually fully effective limitations given above, but it is equally apparent that the resulting process might be inefficient and uneconomical. Practical approaches to design problems are 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. The inclusion of safety features in the construction of equipment rather than in its operation is a preferred practice which cannot be overemphasized since it eliminates dependence upon process conditions which may become altered by irregularities in operation. Control of safety through limitations imposed on the mass of material or the chemical concentration, for example, is less certain than control by features embodied in the equipment. The latter include, in addition to shape and size, the presence of neutron absorbers exemplified by filling large vessels with freely packed, short lengths of borosilicate glass tubing, called Raschig rings. In instances where both the chemical compatibility of the process solution with the glass and the absence of its mechanical damage are assured, this practice has been satisfactory.

There are also operations limited to uranium of some

Table I

VALUES OF BASIC NUCLEAR PARAMETERS

	U^{235}		U^{233}		Pu^{239}		
	Recommended	Minimum Critical	Recommended	Minimum Critical	Recommended	Minimum Critical	
Mass, kg:							
Solution	0.35	0.82	0.25	0.59	0.22	0.51	
Metal	10.0	22.8	3.2	7.5	2.6	5.6	α phase
					3.5	7.6	δ phase
Diameter of Infinite Cylinder, in.:							
Solution	5.0	5.4	3.7	4.4	4.2	4.9	
Metal	2.7	3.1	1.7	1.9	1.4	1.7	α phase
					1.8	2.1	δ phase
Thickness of Infinite Slab, in.:							
Solution	1.5	1.7	0.8	1.2	0.9	1.3	
Metal	0.5	0.6	0.2	0.3	0.18	0.24	α phase
					0.22	0.28	δ phase
Solution Volume, liters	4.8	6.3	2.3	3.3	3.4	4.5	
Chemical Concentration of Aqueous Solution, g (of isotope)/liter	10.8	12.1	10.0	11.2	6.9	7.8	
U^{235} Enrichment of Homogeneous Hydrogen-Moderated Uranium, wt %	0.95	1.0	--	--	--	--	

maximum U^{235} enrichment which can be carried out in equipment sized larger than that described above. Assurance of this enrichment control combined with appropriately dimensioned vessels is another example of a practical combination of safety features to effect over-all safety and economy of an operation.

Process designs should, in general, incorporate sufficient safety features to require the occurrence of at least two unlikely, independent, and concurrent changes in one or more of the conditions originally specified as essential to nuclear safety before a nuclear accident is imminent.

As mentioned earlier, the bases for the design of equipment and processes for the fissionable isotopes are almost entirely founded upon results from necessarily restricted critical experiments or on interpolations or short extrapolations of these results. Many experiments have also been performed which show that particular situations are not critical – important information but of limited application. In spite of an impressive accumulation of background data, many gaps exist which must be covered by conservative estimates. Thus the recommendations given in the succeeding sections may prove to be overly conservative in some cases; it is believed 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. Piping, for example, is usually designed on the assumption that it may become surrounded by a thick layer of water – perhaps it will through 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 own satisfaction that the stated conditions will not be violated.

INSTRUMENTATION

Although radiation-detecting instrumentation is, in principle, useful in warning of impending hazard, there are some practical limitations in its use. An approach to a chain reaction is manifested by the multiplication of the neutron field by fissionable nuclei. Experience has shown that the three components of such a multiplication-measuring system – the neutron source, the detector, and the multiplying medium – must be judiciously placed relative to each other. Spontaneous fissions and other nuclear reactions arising in process materials, the interaction of alpha particles from plutonium with oxygen in a solvent, for example, may yield a well-distributed source in the multiplying medium. In other instances an encapsulated intimate mixture of beryllium with plutonium or with polonium, placed adjacent to or within process vessels, is satisfactory. Multiplication

by the fissionable material of neutrons from any of these sources may establish in a neutron-sensitive device a signal which is some function of the fissionable mass. Unless the instrumentation is arranged with particular care, the signal strength may not reach a significant value until the system becomes supercritical; then the time rate of change of the radiation level will increase rapidly.

Properties of fissionable isotopes, or of other materials closely associated with fissionable isotopes in chemical processes, can be utilized in indirect methods for criticality control. An example is the detection of accumulations of U^{235} through measurement of its characteristic gamma radiation by appropriate instruments before accumulations become sufficiently large to endanger the process in which they occur. As another example the absorption, by the heavy elements, of gamma rays directed through a process stream is a function of the chemical concentration of the solution and, with suitable instrumentation, can be used for concentration control. In a third case, the isotope Pu^{240}, which has a high spontaneous fission rate, usually accompanies Pu^{239} in some proportion characteristic of the material history. The neutron background in a plutonium process is therefore a measure of the Pu concentration, and an increase from an established background can signal an abnormal condition in the process stream. All of these indirect methods of safety control are empirical and must be based upon the calibration of appropriate instruments.

Instrumentation has, of course, been installed in many operations to indicate the radiation hazard existing after the occurrence of a radiation accident, and reference is made to standard Health Physics procedures for the description of recommended equipment.

NUCLEAR ACCIDENT EXPERIENCE

It is obviously impossible to predict with exactness the consequences of a nuclear accident since its intensity will depend not only upon the characteristics of the material and the manner in which it is made critical but also upon the immediate environment in which the accident occurs. The accident experience is too small to allow formulation of other than generalized expectations. That rates of energy release from critical accumulations of fissionable isotopes mixed with hydrogenous or other moderating materials will exceed those from typical steam explosions is believed to be highly improbable. On the other hand, the rapid consolidation of a number of pieces of U^{235} metal due, say, to the collapse of shelving, could yield a power release equivalent to that from the detonation of a quantity of high explosive.

Most of the nuclear accidents which have occurred in chemical plant operations and in the performance of critical experiments have been analyzed.[1] One fatality and a few other significant personnel exposures resulted from the chemical plant accidents. Although most of the accidents in critical assemblies have occurred in laboratories designed with adequate shielding to protect the experimenters, three fatalities and a number of exposures of varying severity have occurred. Only a brief summary of these accidents will be included here since all have been reported in the literature.

Perhaps of greatest interest are those accidents in process operations. The one recorded[2] fatality stemmed from a mishap in a plutonium recovery operation preparatory to an inventory at the Los Alamos Scientific Laboratory late in 1958. About 3 kilograms of plutonium were inadvertently accumulated in a 225-gallon, 38-inch-diameter solvent-treating tank together with aqueous and organic reagents. The quantity of organic solvent and the affinity of its contained tributyl phosphate for the plutonium resulted in a slab-like layer of liquid, relatively rich in plutonium, of sufficient dimensions and concentration to be only slightly subcritical. The action of a stirrer, started by an operator proximate to the tank, caused an immediate relative displacement of the immiscible liquids which thickened the organic layer sufficiently to initiate a chain reaction. Continued operation of the stirrer, with some mixing by the energy released from the nuclear reaction, distributed the plutonium throughout a larger and, hence, subcritical volume. The energy release was apparently limited to a single burst of about 10^{17} fissions, equivalent, in more common units of energy, to approximately 1 kw-hr. The operator received an exposure of the order of 10^4 rem and survived only about 36 hours. It is interesting to note that the pressure developed was insufficient to rupture the closed tank although the shock displaced it horizontally about 3/8 inch at its supports. There was no dispersal of plutonium outside of the system.

Another industrial nuclear accident[3] occurred in mid-1958 at the Y-12 Plant operated in Oak Ridge by the Union Carbide Corporation for the U.S. Atomic Energy Commission. This accident also happened in a salvage process, of U^{235} in this case, and at a time when normal production procedures were interrupted in order to make a material inventory. One section of a chemical-operations complex had been restarted while another section, downstream, was being cleaned and reassembled. Solution having a uranium concentration of about 50 grams per liter accumulated fortuitously in some restricted-geometry equipment and was subsequently drained into a standard 55-gallon drum in an operation intended only for the water used in leak testing the reassembled equipment. The solution was followed into the drum by the water. The quantity of U^{235}, 2.5 kilograms, became critical initially in a volume of about 50 liters and remained critical for some 20 minutes until dilution of the solution by the continuing inflow of water terminated the reaction. During this interval approximately 1.3×10^{18} fissions occurred. Personnel, all of whom were at least 3 feet from the source, evacuated expeditiously and received doses of less than 500 rem resulting from exposure to only the initial portion of the energy release.

In October 1959 an accidental excursion in the Idaho Chemical Processing Plant operated at the National Reactor Test Station by the Phillips Petroleum Company, resulted from the accidental transfer of enriched uranium solution from restricted-geometry equipment into a large waste-storage tank[4]. The transfer resulted from an abnormal pneumatic pressure, arising from the maloperation of air sparges in the storage system, which initiated a syphon action. Approximately 200 liters of solution at a uranium concentration of 170 g/liter drained into a 5000-gallon tank where it mixed with about 600 liters of very dilute solution. The uranium was enriched to about 90 percent in U^{235}. At some stage of mixing the solution became critical and remained so for an undetermined time, generating about 4×10^{19} fissions. Gaseous and air-borne contamination apparently was forced from vent lines and drain connections by some mechanism activated by the released energy. The occurrence was signaled by the response of air and radiation-level monitors to this contamination ejection. Since the waste tank is 50 feet below grade and is covered by a 4-foot-thick layer of concrete, personnel exposures were primarily from air-borne radioactivity. External exposures of personnel to both beta and gamma rays did not exceed 50 rem. There were no significant neutron exposures or internal doses from inhalation. No damage occurred to the equipment.

Several individuals received radiation exposures as a consequence of an accident which occurred during the performance of critical experiments in October, 1958 at the Yugoslav critical experiments laboratory near Belgrade[5]. One fatality resulted from these exposures. The critical assembly consisted of a lattice of natural uranium which was made critical by the addition of D_2O. In the operation in which the exposures occurred, the heavy water was apparently added accidentally by a means not clearly reported and without the knowledge of eight persons located from 10 to 25 feet away. The system remained critical for about 10 minutes and generated 2.4×10^{18} fissions.

Two experimenters were killed by the radiation arising from supercritical metal assemblies at Los Alamos in 1945 and 1946. These accidents resulted from errors in judgment during the hand manipulation of components of the assemblies[1,6].

All of the other excursions in critical assembly work in the United States[1,7,8] occurred in laboratories which were equipped for remote control operation and were provided with shielding for the protection of the experimenters. No fatalities resulted; only in one case[7], where a control element was inadvertently removed by hand from a water-moderated and -reflected lattice, were there significant personnel exposures. In all cases some shutdown device functioned as designed and the liberated energy was limited to that arising from about 10^{17} fissions. This limitation was probably first imposed by density and temperature changes in the assembly brought about by the excursion itself. The mechanical shutdown prevented a recurrence of a supercritical condition.

It is difficult to predict the effect of the worst, yet realistic, accident which might occur in a process operation and it is emphasized that the limited experience, tragic though it has been, may not be typical of expectations. The consequence of each of these accidents, except for fortunate conditions, could have been many-fold more severe. Apparently the expansion and, in the case of solutions, bubble formation, sets a limit of something like 10^{12} fissions/cm^3 in the first power surge. In the absence of some disassembly mechanism, a volume of solution may oscillate between critical and subcritical conditions, as in the case of the Y-12 accident, until the reaction is arrested permanently by a means peculiar to the environment. This may require a relatively long time with an attendant large emission of energy. If an accident consisted of dropping several only slightly subcritical pieces of metal into an appropriate configuration, the energy release could be of explosive proportion.

This discussion of nuclear accidents is concluded with a strong plea for intensive and eternal vigilance by everyone responsible for operations with fissionable materials. Even designs incorporating restrictive geometry in all areas expected to contain fissionable materials cannot be accepted without reservation because of the ever-present danger of the collapse of procedural control and of the malfunction of equipment causing unexpected diversion of the inventory into large vessels unprotected against nuclear hazards. That this warning is appropriate is amply exemplified by each of the process accidents cited above.

ADMINISTRATION OF NUCLEAR SAFETY

Detailed administrative controls of nuclear safety must be established by each organization through recognition of its unique functions. Those installations having continuing problems as a consequence of their inventory of fissionable materials, or because of frequent alterations in their process, generally assign to a staff group 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.

The responsibility for nuclear safety must be clearly defined within any organization processing potentially critical quantities of fissionable materials. In some organizations individuals directing activities which may involve nuclear hazards are responsible for nuclear safety controls to the same extent that they are responsible for research, design, maintenance, and operation. Guidance in this responsibility is usually obtained from personnel familiar with potential hazards and methods of their control; formal approval of processes and designs by an authorized group may be required in some instances.

PART II

RECOMMENDED NUCLEAR SAFETY LIMITS

INTRODUCTION

The discussion in Part I makes it clear that the potential hazard of a system of fissionable material may be influenced by a multitude of factors that defy generalization. In those instances where any one of the recommended limiting values appearing in Table I may be applied no further restrictions are necessary. Where such blanket coverage is not possible, or where it is desired to take advantage of combinations of mass, geometry, or administrative controls, Part II presents the detailed characteristics of individual systems peculiar to this need. The recommendations do not apply to "reactor compositions" such as dilute fissionable material in heavy water, beryllium, or graphite where the atomic ratios D/X, Be/X, C/X are greater than approximately 100 (where X represents Pu^{239}, U^{235}, or U^{233}), or to systems with thick reflectors of any of these materials, of normal uranium, or of tungsten. This section also includes recommendations on interaction between units of fissionable material in regular arrays applicable to storage, transportation, and plant design. Obviously some problems may be sufficiently complex to require more specific information or a more detailed method of analysis. For such cases, the listed references offer a propitious source of information. The recommendations presented in the following graphs and tables are deemed adequate to ensure the safety of individual units.

INDIVIDUAL UNITS

Basic criteria for simple, aqueous, homogeneous, individual units as a function of concentration of the fissionable isotope are stated alternatively as mass limits in Figures 1, 5 and 9, as volume limits in Figures 2, 6 and 10, and as dimensional limits in Figures 3, 4, 7, 8, 11 and 12. Critical parameters and some supporting calculations upon which the limits are based are given in the references listed on the figures. The mass limits include factors of safety of about 2.3 as a safeguard against double batching. There are no provisions for analytical, sampling, and calculational errors. Volume limits include factors of safety of about 1.3, and the equivalent margins appear in dimensional limits even with unspecified dimensions infinite.* Allowance is made for uncertainties in critical data on which the limits are based.

*Upper limits for the diameter of infinite cylinders and the thickness of infinite slabs were obtained from constant-buckling conversions of volumes in Figures 2, 6 and 10, with empirical extrapolation distances. The subject of constant-buckling conversions is treated in most elementary text books in the field of nuclear engineering.[23,24]

Specifications for three reflector conditions are expressed in terms of both the effective density of the fissionable isotope and the degree of moderation, that is, the atomic ratio H/X.

Although reflectors such as beryllium, D_2O, uranium, and tungsten are more efficient than water[14], water is the most effective common reflector. It is, indeed, one of the most effective reflectors in thicknesses of 3 inches or less. A full reflector is water at least 3 inches thick, or its nuclear equivalent. A nominal reflector is one of water not more than 1 inch thick, or its nuclear equivalent. A 1.5-inch-thick shell of graphite or steel surrounding fissionable metal is equivalent to a 1-inch-thick layer of water. Equal thicknesses of steel and water are approximately equivalent[25] as reflectors for solutions. A minimal reflector is no more than a 1/8-inch thickness of stainless steel or other common metal such as iron, copper, aluminum, nickel, or titanium. Unless reflector conditions are rigidly controlled, the appropriate limit for a full reflector should be used.

The above limits are not applicable if the density and the H/X of the fissionable material do not have the correspondence presented in the abscissa of Figures 1 through 12. In the event that the density of fissionable material ρ is greater than the density ρ_0 corresponding to a given H/X on the appropriate abscissa, the mass limits of Figures 1, 5 and 9 should be reduced by the ratio $(\rho_0/\rho)^2$; the container capacity limits of Figures 2, 6 and 10 by $(\rho_0/\rho)^3$, and the container linear dimensions of Figures 3, 4, 7, 8, 11 and 12 by (ρ_0/ρ). If ρ is less than the ρ_0 of a given H/X, however, limits must not be increased by these ratios.

Annular Cylindrical Geometry

A method for increasing storage capacity is to employ annular geometry[26] embodying a neutron absorber in its construction. An effective arrangement is to line the inner cylinder with cadmium and to fill it with water or other hydrogen-containing equivalent compound. Presented in Table II are acceptable annular thicknesses for any concentration of solution of the three fissionable isotopes for any combination of inner and outer radii defining the specified annular thickness, provided the inner cylinder has a 20-mil-thick cadmium liner and is water filled. There is no restriction on height.

Slurries

Limited experimental data available on slurries[27,28] indicate that, for the same H/U^{235} atomic ratio and uranium density, slurries have critical parameters essentially the same as UO_2F_2 solutions, provided the

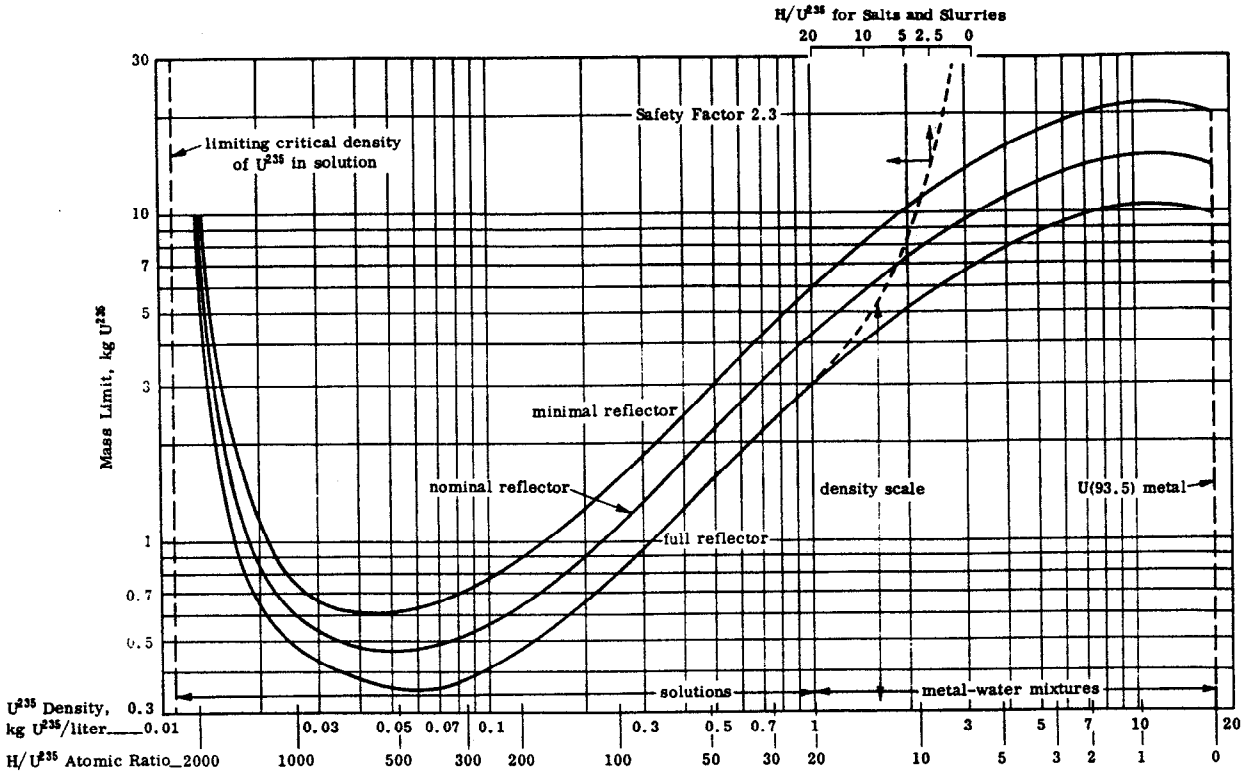


FIG. 1. MASS LIMITS FOR ISOLATED UNITS OF HOMOGENEOUS WATER-MODERATED U SPHERES (93.5% U^{235}) (References 9-14)

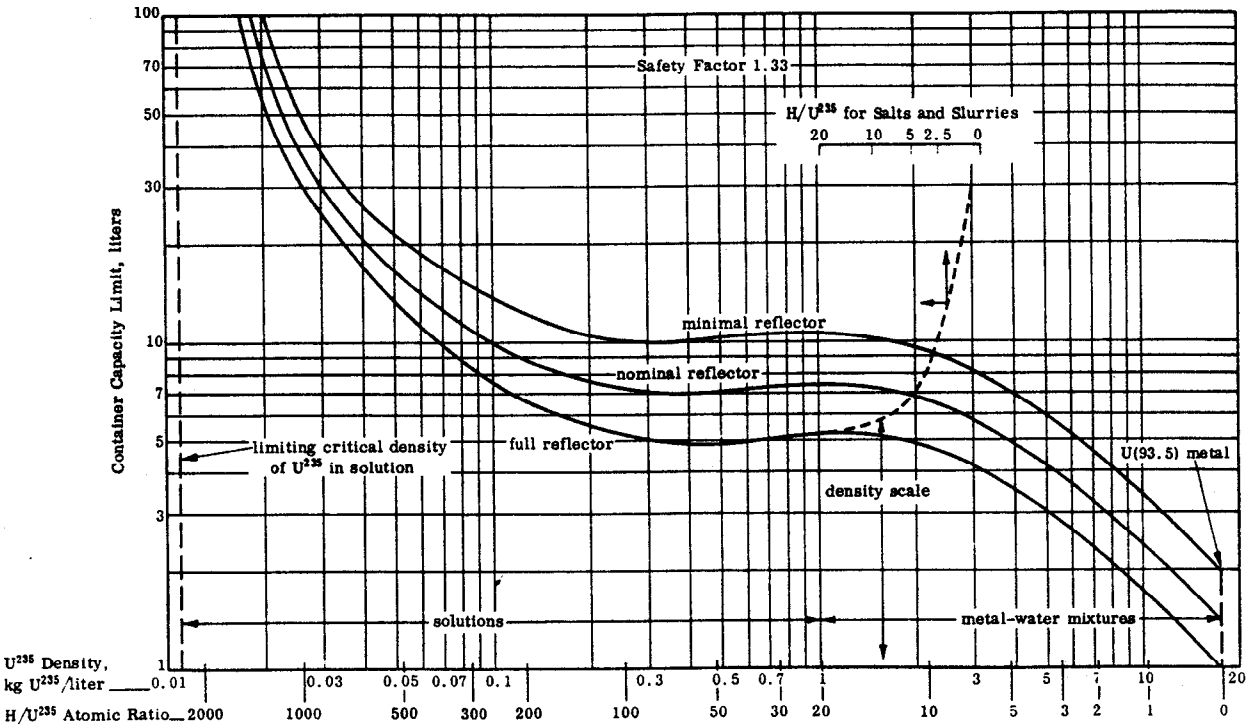


FIG. 2. CONTAINER CAPACITY LIMITS FOR ISOLATED UNITS OF HOMOGENEOUS WATER-MODERATED U SPHERES (93.5% U^{235}) (References 10-13)

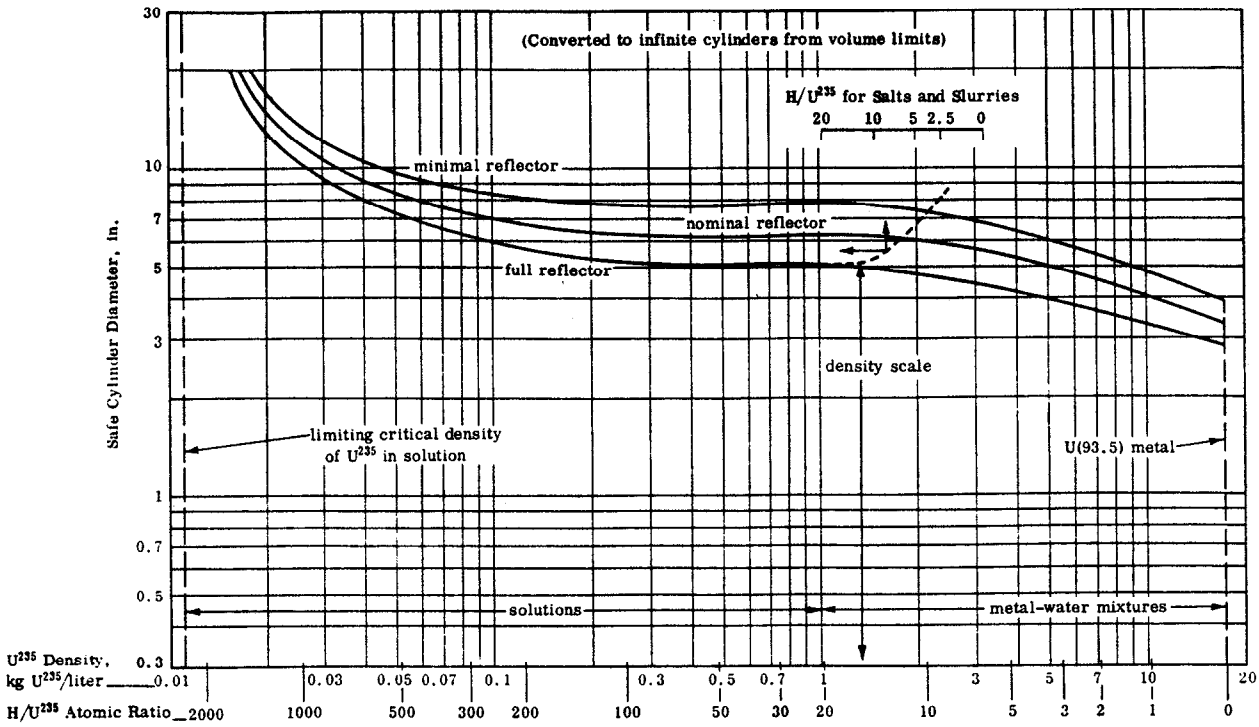


FIG. 3. SAFE DIAMETERS OF ISOLATED CYLINDERS OF HOMOGENEOUS WATER–MODERATED U (93.5% U^{235}) (References 10, 12-14)

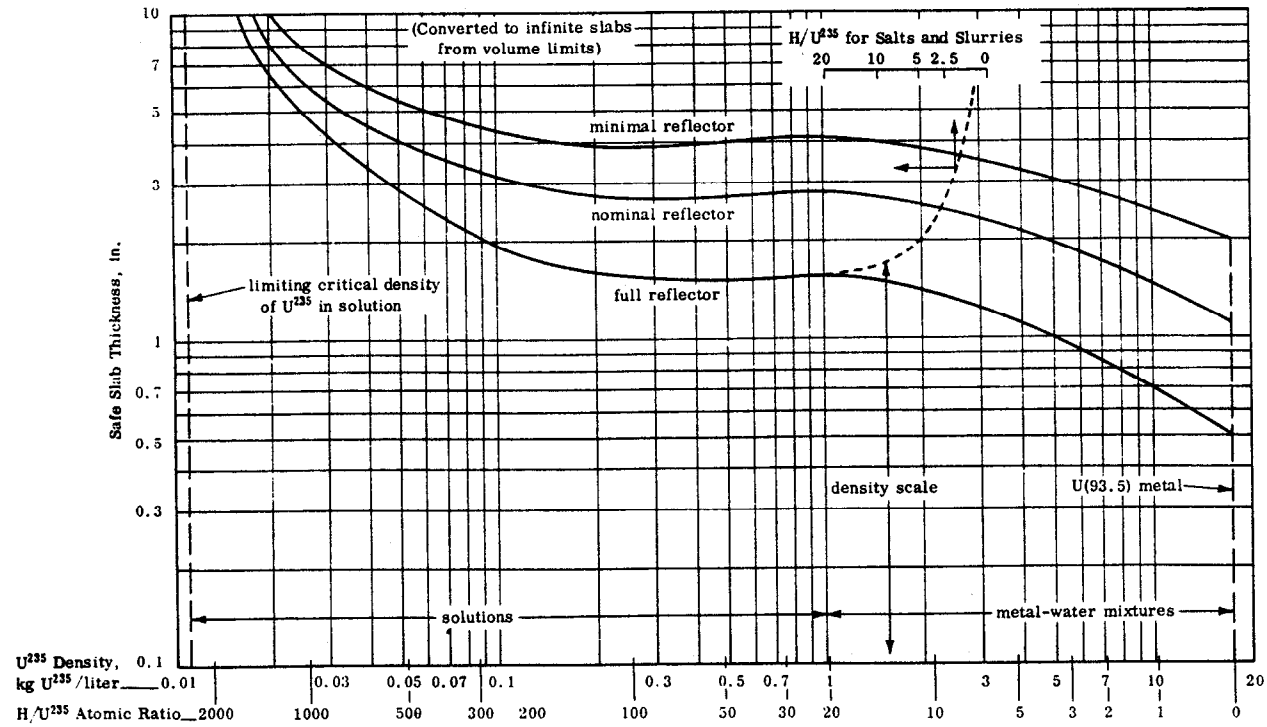


FIG. 4. SAFE THICKNESSES OF ISOLATED SLABS OF HOMOGENEOUS WATER-MODERATED U (93.5% U^{235}) (References 12, 14-16)

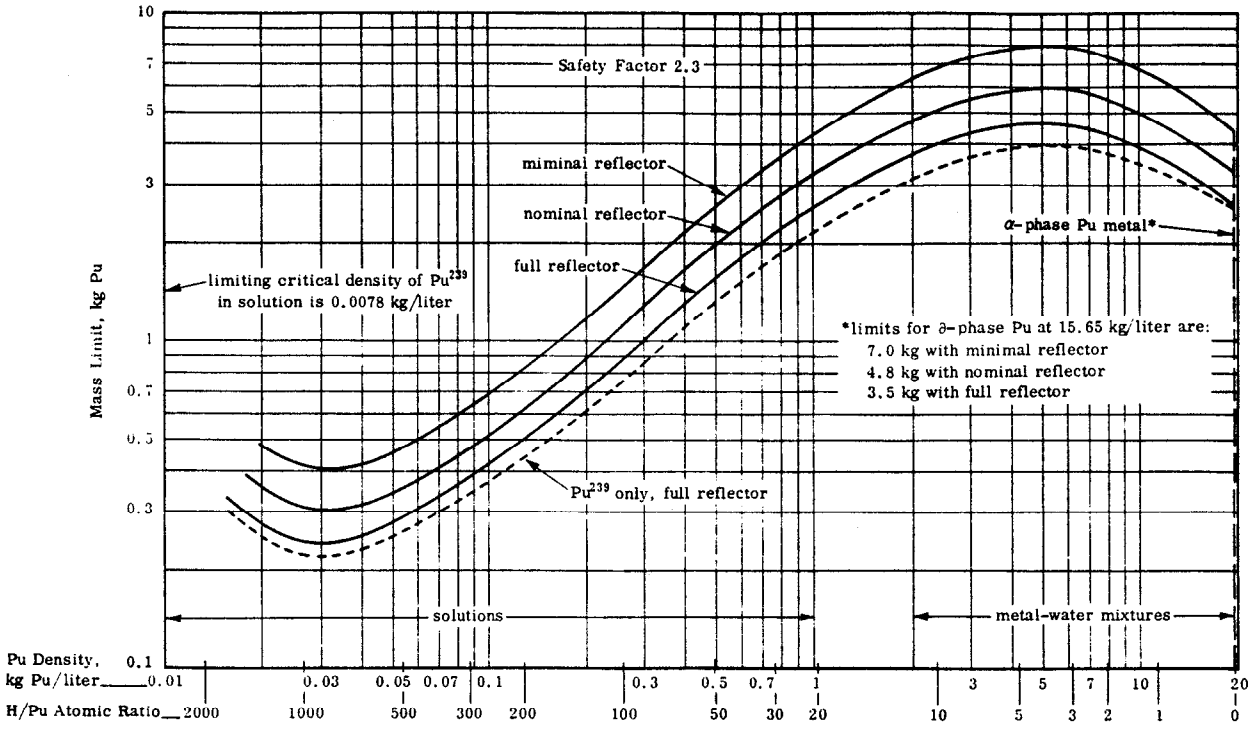


FIG. 5. MASS LIMITS FOR ISOLATED UNITS OF HOMOGENEOUS WATER-MODERATED Pu SPHERES (3% Pu^{240}) (References 12, 14, 17-20)

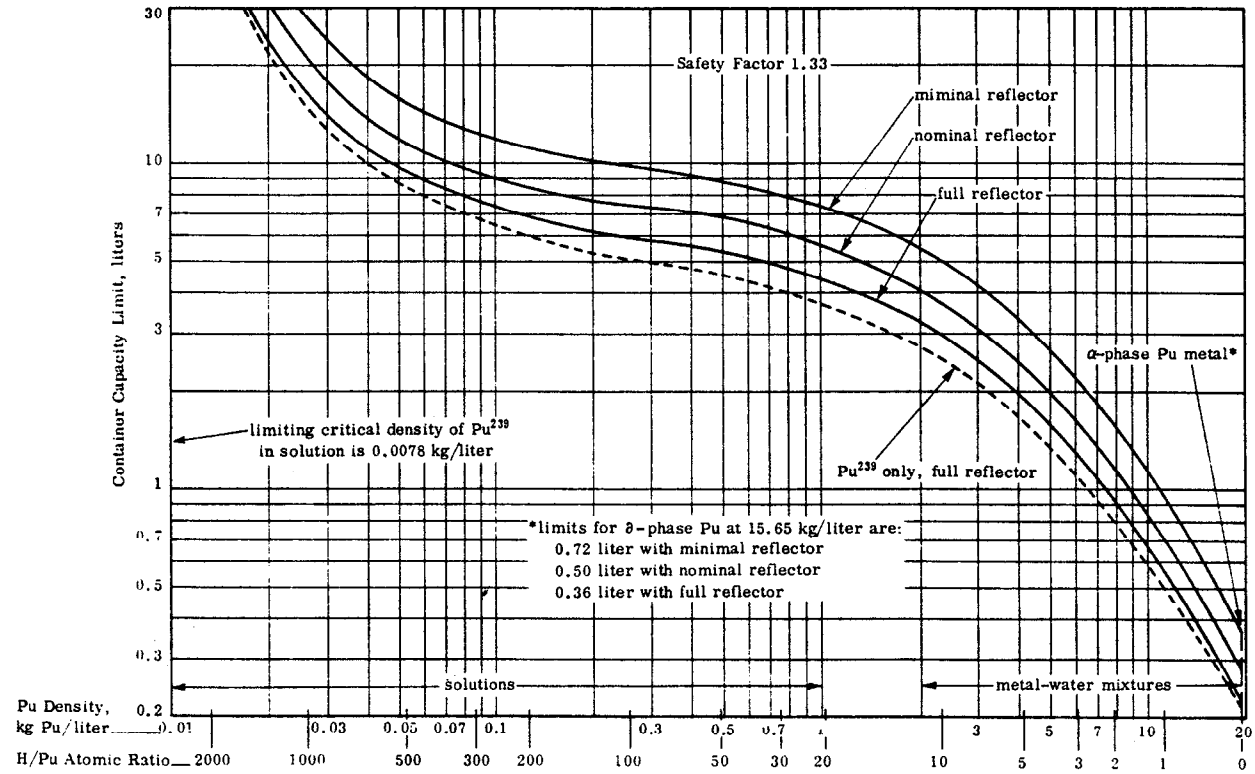


FIG. 6. CONTAINER CAPACITY LIMITS FOR ISOLATED UNITS OF HOMOGENEOUS WATER-MODERATED Pu SPHERES (3% Pu^{240}) (References 12, 17-20)

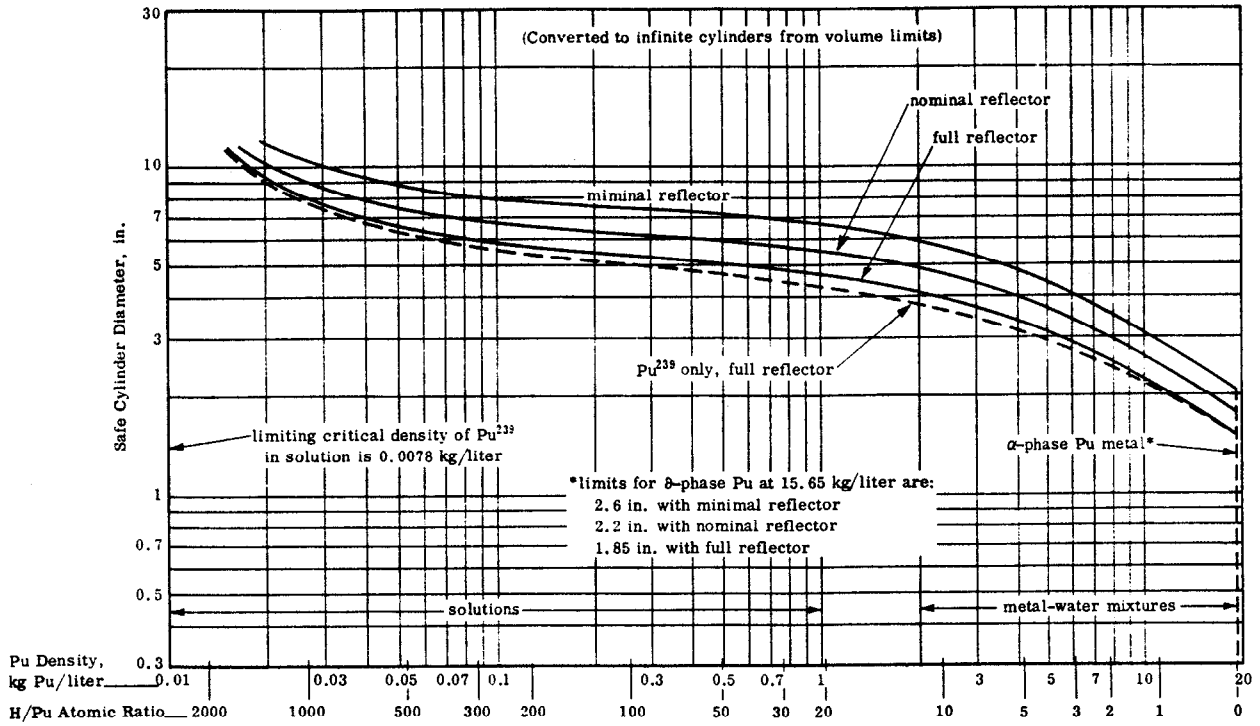


FIG. 7. SAFE DIAMETERS OF ISOLATED CYLINDERS OF HOMOGENEOUS WATER-MODERATED Pu (3% Pu^{240}) (References 12, 14, 17-20)

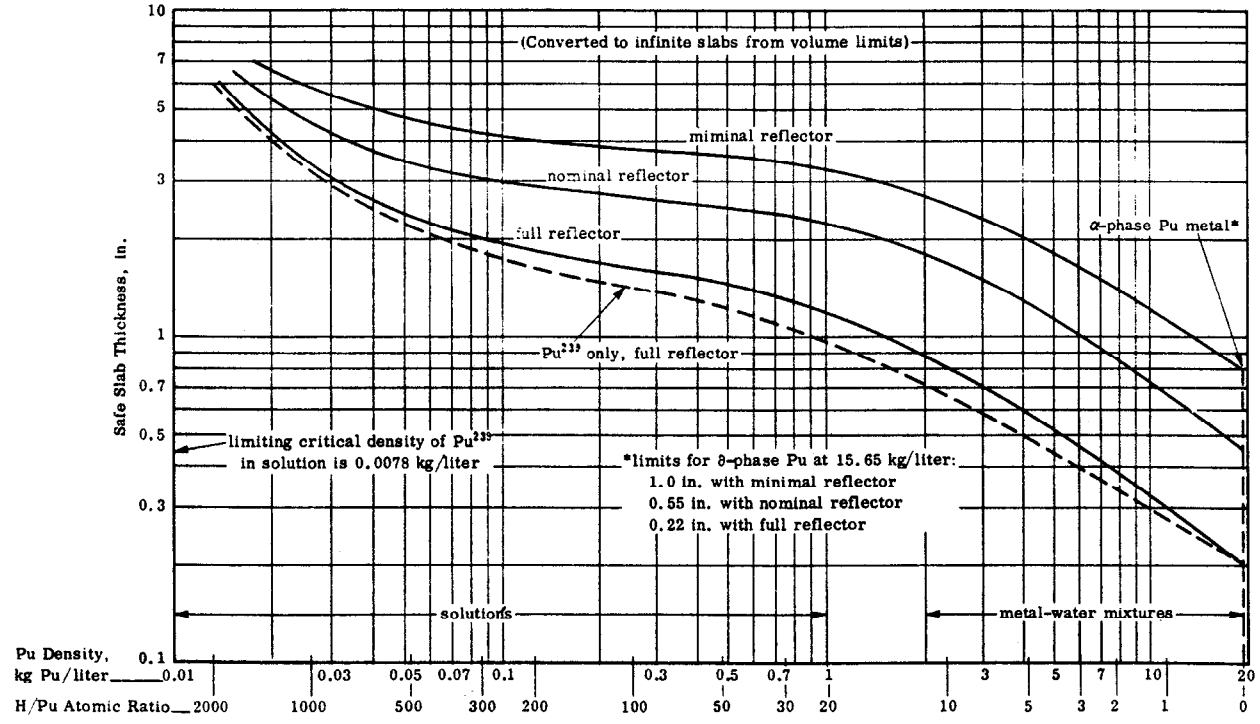


FIG. 8. SAFE THICKNESSES OF ISOLATED SLABS OF HOMOGENEOUS WATER-MODERATED Pu (3% Pu^{240}) (References 12, 14, 17-20)

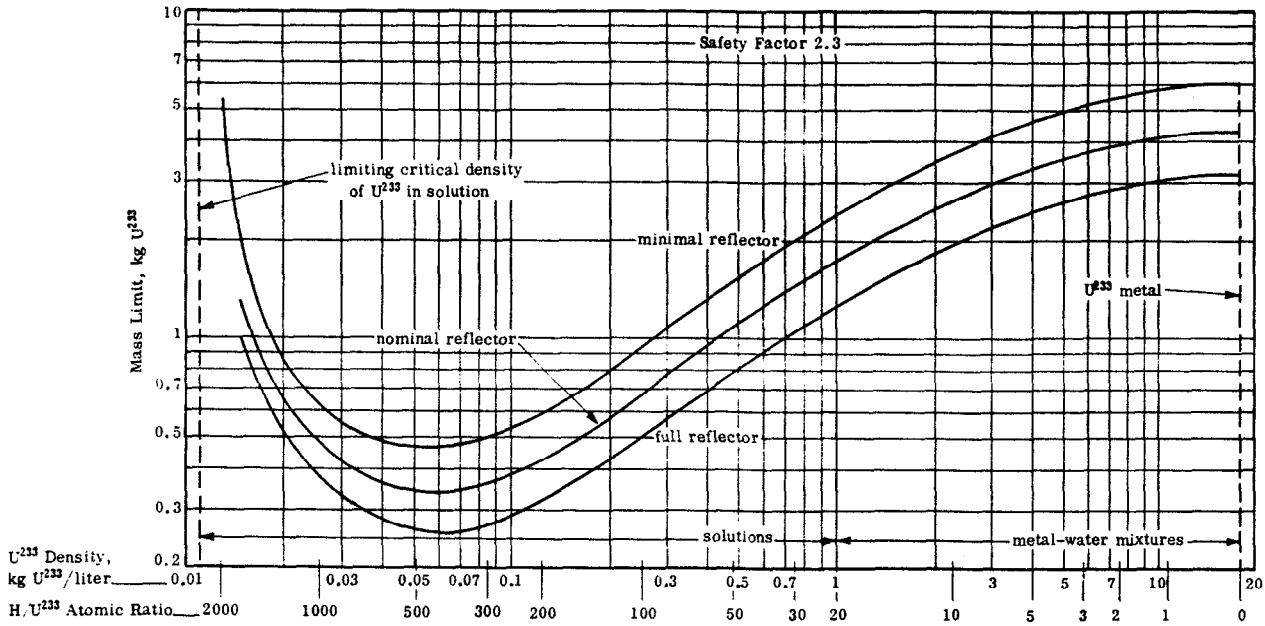


FIG. 9. MASS LIMITS FOR ISOLATED UNITS OF HOMOGENEOUS WATER-MODERATED U^{233} SPHERES (References 12, 14, 17, 18, 21, 22)

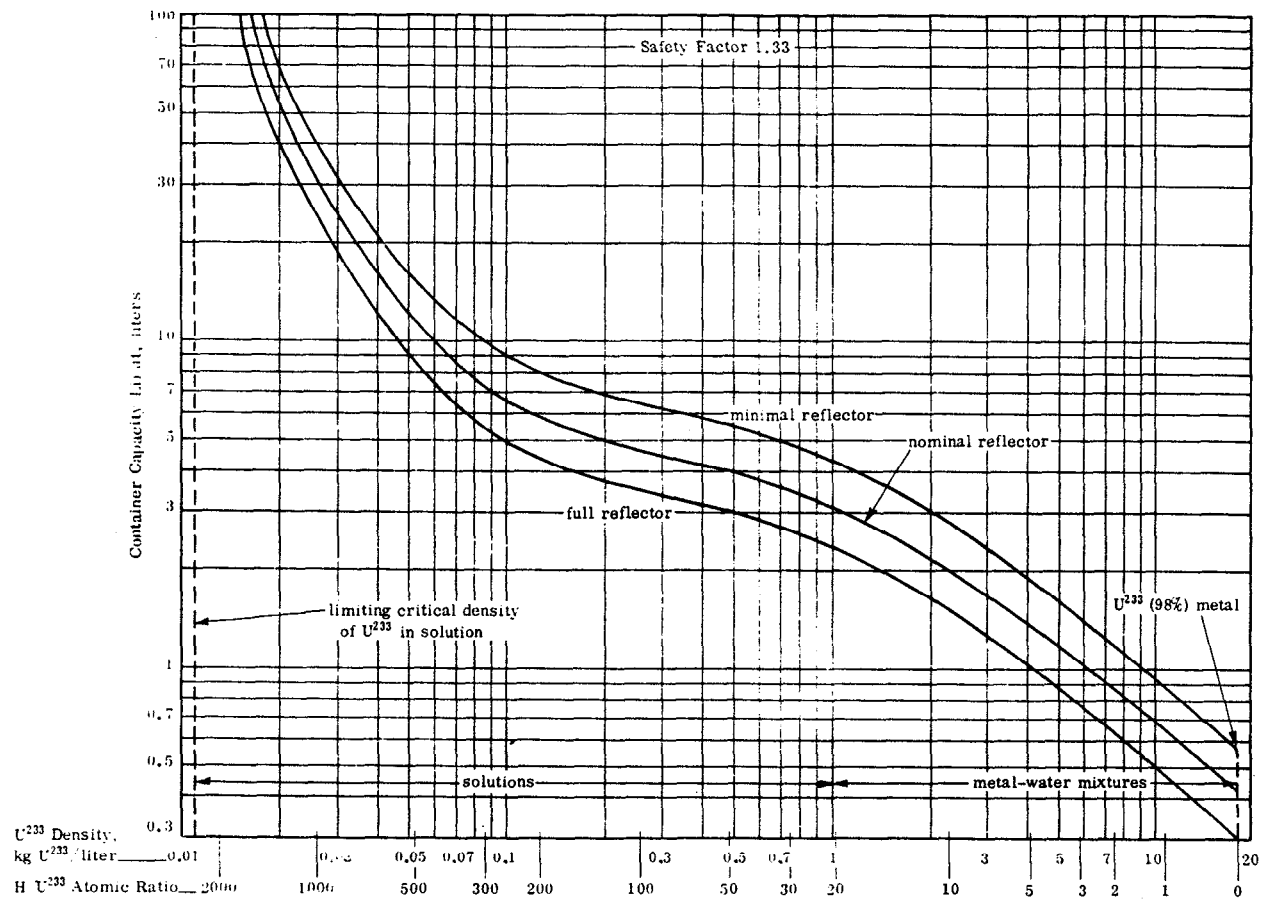


FIG. 10. CONTAINER CAPACITY LIMITS FOR ISOLATED UNITS OF HOMOGENEOUS WATER-MODERATED U^{233} SPHERES (References 12, 21, 22)

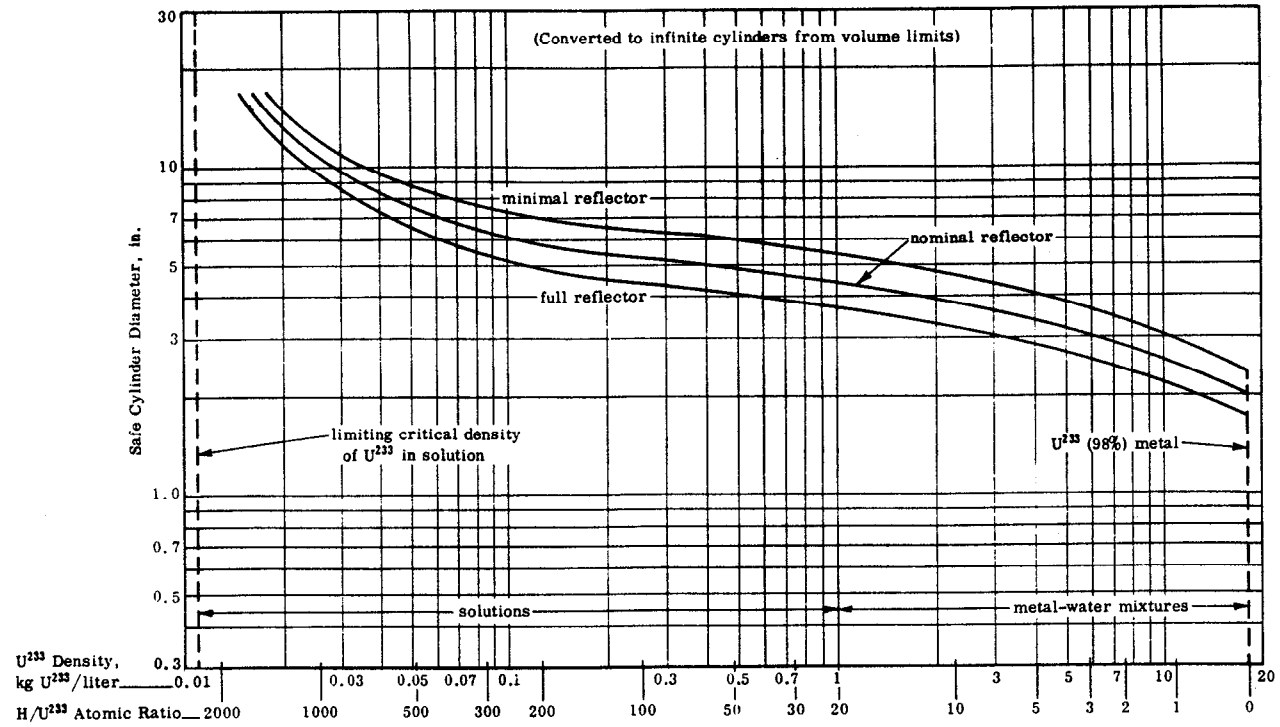


FIG. 11. SAFE DIAMETERS OF ISOLATED CYLINDERS OF HOMOGENEOUS WATER-MODERATED U^{233} (References 12, 14, 21, 22)

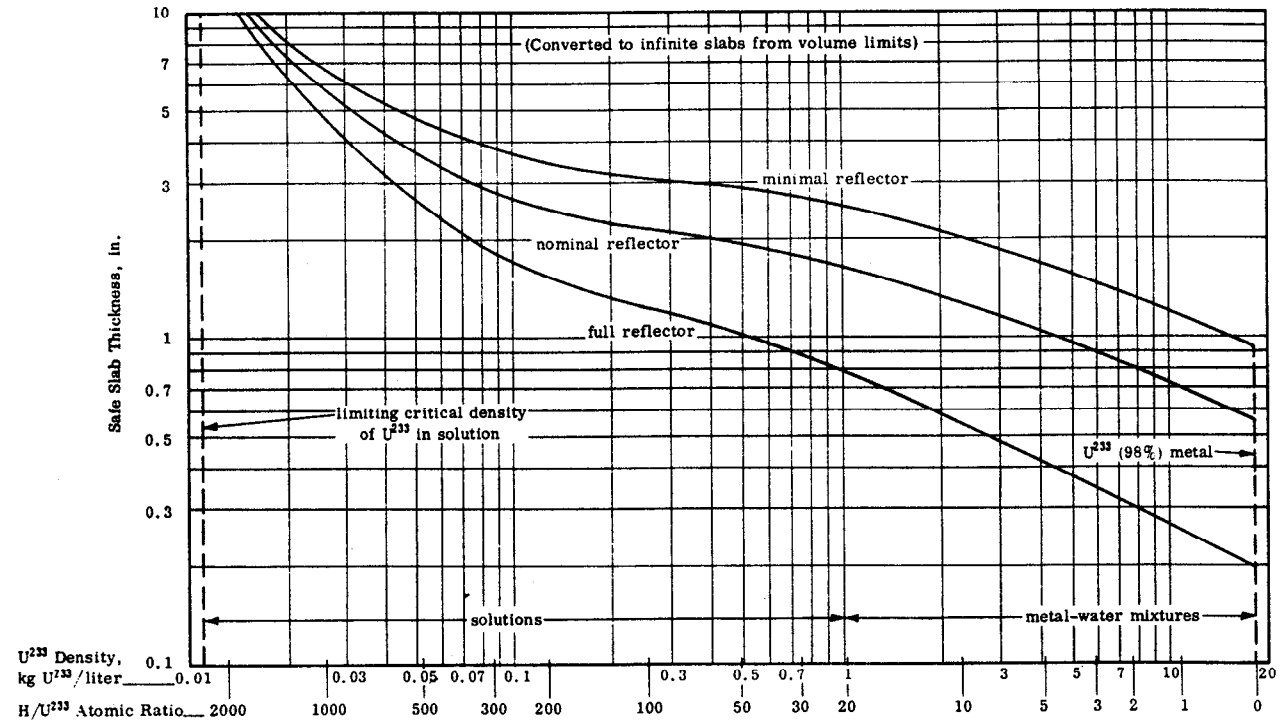


FIG. 12. SAFE THICKNESSES OF ISOLATED SLABS OF HOMOGENEOUS WATER-MODERATED U^{233} (References 12, 14, 22)

particles remain in suspension and do not undergo hydrodynamic pattern changes. Reactivity excursions occur when the uranium distribution is altered by changes in mixing (or stirring) or by settling of the particles. The direction of the reactivity change cannot be foreseen. It follows, therefore, that the rules of this Guide may be applied to slurries when either of the following conditions exists: there is assured maintenance of an established distribution of solids, or the solids are completely settled with no possibility of being stirred. Very little can be said for conditions other than these of steady state, without further experimentation.

Table II

SAFE ANNULAR THICKNESS FOR AQUEOUS SOLUTIONS*

External Reflector Condition	Annular Thickness (in.) U^{235}	U^{233}	Pu^{239}
Minimal	3.5	2.3	3.0
Nominal	3.0	1.8	2.5
Full	2.5	1.4	2.1

*Inner cylinder is cadmium-lined and water-filled.

Pipe Intersections

Table III recommends sizes of intersecting pipes containing solutions of U^{235}, Pu^{239}, and U^{233} salts[29-31]. These values do not apply to metals.

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

Other intersections of individually safe pipes are also permissible if the sum of the cross-sectional areas of all pipes is equal to or less than the corresponding area of the intersection given in the table. Thus the effective diameter, d_e, of an intersection is:

$$d_e = \left[\left(\sum_i^n d_i^2\right)/n\right]^{\frac{1}{2}}$$

where: d_i = diameter of the "i^{th}" branch of the intersection

n = number of branches:
2 for ells
3 for tees and wyes
4 for crosses

An intersection is safe if d_e is equal to, or less than, the tabulated value and if no pipe exceeds the safe diameter given in Figures 3, 7 and 11.

Table III

RECOMMENDED INSIDE PIPE DIAMETERS* FOR INTERSECTIONS CONTAINING FISSIONABLE SOLUTIONS (H/X ≥ 20)

	Inside Pipe Diameter (in.) U^{235}	Pu^{239}	U^{233}
Ells:			
Full Reflector	4.6	4.0	3.4
Nominal Reflector (≤ 1 inch water)	5.3	4.7	3.8
Minimal Reflector (≤ 1/8 inch S.S.)	6.0	5.4	4.2
Tees:			
Full Reflector	4.2	3.8	3.2
Nominal Reflector (≤ 1 inch water)	5.1	4.6	3.7
Minimal Reflector (≤ 1/8 inch S.S.)	6.0	5.4	4.2
Crosses or Wyes:			
Full Reflector	3.8	3.4	2.8
Nominal Reflector (≤ 1 inch water)	4.9	4.4	3.5
Minimal Reflector (≤ 1/8 inch S.S.)	6.0	5.4	4.2

*Reduced diameters should extend 18 inches from intersection.

Lattices of Slightly Enriched Uranium Rods

Figures 13, 14, 15 and 16 show graphs for safe mass limits, container capacity limits, infinite cylinder diameters, and slab thicknesses of heterogeneous systems of slightly enriched uranium in light water for the systems given.[32]

There is some question concerning the appropriate limits for a heterogeneous system of natural uranium in light water. Consistent with the assumption that the quantity of natural uranium required for criticality is sufficiently large to preclude such an accidental occurrence, the curves approach unlimited values at 0.7 percent U^{235} enrichment.

RELAXATION OF NUCLEAR SAFETY LIMITS

The following remarks pertain to situations wherein the preceding recommended limits may be increased, provided the specified conditions be assured.

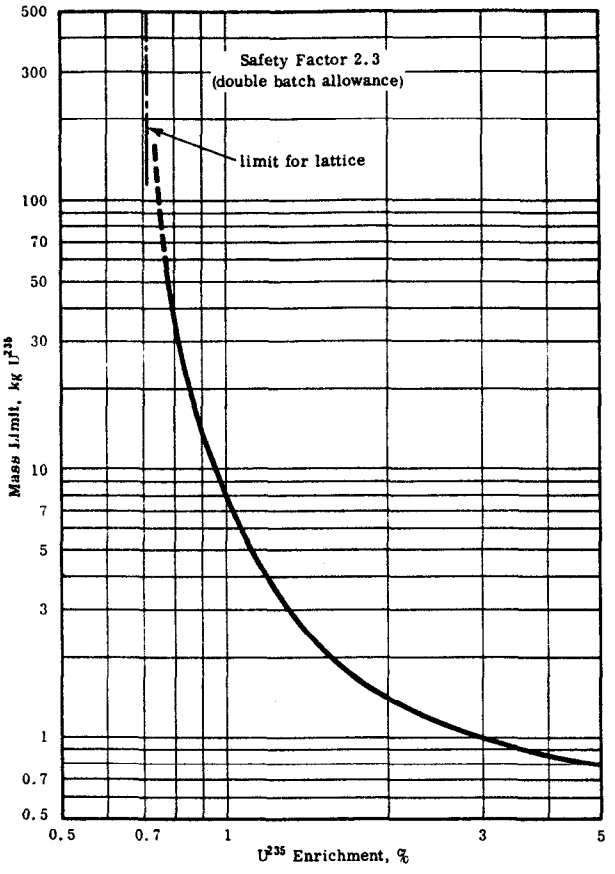


FIG. 13. MASS LIMITS FOR WATER-REFLECTED URANIUM RODS IN LIGHT WATER

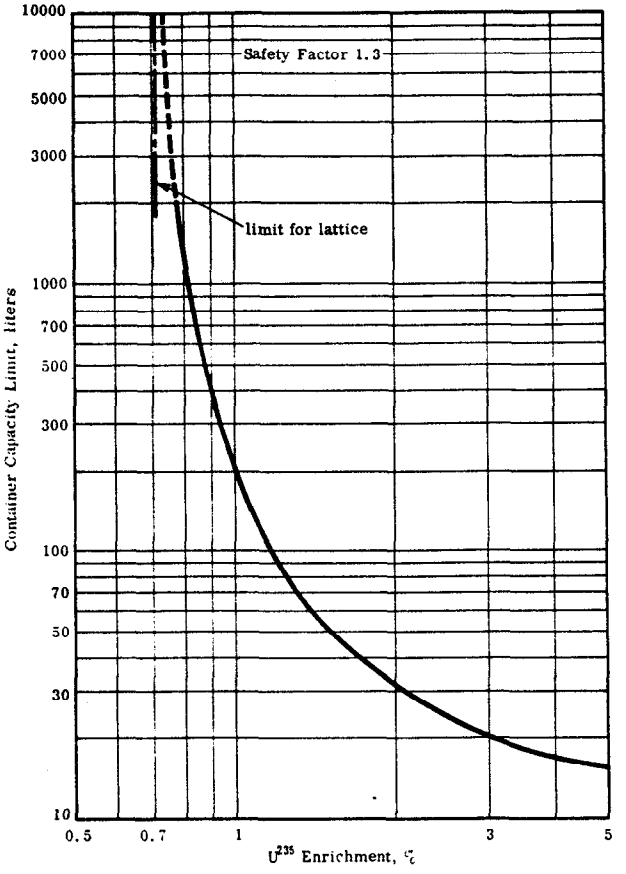


FIG. 14. CONTAINER CAPACITY LIMITS FOR WATER-REFLECTED URANIUM RODS IN LIGHT WATER

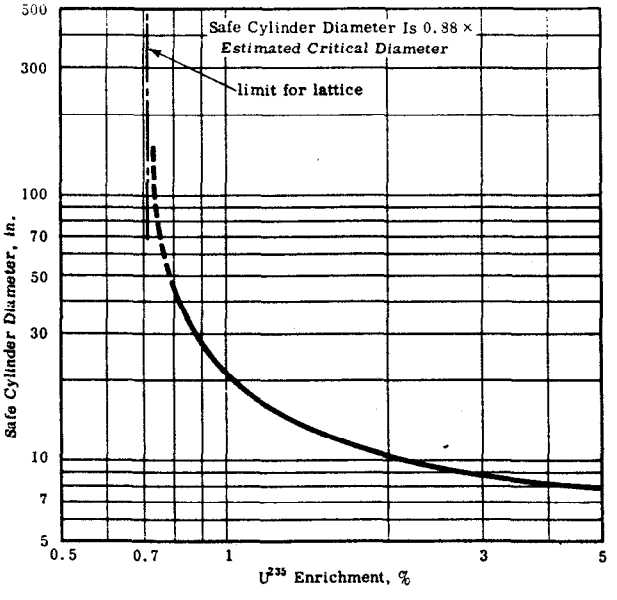


FIG. 15. SAFE DIAMETERS OF INFINITE CYLINDERS FOR WATER-REFLECTED URANIUM RODS IN LIGHT WATER

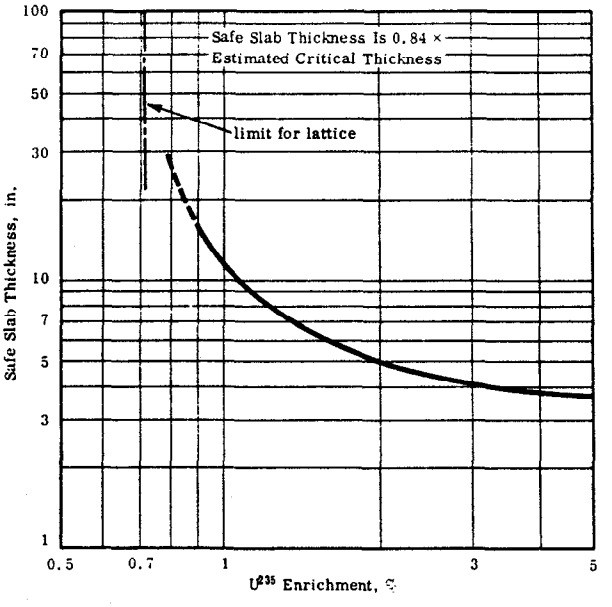


FIG. 16. SAFE THICKNESSES OF INFINITE SLABS FOR LATTICES OF WATER-REFLECTED URANIUM RODS IN LIGHT WATER

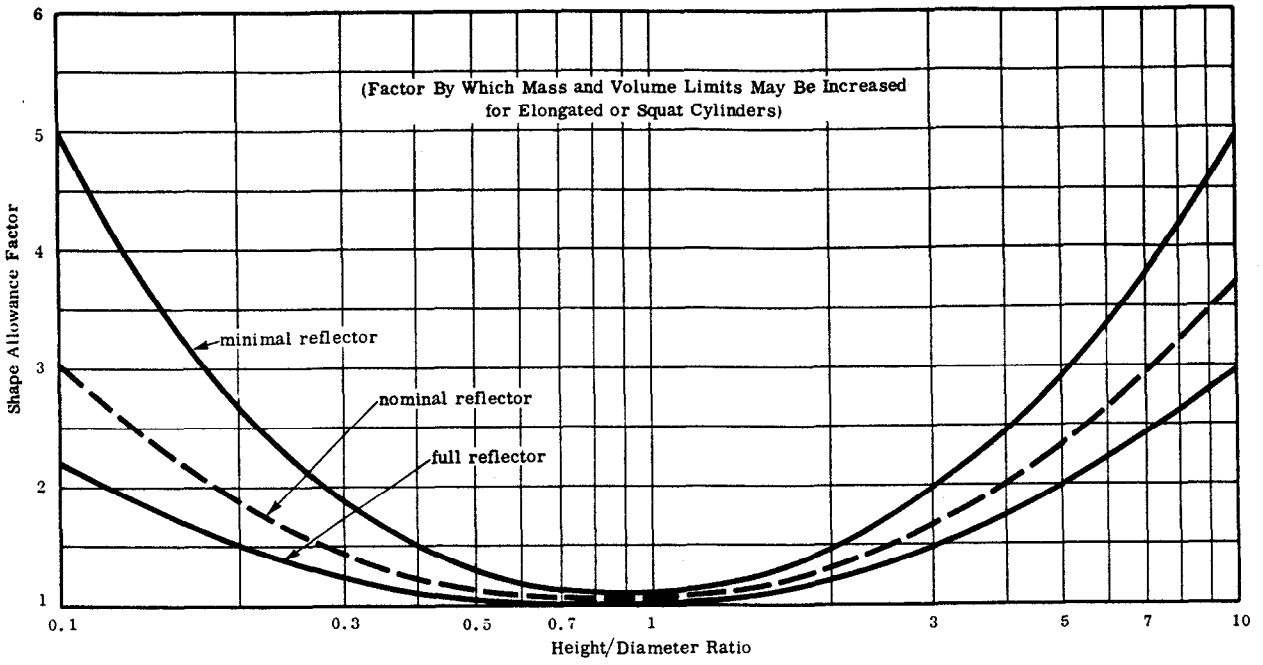


FIG. 17. SHAPE ALLOWANCE FACTORS FOR CYLINDERS

Shape

For certain intermediate shapes of fissionable units, such as elongated or squat cylinders, mass and container capacity limits may be increased by the appropriate factor[12, 14, 17] from Figure 17. This applies to either metals or solutions.

Density

The mass limit of undiluted (unmoderated) fissionable metal at a density less than 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 dry metal turnings) may be increased by the appropriate factor[14] from Figure 18. Factors from this graph may also be applied to solutions with uniformly distributed voids (≤ 1 inch in one dimension), provided "fraction of total density" is defined as the ratio of average density of the solution plus voids to the density of the solution. Generalizations cannot be made for the safe handling of chunks of uranium metal in a liquid having moderating properties. Information which may provide answers to such problems can be found in the literature[26].

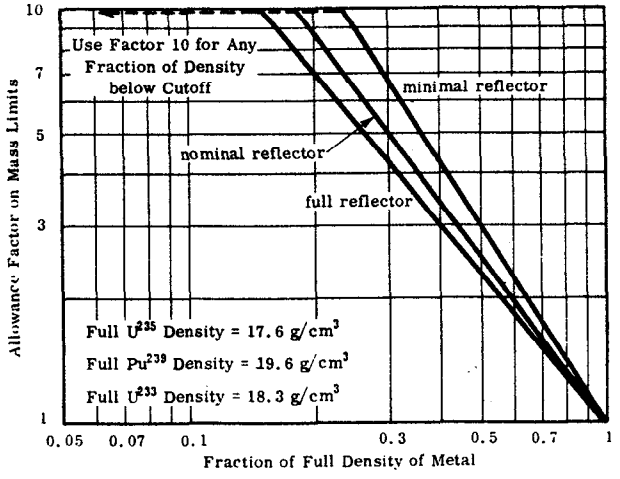


FIG. 18. ALLOWANCE FACTORS FOR REDUCED DENSITY OF U^{235}, Pu^{239}, AND U^{233} AS METAL ONLY

Dilution

Figure 19 shows factors by which the mass limits for fissionable material may be increased if fissionable atoms are mixed uniformly with any of the listed elements either as physical mixtures or chemical compounds[18, 33]. It is emphasized that these factors cannot be applied if hydrogen, deuterium, or beryllium are present. Although these factors are intended primarily for homogeneous systems, they may be used for similar units of fissionable material distributed uniformly in the diluent provided one dimension of the unit does not exceed 1/8 inch for U^{235} or 1/16 inch for Pu^{239} or U^{233}. The factors are not applicable to mixtures having X densities less than 1 percent of the full density in order to guard against moderation by relatively large proportions of nuclei of intermediate atomic number.

Enrichment

In the special case of undiluted uranium metal in which the U^{235} content is less than 93 percent, the U^{235} mass limit may be increased by the appropriate factor[14] from Figure 20. A factor for reduced density of total uranium (not U^{235}), from Figure 18, may be applied in addition to this enrichment factor.

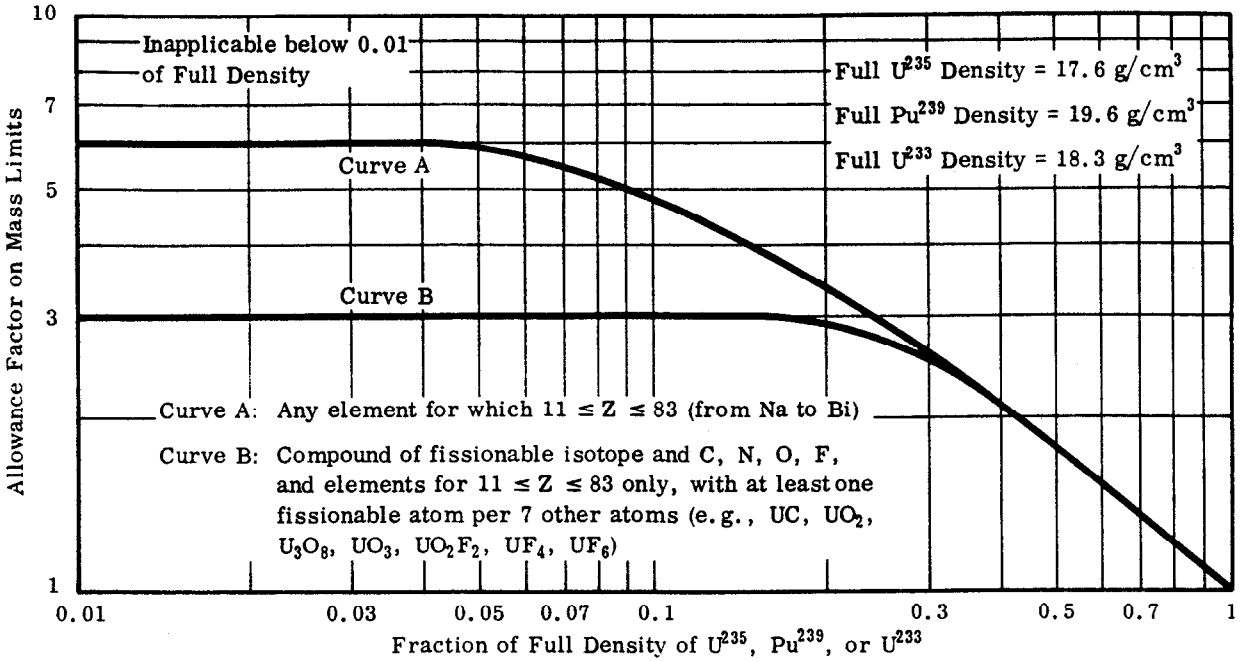


FIG. 19. ALLOWANCE FACTORS FOR U^{235}, Pu^{239}, OR U^{233} MIXED HOMOGENEOUSLY WITH ELEMENTS LISTED (H, D, AND Be EXCLUDED) INDEPENDENT OF REFLECTOR CLASS

Uranium in which the U^{235} enrichment is equal to or less than 5 percent needs no further restriction provided it is: (1) in the form of metal with no interspersed hydrogenous material, e.g., a single piece without reentrant holes; (2) in a solid nonhydrogenous chemical compound; or (3) intimately mixed, either as metal or as a nonhydrogenous compound, with any element of atomic number Z greater than 13 provided the atomic ratio Z/U^{235} is less than or equal to[8] 100.

The full reflector limits for aqueous homogeneous solutions may be increased for reduced enrichment by the allowance factors of Figure 21. It is emphasized that these factors may not be applied to the minimal and nominal reflector limits.

As stated before, the mass limits of Figures 1, 5 and 9 contain a factor of safety of about 2.3 as protection against a double-batching error. Where the possibility of overbatching is excluded, the mass limit may be increased by the factor 1.8.

ARRAYS OF UNITS

Although the following recommendations are specifically directed to the problem of storage and transportation, they nevertheless represent evaluations of critical data pertaining to neutron interaction and in this sense may be interpreted as, and used as, basic information applicable to systems where the exchange of neutrons between components is possible.

General Criteria

Specifications for the spacing of individually subcritical units in an array that is also subcritical have been established empirically. The specifications are based on generalizations of critical data for cubic lattices, so may be applied conservatively to the imperfect arrays that are generally practicable in cases of storage, plant-equipment layout, and shipping. It is necessary to distinguish between two cases when shipping; specifically, the exclusive and controlled use of the carrier (controlled loading and unloading but no off-loading or reloading enroute) and the uncontrolled "partial" use of the carrier (less than carload lot). In the latter case it is assumed that no special control is exercised over the carrier or its environment.

In the following criteria and recommendations, containers of units are assumed to be of nonhydrogenous materials, viz., steel, aluminum, or glass protected by metal, with an average wall thickness less than 1/2 inch. It is assumed further that the unit containers* are spaced by birdcages, porous compartments, or specifically located anchorage such that there will be an

*The term "unit container" refers to the inner or primary container and is not to be confused with the outer or spacing container.

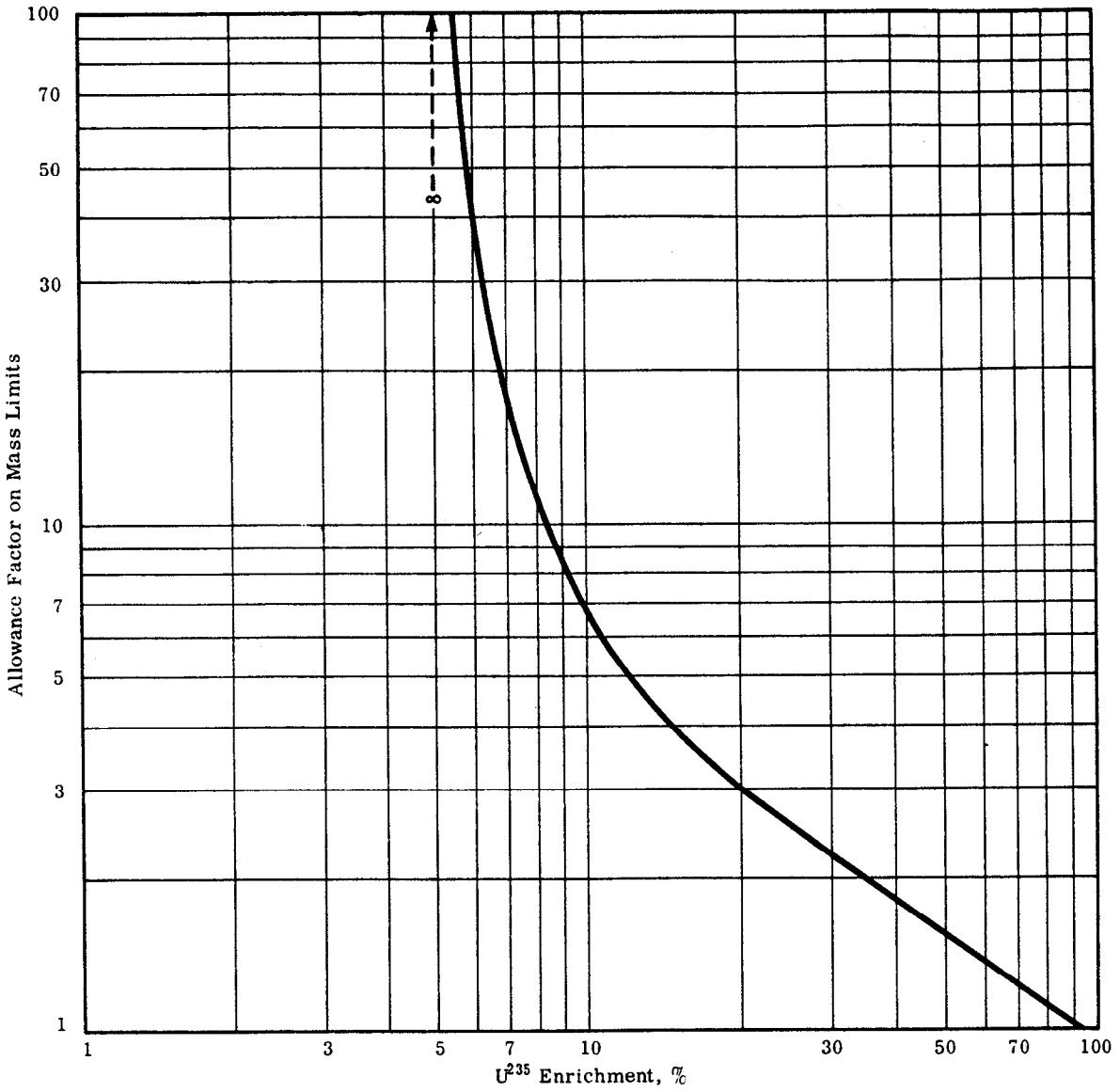


FIG. 20. ALLOWANCE FACTORS ON U^{235} MASS LIMITS FOR URANIUM METAL AT INTERMEDIATE ENRICHMENTS

8-inch minimum thickness of water between unit containers in case of flooding. These requirements on containers and spacers are not assumed for uncontrolled transportation. All unit containers shall be sealed against inleakage of water. They should be individually safe in event of internal flooding if there is doubt about the integrity of seals.

No storage or transportation restrictions are required for:

1. Uranium enriched in U^{235} to 0.95 percent or less as an aqueous homogeneous mixture.
2. Uranium metal enriched to 5 percent or less provided there is no hydrogenous material within the container.
3. Aqueous solutions of U^{235} at concentrations less than or equal to 10.8 g U^{235}/liter, of U^{233} at concentrations less than or equal to 10.0 g U^{233}/liter, or of Pu^{239} at concentrations less than or equal to 6.9 g Pu^{239}/liter.

Maximum Size of Units to Which Storage Limits Apply

The values given in Table IV describe individual, maximum-sized units which are subcritical when immersed in water. These various units are sufficiently similar to allow the application of storage recommendations to combinations of them. It is explicitly assumed that control of the size of individual units is

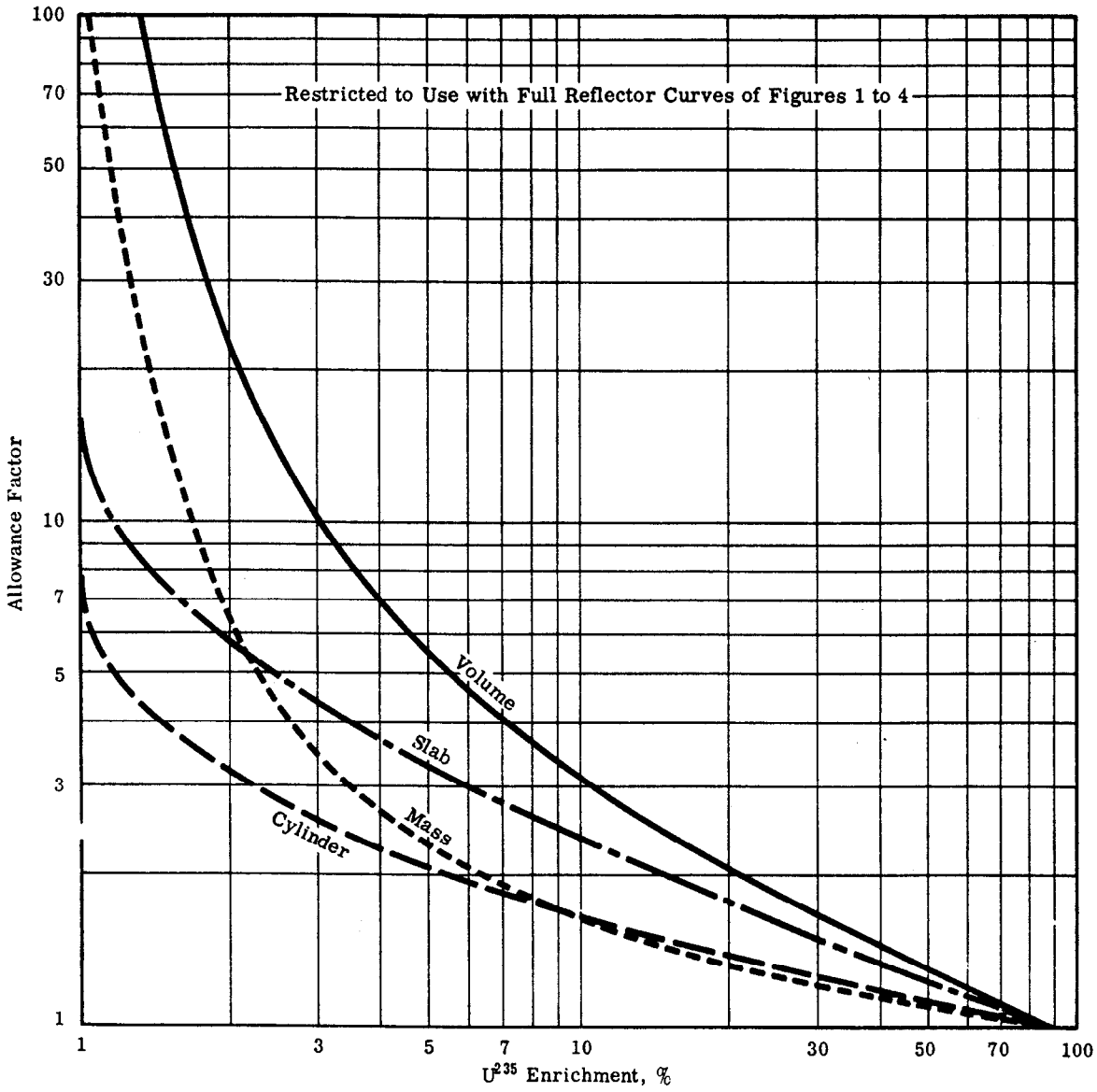


FIG. 21. ALLOWANCE FACTOR FOR AQUEOUS HOMOGENEOUS SOLUTIONS OF U^{235}

more stringent here than for process operations, thereby allowing a relaxation of the customary double-batching safety factors. The allowance factors for shape, density, dilution, or enrichment should not be used to increase the unit sizes listed in Table IV. The recommendations contained in this section are applicable to uranium at any U^{235} enrichment.

Criteria for Storage

Figure 22 gives the allowable number of units, as defined in Table IV, in cubic arrays[34,35] located in storage vaults, or in plant layouts, These specifications can be applied conservatively to other configurations of these units. The figure may be used to determine the allowed number of units from a given birdcage size, i.e., known center-to-center separation, or the required separation for a given number of units. Curve A applies where there is a thick, close-fitting reflector about the array, as a thick-walled vault of concrete, metal, wood, or earth. Curve B holds where reflection about the array is nominal, or where the array is effectively reflected on no more than two sides as, for example, a floor and a wall of concrete, metal, wood, or earth.

The "maximum unit" may consist of a group of smaller units in a single sealed container or distributed among several sealed containers. The spacing between unit containers is effected by birdcages, storage racks, or other means and shall not be less than 8 inches surface-to-surface in any case. When the possibility of flooding is ruled out, the sealed container restriction may be removed.

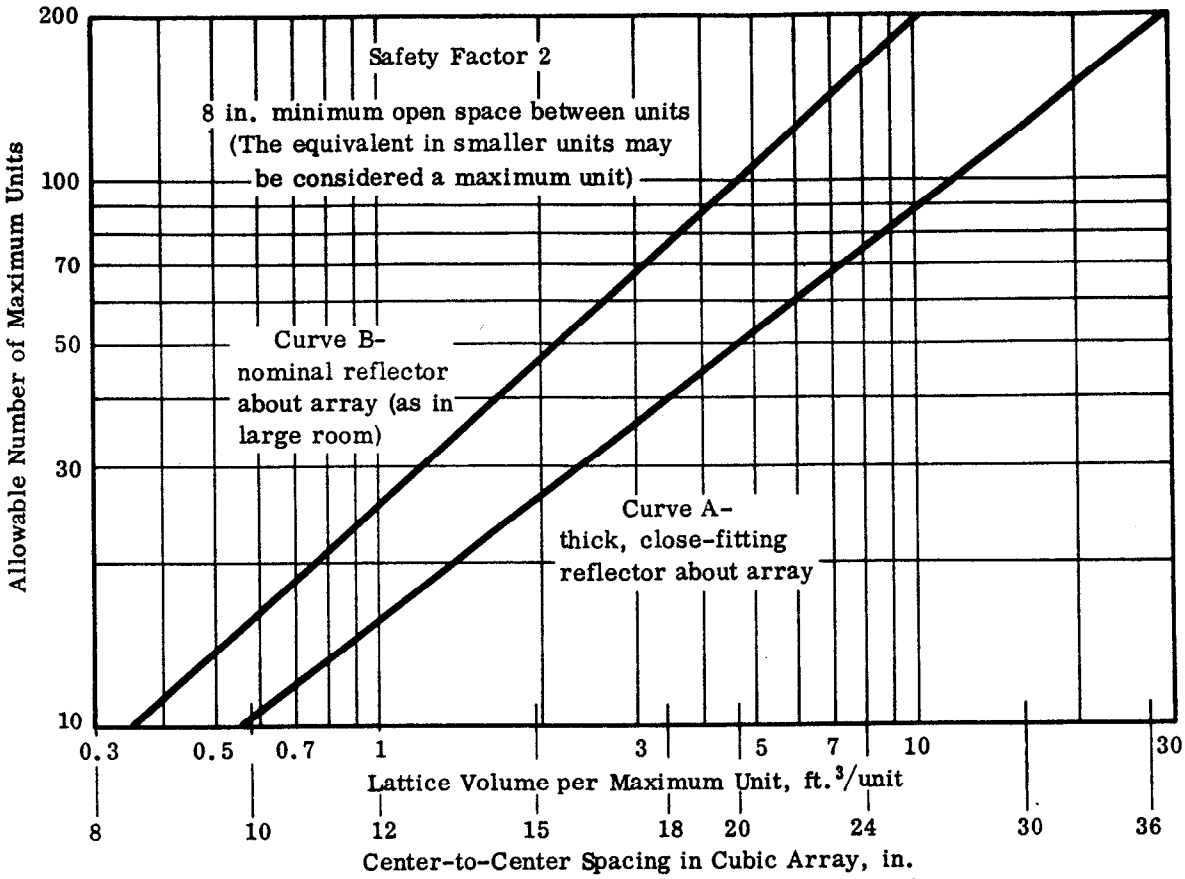


FIG. 22. ALLOWABLE NUMBER OF MAXIMUM-SIZE UNITS (OF TABLE IV) IN A CUBIC ARRAY

Table IV

MAXIMUM SIZES OF SPHERICAL UNITS
TO WHICH STORAGE LIMITS APPLY

Material Type	U^{235}	Pu^{239}	U^{233}
Metal, Compounds, or Mixtures; H/X ≤ 0.5;* mass limit, kg	18.5	4.5†	4.5
Metal, Compounds, or Mixtures; 0.5 < H/X ≤ 2; mass limit, kg	16.0	4.5	4.5
Hydrogenous Compounds or Mixtures; 2 < H/X < 20; mass limit, kg	3.6	2.4	2.0
Solutions or Hydrogenous Mixtures; 20 ≤ H/X; volume limit, liters	3.6	2.4	2.0

*H/X signifies the atomic ratio H/U^{235}, H/Pu^{239}, or H/U^{233}.

†This limit holds for Pu metal at $\rho = 19.6$ g/cm³; for the alloy at $\rho = 15.8$ g/cm³ the corresponding limit is 6.0 kg.

Contained in Table V are permissible spacings of the units described in Table IV when assembled in an isolated linear or plane array*.

The bases for specifications describing permissible spacings between two or more arrays are even less firmly established upon experiment than are those describing single arrays. It is possible, however, to make some specific recommendations for arrangements of plane arrays of the units described in Table IV based on extrapolation of data obtained from experiments with single arrays and on practical experience. These recommendations are also presented in Table V. Isolated and associated arrays referred to in Table V are defined in the following manner. For practical purposes arrays in which the units meet the spacing criteria of Figure 22 or Table V may be considered isolated when separated by a layer of concrete or water at least 8

*Arrays are linear, plane, or cubic depending upon whether the apparent centers of the units can be described by one, two, or three coordinate axes.

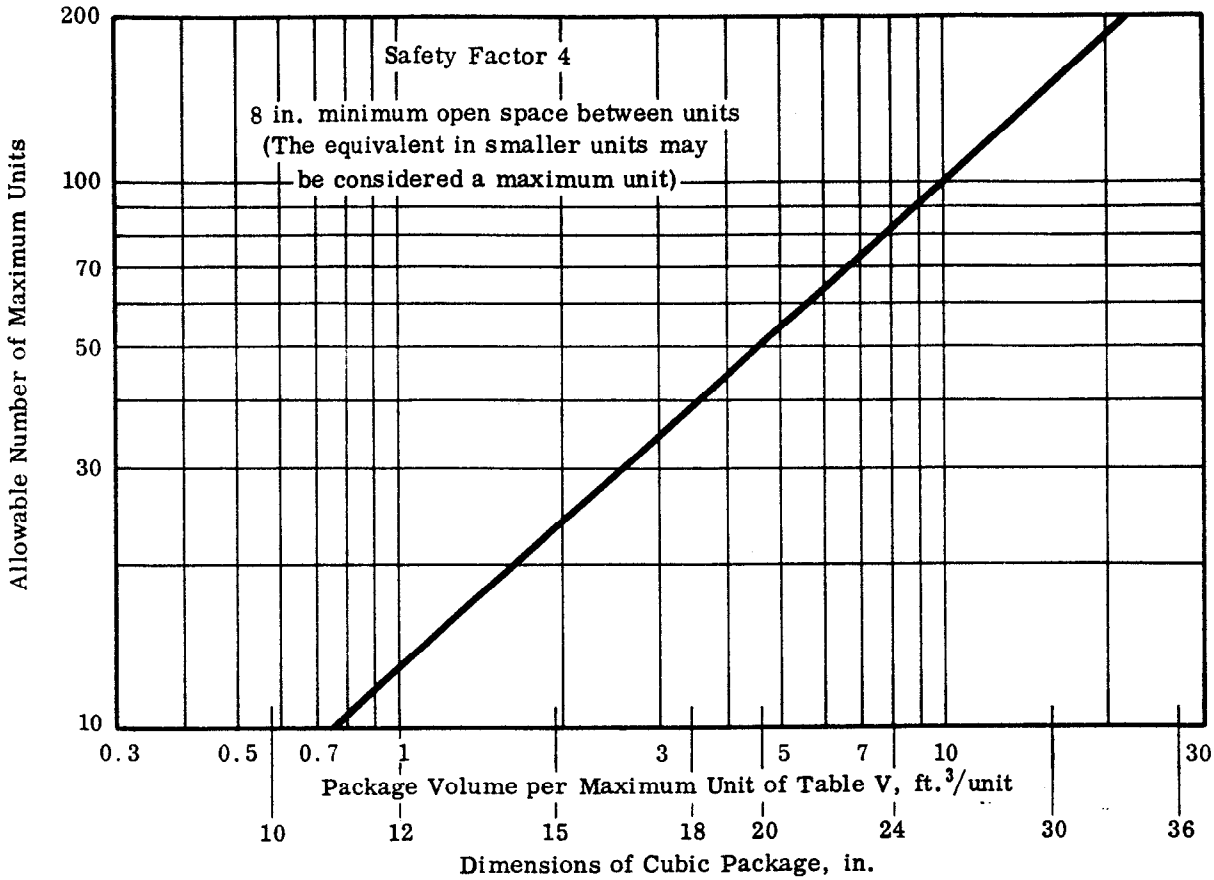


FIG. 23. RELATION BETWEEN PACKAGE VOLUME FOR MAXIMUM UNITS (OF TABLE IV) AND ALLOWABLE NUMBER IN A CUBIC ARRAY WITH NOMINAL REFLECTION

Table V

LIMITS FOR STORAGE OF UNITS DEFINED IN TABLE IV

Type of Array	Minimum Center-to-Center Spacing* of Units of Maximum Size (in.)	Storage Limit per Array, Number of Units of Maximum Size
Isolated linear or plane array	16	No limit
Two or more associated plane arrays	30	120/array; 240 total
	24	90/array; 180 total
	20	50/array; 100 total

*There must be at least 8 inches open space between maximum units.

inches thick*. Two plane or cubic arrays may also be considered isolated if the surface-to-surface separation is greater than the larger of the following quantities: (1) the maximum dimension of either array, or (2) 12 feet. Two linear arrays are isolated, regardless of length, if their separation is at least 12 feet.

Non-isolated plane arrays are associated if the minimum surface-to-surface spacing is at least 7.5 feet; if the spacing is less, they are to be regarded as a single array.

Table V also gives limits on the total number of units allowed both per array and in all associated arrays.

In the case of solution storage in linear arrays of cylinders having diameters no greater than 5 inches for U^{235} or Pu^{239} and 4 inches for U^{233}, there is no limit on

*Separation by at least 12 inches of water or concrete is required for units or arrays of units more reactive than those described above.[13]

Table VI

LIMITS FOR CONTROLLED SHIPMENTS OF UNITS DEFINED IN TABLE IV*

	Maximum Density Established by Birdcage or Other Spacer†			Normal Carload or Truckload Limit (50 Maximum Units)‡		
	U^{235}	Pu^{239}	U^{233}	U^{235}	Pu^{239}	U^{233}
Metal, Compounds or Mixtures;						
$H/X \leq 0.5$§	4 kg/ft^3	1 kg/ft^3	1 kg/ft^3	925 kg	225 kg	225 kg
$0.5 < H/X \leq 2$	3.5 kg/ft^3	1 kg/ft^3	1 kg/ft^3	800 kg	225 kg	225 kg
Hydrogenous Compounds or Mixtures;						
$2 < H/X < 20$	0.8 kg/ft^3	0.5 kg/ft^3	0.4 kg/ft^3	180 kg	120 kg	100 kg
Solutions or Hydrogenous Mixtures in Non-safe Containers;						
$H/X \geq 20$	0.8 liter/ft^3	0.5 liter/ft^3	0.4 liter/ft^3	180 liters	120 liters	100 liters

*Masses apply to U^{235}, Pu^{239}, or U^{233} content of units.

†Birdcages or other spacers shall establish at least 8 inches open space between units; unit containers 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).

§ H/X signifies the atomic ratio H/U^{235}, H/Pu^{239}, or H/U^{233}.

the number of cylinders at a minimum center-to-center spacing of 24 inches. Similarly, for two associated linear arrays where the surface-to-surface spacing in each array is 24 inches there is no limit to the number of cylinders.

Criteria for Controlled Transportation

As specified in the general criteria the exclusive and controlled use of the carrier implies no off-loading or reloading enroute and assurance that a planned arrangement of the cargo will be maintained. Figure 23 may be used to establish limits for the transport of units. The safety factor of two greater than that for similar storage arrays allows for the combination of two shipments as the result of an accident. It is assumed that the integrity of birdcages or shipping cases and of the sealed container will be preserved even in the course of an accident.

Table VI gives specific recommendations for controlled shipment of units as defined in Table IV. Again, maximum units may be made up of groups of smaller units. It is re-emphasized that containers and spacers or anchorage must be sufficiently strong to remain effective through an accident. The total amount of U^{235}, Pu^{239} or U^{233} in a single shipment shall not exceed fifty (50) of the units prescribed in Table IV.

Criteria for Uncontrolled Transportation

Shipments not under the control of the consignor after delivery to the carrier constitute "uncontrolled transportation." This category includes less-than-carload lot (LCL) shipments or partial use of the carrier. Recognizing that such shipments entail complete abandonment of assured open spacings and of environmental control, it is necessary to compensate by imposing more stringent conditions on packages given to such carriers for transport. It is assumed that any cluster of packages is now subject to moderation and either to complete reflection or to nominal reflection with possible combination of two shipments.

Table VII defines the maximum allowable unit for uncontrolled transportation, and no individual package may contain more than this quantity of material. The allowance factors for shape, density, dilution, or enrichment should not be used to increase the unit size, even though the values for uranium are conservatively applicable to any U^{235} enrichment. Figure 24 is to be used in establishing L, the greatest permissible accumulation of packages of a given size. The basic limit, L_o, measured in maximum allowable units is found by entering Figure 24 at the volume defined by the outer dimensions of the shipping container. If the amount of material in each such container is M, and the maximum allowable

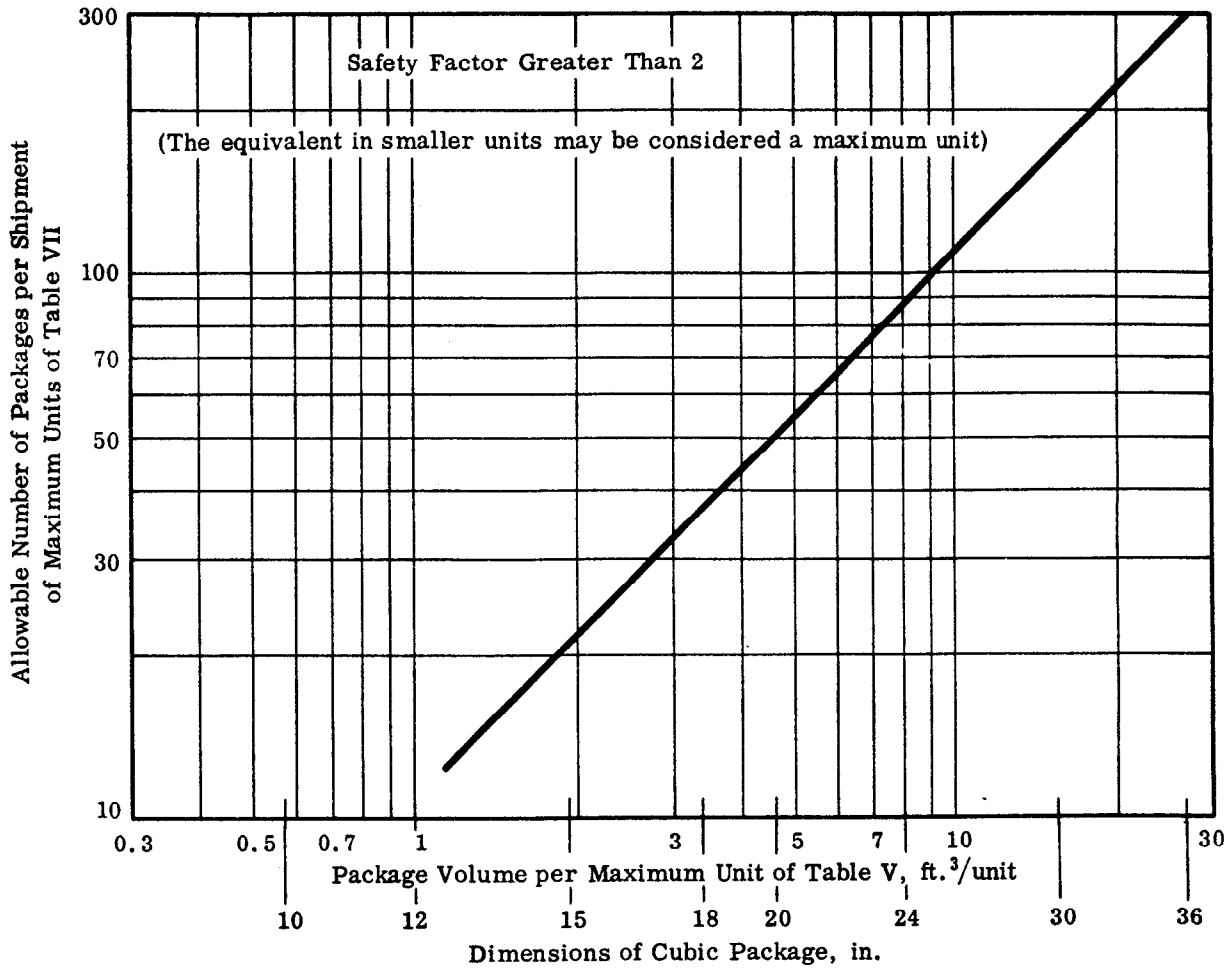


FIG. 24. ALLOWABLE NUMBER OF PACKAGES IN UNCONTROLLED SHIPMENTS OF UNITS (AS DEFINED IN TABLE VII) IN CUBIC ARRAYS WITH OPTIMUM WATER MODERATION AND REFLECTION

unit for the nature and moderation of the material is M_O (from Table VII), then the maximum permissible accumulation of packages in the shipment is $L = L_O(M_O/M)$.

The greatest permissible accumulation of packages of different sizes is to be established by weighting each container in proportion to its individual allowable limit; thus, an accumulation of packages must be such that $1 \geq \Sigma(N/L)$ where N is the number of packages whose individual limit (from Table VII and Figure 24) is L.*

For example, suppose one has eleven packages 15 inches on an edge, ten 20-inch packages and twenty 24-inch packages. Can these 41 packages be placed in a single array? The allowed numbers of packages for 15-, 20-, and 24-inch center-to-center spacing are 22, 50, and 86, respectively; consequently:

$$11/22 + 10/50 + 20/86 < 1$$

and they may be assembled in a single array.

Packaging shall comply with all existing regulations on containment of radioactive materials in transit, and must be sufficiently strong to remain effective through an accident.

In packages that are at least 20 inches in any dimension, an accumulation of 50 maximum allowable units (Table VII) would have a safety factor of at least two even if water or other hydrogenous material were intermixed in any proportion (the factor of safety is ten without

*The objectives of both Health Physics and Nuclear Safety can be achieved if the accumulation of random containers in transit is governed by the equation $40 \geq \Sigma[(N/L)40]$. Control may be accomplished by assigning as the number of radiation units on each package the larger of the following quantities: (1) the number of actual radiation units; or, (2) 40 divided by the allowable number of units from Figure 24, i.e., $40/L_O$. The Health Physics aspects of shipments are defined in federal regulations coded as 49CFR 77.841(2).

Table VII

MAXIMUM SIZES OF UNITS
IN UNCONTROLLED TRANSPORTATION

	U^{235}	Pu^{239}	U^{233}
Metal, Compounds, or Mixtures; $H/X \leq 2^*$; mass limit, kg	9.5	3.4†	4.0
Hydrogenous Compounds or Mixtures; $2 < H/X < 20$; mass limit, kg	2.0	1.3	1.3
Solutions or Hydrogenous Mixtures; $20 \leq H/X < 800$, volume limit, liters	2.0	1.3	1.3
Solutions or Hydrogenous Mixtures: $H/X \geq 800$; volume limit, liters	4.0	3.0	3.0

*H/X signifies the atomic ratio H/U^{235}, H/Pu^{239}, or H/U^{233}.

†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 4.5 kg.

intermixed hydrogenous material, but with hydrogenous reflector about the array). There is insufficient allowance for large quantities of D_2O, beryllium, or graphite within the array, though a large stack against one side would not override the safety factor.

For transportation by ship, the land vehicle limitation may be applied to any isolated array provided there is a physical barrier between the array and any other fissionable material.

SHIPMENT OF REACTOR FUEL ELEMENTS

The following generalized recommendations are applicable to the shipment of reactor fuel elements. It is recognized that elements of a wide variety of both fuel content and mechanical form will require nuclear safety specifications and it is believed that reactor design, supported in many cases by critical experiments and possibly even reactor operation, will yield the information required as bases for these recommendations before they need be effected.

1. The value of the effective neutron multiplication constant, k_{eff}, of a single container of elements shall not exceed 0.90 with due credit for neutron absorption by both intentionally built-in poisons and the carrier structure. Determination of the multiplication constant shall be based on the following assumptions, where applicable:

   a. If the elements have been used, the fuel should be considered as unirradiated fuel if reactivity decreases with burnup; or it should be considered as irradiated fuel at the condition of maximum reactivity if reactivity increases with irradiation.

   b. The fuel should be considered as melted fuel in the most reactive configuration unless it has been demonstrated conclusively that melt-down of the fuel elements is impossible.

   c. The carrier shall be assumed to contain a hydrogenous liquid in such quantity and so distributed as to produce maximum reactivity.

   d. The carrier must be so designed, and the fuel elements must be so supported within it, that the fuel elements cannot be rearranged into a configuration more reactive than that for which the shipment is designed.

   e. Neutron absorbers intentionally built into the carrier components or fuel elements may be considered in the reactivity evaluation provided there is assurance that the absorbers cannot change their effectiveness by, for example, mechanical shock during normal shipment or as a result of any credible accident.

2. Consideration must be given to the proximity of any carrier to other containers of fissionable material during transit to preclude unsafe conditions arising from neutron interaction.

PART III

APPLICATION TO PROCESSING PLANTS

INTRODUCTION

The typical process plant contains an arrangement of tanks, pipes, and columns with interconnections and nearby structures rather than the simple units described in Part II. In order to utilize available plant floor area and equipment in the most advantageous manner, it is often necessary to make nuclear measurements on either a portion of the actual process or on a mocked-up version of the process in a critical experiments laboratory. Basically, the restrictions or limits imposed upon a system will depend upon the application. Mass limits are appropriate for handling metal or compounds, or for processing batches of solution where there can be neither volume nor dimensional controls. Restricted diameter is best suited to solutions. Safe slab thicknesses are particularly useful for the processing container or for control of metal sheets.

By way of introduction to possible mishaps frequently encountered in practice, a partial list of observed deviations from standard conditions in processing is presented. This is by no means inclusive but merely suggestive of potential sources of difficulty. As an aid to the evaluation of reflector conditions, a short paragraph contains rules for the selection of the proper condition. Brief attention is paid to the use of neutron absorbers in processing, and a few approved rules are stated. Finally, several problems are given and acceptable solutions presented in detail sufficient to illustrate the vagaries of this art.

NOTED MISHAPS

Following are examples of common accidental conditions that should be considered in criticality control.

Sampling and Analysis: (1) Non-representative sampling of solutions with unsuspected concentration gradients, as in ion-exchange columns. (2) Significant errors in estimating fissile material content of heterogeneous mixtures of solids for recovery. (3) Errors in reported analytical data, particularly misplaced decimal points.

Solution Makeup and Processing: (1) Double-batching. (2) Unsuspected transfer to other process vessels or to auxiliary vessels such as traps and scrubbers. (3) Filter failure, allowing precipitate to flow into a vessel intended for normally dilute filtrate. (4) Unsuspected transfer of organic solvent into a vessel containing aqueous solution, with a resulting extraction of the fissionable material into the organic phase. (5) Accidental precipitation. (6) "Layering" in solutions of different density having a common solvent.

Metal Processing: (1) Neat stacking of spaced containers by a janitor. (2) Crucible or mold failure resulting in conical pileup on the floor of a casting furnace. (3) Damaged pouring crucible resulting from either a freeze-up or an abnormally high crucible temperature. (4) Flooding of the casting furnace as result of a leak in the internal water-cooling coils. (5) Unanticipated combustion. (6) Disarrangement of containers as the result of accidents.

INCIDENTAL REFLECTORS

Masses of concrete, steel, or wood within "six volume-averaged radii"* of the center of a vessel increase minimal reflection to nominal reflection, or nominal reflection to full reflection[36]. They do not influence a system having full reflection. Such structures may be ignored if they are beyond this distance. Effects of personnel as neutron reflectors may be neglected when systems are considered nominally or fully reflected.

USE OF NEUTRON ABSORBERS

The use of neutron absorbers[37] as a primary safety in chemical processing has become an accepted practice. Not only is the nuclear poison used in cases where active materials are expected in a process train, but also as a protective measure in large volumes which may receive fissionable material due to a misoperation in the process. The above remarks are specifically directed to fixed poisons. It is strongly recommended that the use of soluble poisons as primary controls be limited to processes which take place behind suitable shielding, such as the recovery of spent fuel from a reactor. Such controls used outside of a shielded area should require absolute experimental evidence that the procedure is safe.

In any contemplated use of neutron absorbers, the user should assure himself of the integrity of the absorber against chemical attack or mechanical dislodgement, particularly for soluble absorbers where some chemical reaction may selectively precipitate the poison. This procedure will necessarily invoke administrative controls in order to ensure the presence of the absorber either by routine visual inspection, or by neutron absorption or other indirect measurements. The user is encouraged to investigate those experimental measurements that have been made as well as those practices which are in existence and to understand completely any restrictions or conditions pertinent to the operation before accepting a neutron absorber as a primary safety. Examples of conditions which must be considered are concentration, heterogeneity, and self-shielding effects.

*"Six volume-averaged radii" is equal to six times the radius of a sphere having the same volume as the unit in question.

Precedent dictates against stating rules when there is a paucity of data upon which to base them. The proposed use of neutron absorbers is of this category. Yet, it is deemed advisable at this time to give two very general rules for consideration in such problems.

Soluble Poisons

When mixed homogeneously in solution, the fissionable isotope and cadmium, or its nuclear equivalent, should be present in equal molar quantities.

Solid Poisons

The use of an absorber as a primary safety is recommended for aqueous solutions in which the concentration of the fissionable isotope does not exceed 25 g/liter provided the absorber contains at least 4 weight percent boron (or its nuclear equivalent), occupies a minimum of 17.5 volume percent of the vessel, and is uniformly distributed throughout the volume.

EXAMPLES OF PLANT APPLICATION

Several problems typical of those arising in chemical or metallurgical plants processing sizable quantities of fissionable materials are presented in this section.

Pouring Crucible and Mold Limits for 40-Percent-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. The graphite walls of the crucible and the mold plus insulation and heating coils are sufficiently thin to be classed as a nominal reflector, and there is no possibility of internal flooding.

The mass limit for nominally reflected metal given in Figure 1 is 14.0 kg U^{235}. Figure 20 gives an allowance factor of 1.8 for reduction of U^{235} concentration from approximately 93 to 40 percent. This leads to an allowable charge of 25 kg U^{235}, which corresponds to 62.5 kg of uranium of this enrichment.

Pouring Crucible and Mold Limits for 10-Percent U^{235} - 90-Percent Aluminum Alloy

The problem is to suggest a safe charge of a 10 wt % U^{235} – 90 wt % aluminum alloy for compactly shaped melting crucibles and molds. When crucible and mold walls exceed 2 inches in thickness, full reflection must be assumed. The 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. The mass limit for fully reflected metal given in Figure 1 is 10 kg U^{235}, and Figure 19 gives an allowance factor of 6 for this aluminum dilution. Thus, the limit is 60 kg U^{235}, which corresponds to about 600 kg of alloy. (Note: If the alloy were to be compounded during melting, the allowance factor would be disregarded and the limit would be 10 kg U^{235}.)

Safe Mass Limits for Pu^{239} - Al Alloy Rods

The problem is to suggest a safe mass limit for an isolated system of Pu^{239}-Al alloy fuel rods. In contrast to the preceding examples, the limit will be evaluated for the case in which the array may be flooded, i.e., consider fuel element fabrication processes in which the fuel elements may be placed in an etching bath and subsequently washed with water.

The amount of Pu recommended for application in the control of nuclear safety, is from Table I, 0.22 kg for Pu solutions (also see Figure 5). This quantity may be used for Pu-Al alloy fuel elements immersed in water, but the limit may be unnecessarily restrictive depending on the diameter and percentage of Pu in the alloy rods.

There are some experimental data for U^{235}-Al fuel elements of 7 wt % U and also for Pu-Al rods of 5 wt % Pu immersed in water[38,39]. As a specific example, the safe mass limit for 5 wt % Pu-Al alloy rods of 1/2-inch diameter is 0.52 kg Pu.

As the diameter of the rod approaches zero and the percentage of Pu in the alloy increases, the safe mass limit would become 0.22 kg as recommended for solutions.

Suggested safe mass limits for several other rod diameters and enrichments are listed in Table VIII.[40]

Table VIII

EXAMPLES OF MASS LIMITS FOR ISOLATED UNITS OF Pu-Al ALLOY RODS IN WATER

Composition (wt % Pu in Alloy)	Rod Diameter (in.)	Safe Mass Limit* (kg Pu)
5.0	0.25	0.39
	0.50	0.52
	0.75	0.65
15.0	0.25	0.35
	0.50	0.61
	0.75	1.00

*The safety factor is about 2.3.

Extraction Column (Infinite Pipe System)

The problem is to choose a safe diameter for an extraction column, with the following pertinent data given:

1. The column, having a 3/32-inch thick stainless steel wall, is to be mounted on a concrete wall at a distance of five column radii (the 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} in the column is not to exceed 150 grams U^{235} per liter of solution.

4. The column length is 5 feet or more and must be considered effectively infinite.

The safe diameter is 6.6 inches; this is determined from Figure 3.

It is common practice to design an extraction 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 6.6-inch diameter is the maximum safe diameter for all parts of the system, unless further safeguards are provided for larger phase-separative components.

COMMENTS CONCERNING THE DETERMINATION OF SAFE MASS LIMITS AND CONTAINER VOLUMES FOR SLIGHTLY ENRICHED URANIUM FUEL ELEMENTS

The following example illustrates the relatively sophisticated approach that some nuclear safety problems require and gives insight into the considerations which were used in deriving the safe parameters given previously.

Experiments indicate that aqueous homogeneous solutions containing uranium with enrichment less than 1 wt % U^{235} cannot be made critical. Therefore, mass limits or volume limits would not be required in order to insure nuclear safety of these solutions. However, when the fuel is lumped to form a heterogeneous system, criticality problems will be encountered for enrichments less than 1 percent. The heterogeneous system is more reactive because of the larger value of the resonance escape probability which results from lumping the fuel. In processing slightly enriched uranium the usual procedure is to design equipment to be safe by geometry. When it is necessary to dissolve uranium in containers which are not geometrically safe, mass limits are specified.

As an illustration, mass and volume limits will be considered for a dissolver in which uranium fuel elements of 3.1 wt % U^{235} are to be processed. In all cases the systems are assumed to be fully reflected.

The critical mass of a slightly enriched heterogeneous system (fuel rods in water) depends on the fuel element diameter and the H_2O/U volume ratio (degree of moderation) of the lattice. For a given rod diameter there is one H_2O/U volume ratio which gives the highest material buckling (smallest critical size) and a second which results in the smallest critical mass (fewest number of fuel elements for criticality). For a given enrichment there is also a rod diameter which further defines the maximum possible buckling, and a rod diameter which results in the minimal critical mass (as the enrichment increases the smallest mass is obtained for the homogeneous system; the enrichment for which this occurs is about 5 percent). Data are given in Table IX which show these effects for 3.1-percent-enriched uranium[41-43].

In order to specify the largest safe container dimension the maximum buckling must be used. If the fuel elements are to be processed in nonsafe containers, the batch limit must be based on the smallest critical mass (not derived from the maximum buckling per se).

The maximum material buckling for 3.1 percent enriched uranium rods in water is estimated to be $15,570 \times 10^{-6}$ cm^{-2}. This is obtained from a rod diameter of about 0.4 inch at an H_2O/U volume ratio of approximately 3.9. The critical mass (spherical geometry) for this rod diameter and H_2O/U ratio is about 240 pounds of uranium (the smallest mass for this rod diameter occurs for an H_2O/U ratio of about six and is approximately 220 pounds).

The minimum critical mass for this enrichment, obtained with a rod diameter of about 0.1 inch with an H_2O/U ratio of approximately 10.5, is estimated to be 165 pounds. Thus, in this case the mass limit, if calculated from the maximum buckling, would be too high by nearly 50 percent. Although the critical mass is less for rods of 0.1 inch diameter, the critical volume is larger than that with the 0.4-inch rods since this minimal mass occurs at the larger H_2O/U ratio of approximately 10.5.

The smallest infinite cylinder diameter which can be made critical is estimated to be 10.2 inches from the maximum buckling, and the safe value is 9.0 inches.

For this enrichment, calculations show that the uranium rods when placed in a uranium solution will be less reactive than for the optimum condition of the uranium rods in water. Therefore, if the safe dimensions are based on a heterogeneous water-uranium system, the system will also be safe during the dissolution process. Then the safe cylinder diameter for 3.1-percent-enriched uranium (for a cylindrical dissolver) is 9.0 inches.

The estimated minimum critical mass for the 3.1-

Table IX

DEPENDENCE OF MATERIAL BUCKLING AND MINIMUM CRITICAL MASS ON FUEL ROD DIAMETER AND H_2O/U VOLUME RATIO AT 3.1 WEIGHT PERCENT U^{235} ENRICHMENT

Rod Diameter (in.)	Maximum Buckling ($\times 10^{-6}$ cm^{-2})	H_2O/U Volume Ratio	Minimum Mass, Spherical Geometry (lb. U*)	H_2O/U Volume Ratio
0.925	14,220	2.2	387	3.2
0.600	15,250	2.8	282	4.3
0.300	15,450	4.5	194	7.0
0.175	14,400	5.3	170	8.9

*Total uranium including U^{238}.

percent enrichment is 165 pounds of uranium. If the possibility of double batching cannot be excluded, the batch limit for a nonsafe container would be 72 pounds. If double batching can be excluded, the safe limit could be increased to 130 pounds. After dissolution of the fuel elements the subsequent process vessels could be increased in size based on the safe parameters for salts or solutions.

Concentration control may be used to achieve nuclear safety of the uranium solutions in process vessels which are not otherwise geometrically safe. Experiments have shown that k_∞ of aqueous homogeneous solutions of 3-percent enriched UO_3 will be unity for an H/U atomic ratio of 44 (about 530 grams of uranium per liter of solution).[44]

The solution can be further made safe by the addition of a soluble poison. The addition of about 0.011 atom of boron per atom of uranium* would render the 3-percent solution safe for the maximum value of k_∞.

The effect of a natural uranium reflector on the critical mass of enriched uranium must be considered; the condition could arise if enriched fuel elements were inadvertently placed in a dissolver with natural uranium.

Experiments with aluminum-uranium alloy fuel elements reflected with closely packed natural uranium fuel elements in a water system show that the critical mass is approximately halved.[38]

SOLID ANGLE METHOD OF CALCULATION FOR SPACING INTERACTING UNITS

Subcritical arrays, consisting of safely spaced individually subcritical units, can be assembled by the use of a set of empirically formulated rules generally identified as the solid angle method of calculation for spacing interacting units. The method is especially useful for establishing the safe spacing of process piping and equipment, although it is not restricted to this use. The set of rules is predicated on the assumption 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 the total solid angle subtended at a unit by the other components of the array.

The currently applicable rules for unit spacings were determined by a method presented in references 45 and 46. The reactivity of each unit is estimated by a two-group diffusion theory, and the total solid angle is then obtained from an empirical relationship. Adherents of the method have correlated it with extensive experimental measurements of the critical conditions for many different arrays of variously shaped vessels containing U^{235} in a variety of forms[13,47].

The solid angle between units is calculated by the "point-to-plane" method illustrated in Figure 25. The total solid angle at a unit is the sum of the angles subtended by the visible, surrounding, individual units. The unit, around which one determines the total solid angle, must be selected so as to give the greatest spacing within the configuration. It is thus one of the following: it is the most reactive component of the system and accordingly has the highest k, or it is the "most central" unit and thus has the largest solid angle subtended, or it is chosen on the basis of a combination of these factors. For regular arrays of identical containers, the most central unit would be appropriate. On the other hand, for groups of containers having different reactivities, separation could be determined by the high reactivity of a non-central unit.

The allowable total solid angle, subtended at the unit which "sees" the others to the greatest extent, is based upon the prevailing neutron multiplication factor, k. The relationship between them is shown in Figure 26. In calculating the total solid angle, fully shielded units and the shielded portions of partially visible units may be ignored; e.g., the first and fifth of five identical

*This is equivalent to 0.36 atom of boron per atom of U^{235}.

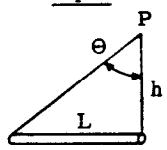
cylinders with axes parallel and coplanar do not contribute to the solid angle at the center one. In those instances where flooding of the array by water is a possibility, a concomitant rule is the requirement that each vessel be spaced from its nearest neighbor by at least 12 inches, or by 8 inches if there are only two units. The rule is based on the observation that these thicknesses of water or materials of comparable hydrogen density effectively isolate each unit.[34]

FORMULAE

General

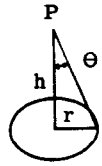
$$\Omega = \frac{\text{cross-sectional area}}{(\text{separation distance})^2}$$

Pipes



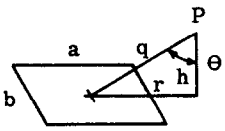
$\Omega = (d/h) \sin \Theta$

Discs

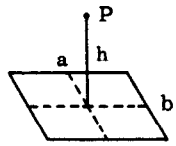


$\Omega = 2\pi (1 - \cos \Theta)$

Planes



$\Omega = (ab/q^2) \cos \Theta$

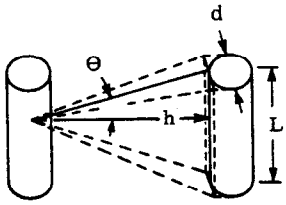


$$\Omega = 4 \sin^{-1} \frac{(a/2)\,(b/2)}{\sqrt{(a/2)^2 + h^2}\,\sqrt{(b/2)^2 + h^2}}$$

APPLIED METHODS

Cylinders

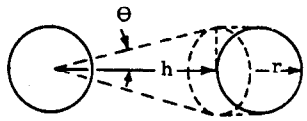
(Reduce to planes center-to-edge)



$\Omega = (2d/h) \sin \Theta$

Spheres

(Reduce to discs center-to-edge)



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

Conversion of Fractional Solid Angle, Ω_f, to Steradians

Ω_f	steradians	Ω_f	steradians	Ω_f	steradians
1.000	12.56 (4π)	0.350	4.40	0.100	1.26
0.750	9.42 (3π)	0.250	3.14 (π)	0.050	0.63
0.500	6.28 (2π)	0.150	1.88	0.000	0.00

FIG. 25. SOLID ANGLE CALCULATIONS

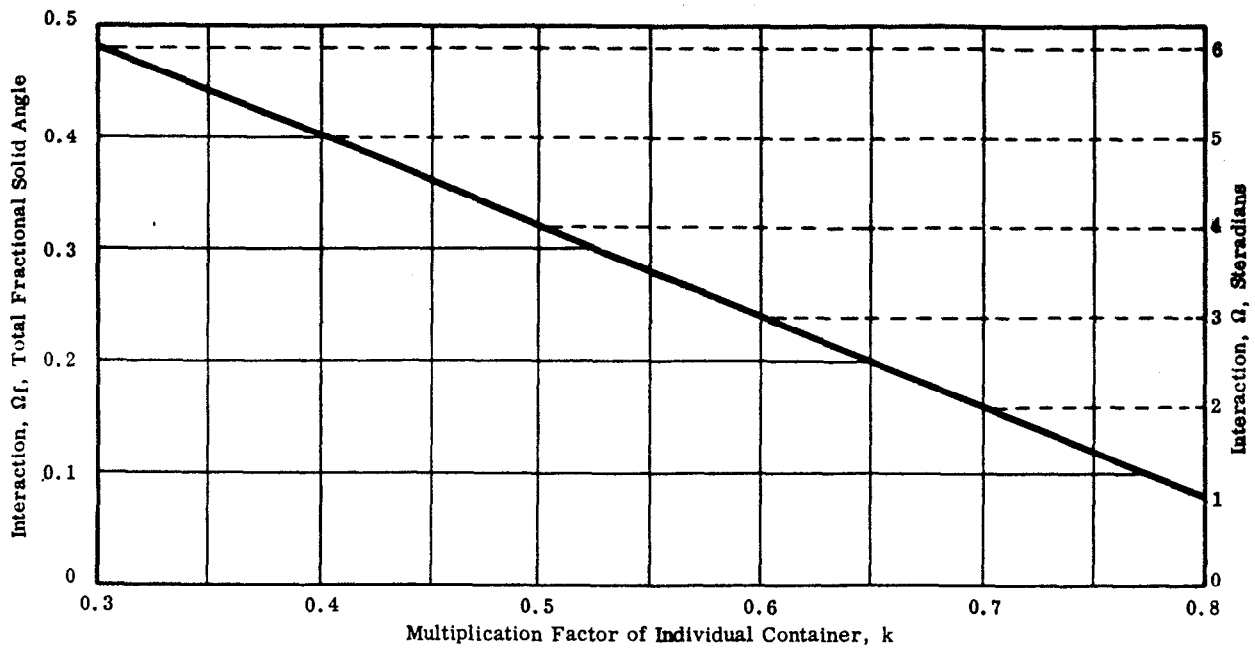


FIG. 26. SAFE INTERACTION FOR SPECIFIED MULTIPLICATION FACTORS

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