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LOS ALAMOS SCIENTIFIC LABORATORY

OF THE UNIVERSITY OF CALIFORNIA ○ LOS ALAMOS NEW MEXICO

NUCLEAR SAFETY GUIDE

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NUCLEAR SAFETY GUIDE

by

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

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PREFACE

The NUCLEAR SAFETY GUIDE was conceived by a group that met at Rocky Flats in October 1955 to discuss industrial nuclear safety problems. A committee was selected to prepare a draft for consideration by the group during its following meeting at Richland, in 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 Company (Rocky Flats):
M. G. Arthur, D. F. Smith

E. I. du Pont de Nemours and Company (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, G. W. Stewart

[redacted]

Goodyear Atomic Corporation:
D. H. Francis, F. Woltz

Los Alamos Scientific Laboratory:
J. A. Grundl

Phillips Petroleum Company (NRTS):
R. B. Lemon

Union Carbide Nuclear Company (K-25):
H. F. Henry, A. J. Mallett, C. E. Newlon

Union Carbide Nuclear Company (ORNL):
R. Gwin, J. T. Thomas

Union Carbide Nuclear Company (Y-12):
J. D. McLendon, J. W. Wachter

University of California Radiation Laboratory (Livermore):
C. G. Andre, F. A. Kloverstrom

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

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PART I.

THE NUCLEAR SAFETY PROBLEM

Introduction

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

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

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15 or 20 percent. One has to depend, then, on experimental measurements of critical mass and extensions of these by theory.

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

Finally, we consider a third type of problem which is here described as administrative. Work on an industrial scale involves men and equipment. In considering the possible events which may lead to dangerous configurations of fissionable material, it is necessary to know the rules under which the men operate the process equipment, what violations, intentional or not, are possible, what physical controls exist to minimize violations, and so forth. It is only with such knowledge that a careful administrative system of

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routine checks can be set up and carried out effectively.

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

In this guide we deal in varying emphasis with all three aspects of the nuclear safety problem. In succeeding sections is given a discussion of the factors that govern the critical condition. In Part II, we come to the main content of the guide which is a compilation of known safe configurations of the three fissionable isotopes U^{233}, U^{235}, and Pu^{239}. These are based on existing experimental data and extrapolations thereof. In Part III, entitled "Applications," there is a description of a few methods and examples illustrating applications to actual industrial equipment.

In concluding these introductory remarks, it seems appropriate to say that this guide is by no means to be considered as an authoritative "last word" on the subject. It

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is rather a preliminary compilation based on experimental data for use in industrial nuclear safety work. At the present time a systematic and thorough treatment is not possible. As mentioned before, we do not know how to calculate critical masses accurately, even in simple, idealized geometries. Further, we do not have the necessary data on the nuclear cross sections and other constants. Thus, much experimentation remains to be done before definitive theoretical methods can be developed and a systematic and complete treatment of critical masses can be given. Meanwhile, it is hoped that this preliminary guide will assist those whose purpose and responsibility it is to achieve nuclear safety in industrial plants.

Critical Parameters

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

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

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

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is a "thin" one consisting of a 1-in.-thick layer of water (or the equivalent) exemplified by the water in a cooling jacket.

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

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

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Strong neutron absorbers have not been generally used to increase capacities because they must be homogeneously mixed with the process materials for effects to be predictable, thereby presenting subsequent purification problems. Coating a thin-wall, otherwise unreflected, vessel with cadmium, for example, actually increases the reactivity since additional neutron reflection is provided by the cadmium. Were the vessel submerged in water, the reactivity would be significantly less with the cadmium than without it. The presence of nitrogen in the nitrate solutions often used in chemical processing, or of Pu^{240} as an impurity in plutonium solutions, increases the margin of safety.

Most homogeneous accumulations of fissionable materials have negative temperature coefficients of reactivity which are due to density changes, including the formation of vapors in liquid systems, and the change in neutron energy distributions. Although this property is important in reactor designs where it facilitates shutdown in case of a power excursion, it does not contribute to the prevention of such excursions. Much damage can occur before the temperature effect begins to control a reaction initiated at a low temperature. It is pointed out that the values of the temperature coefficient depend upon the material, the geometry of the system, and the temperature range. The

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presence of resonances in the energy distribution of cross sections may alter the relative importance of the density and neutron energy contributions to the over-all coefficient.

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

Design Criteria

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

As mentioned in the introduction, the bases for the design of equipment and processes for the fissionable isotopes are almost entirely predicated upon results from necessarily restricted critical experiments or upon interpolations or extrapolations of these results. Many experiments have also been performed which show that particular

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

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Instrumentation

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

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

Consequences of a Nuclear Accident

It is obviously impossible to predict the results of an accidental accumulation of a supercritical quantity of

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

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

Administration of Nuclear Safety

The administration of nuclear safety practices is determined in detail by the functions of the organization. Those installations having continuing problems as a consequence of

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their inventory of fissionable materials or because of frequent alterations in their process, have, in the past, assigned to staff groups the responsibility for advising design and operating personnel in these matters. The infrequent problems of facilities processing only small amounts of material have often been referred to qualified persons in other organizations. A representative example of the administrative practices in an organization of the former class is described here. It is recognized that modification will be necessary to meet the needs of others.

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

In the administration of the safety practice, line supervision responsible for any design or operations obtains approval of those parts which involve nuclear safety. Necessary information is furnished to the approvals committee,

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including the type, quantity, and chemical composition of the material, its concentrations and density, the dimensions and geometric shapes of the containers, and a flowsheet of the process. The committee investigates each problem, advises the originating group on the hazards which may be incurred, and approves the final design and procedure. In general, such approval specifies necessary operating restrictions.

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

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PART II.

BASIC NUCLEAR SAFETY RULES

Rules For Individual Systems

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

Basic Rules for Individual Systems. Basic regulations for simple, homogeneous, individual systems are stated alternatively as mass limits in Table I (kilograms of fissionable isotope), container capacity limits in Table II, and as dimensional limits in Tables III and IV. References in the

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TABLE I.

MASS LIMITS FOR INDIVIDUAL SYSTEMS

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

	metal; low H mixtures, compounds	principally hydrogenous compounds, mixtures	principally solutions	
	$0 \leq H/X \leq 2$	$H/X \leq 20$	$H/X \leq 100$	H/X unlimited[a]
U^{235} (Refs. 1, 3, 4, 5, 14, 25)				
thick water reflector	11.0	2.5	0.80	0.35
nominal reflector (≤ 1" water)	15.0	3.5	1.04	0.43
minimal reflector (≤ 1/8" ss)	22.0	5.0	1.40	0.55
Pu^{239} (Refs. 5, 22, 25, 27)				
thick water reflector	2.6[b]	2.2	0.50	0.25
nominal reflector (≤ 1" water)	3.3[b]	3.2	0.70	0.32
minimal reflector (≤ 1/8" ss)	4.4[b]	4.8	1.00	0.43
U^{233} (Refs. 5, 16, 25, 27)				
thick water reflector	3.0	1.3	0.48	0.25
nominal reflector (≤ 1" water)	4.1	1.7	0.69	0.33
minimal reflector (≤ 1/8" ss)	6.0	2.3	0.90	0.45

(a) See p. 29 for values of H/X beyond which no limit is required.

(b) These limits apply to Pu metal at $\rho = 19.6$ gm/cm^3; for alloy at $\rho = 15.8$ gm/cm^3 the corresponding limits are 3.5 kg with thick water reflector, 4.8 kg with nominal reflector, and 7.0 kg with minimal reflector.

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TABLE II.

CONTAINER CAPACITY LIMITS FOR INDIVIDUAL SYSTEMS

Maximum Volume in Liters

	principally solutions		
	$20 \leq H/X$	$400 \leq H/X$	$800 \leq H/X$
U^{235} (Refs. 3, 4, 5, 14)			
thick water reflector	4.8	9.5	20.0
nominal reflector (≤ 1" water)	6.0	11.3	24.0
minimal reflector (≤ 1/8" ss)	8.0	14.0	30.0
Pu^{239} (Refs. 5, 22, 27)			
thick water reflector	3.3	6.8	11.4
nominal reflector (≤ 1" water)	5.0	9.3	14.7
minimal reflector (≤ 1/8" ss)	6.6	13.0	19.7
U^{233} (Refs. 5, 16)			
thick water reflector	2.0	6.0	12.0
nominal reflector (≤ 1" water)	3.0	8.4	14.4
minimal reflector (≤ 1/8" ss)	4.0	12.0	18.0

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TABLE III.

"SAFE" CYLINDER DIAMETERS FOR INDIVIDUAL SYSTEMS

Maximum Diameter of Cylinder of Fissionable Material in Inches
(For Solution, ID of Containing Cylinder)

		principally solutions		
	metal at full density	$20 \leq H/X$	$400 \leq H/X$	$800 \leq H/X$
U^{235} (Refs. 3, 5, 14, 25)				
thick water reflector	2.5"	5.0"	6.9"	9.1"
nominal reflector (≤ 1" water)	3.0"	5.8"	7.7"	10.2"
minimal reflector (≤ 1/8" ss)	3.8"	6.7"	8.5"	11.0"
Pu^{239} (Refs. 5, 22, 25, 27)				
thick water reflector	1.4"[a]	4.5"	6.1"	7.4"
nominal reflector (≤ 1" water)	1.7"[a]	5.7"	7.2"	8.5"
minimal reflector (≤ 1/8" ss)	2.0"[a]	6.8"	8.3"	9.6"
U^{233} (Refs. 5, 16, 25)				
thick water reflector	1.5"	3.7"	5.8"	7.4"
nominal reflector (≤ 1" water)	1.9"	4.7"	6.9"	8.4"
minimal reflector (≤ 1/8" ss)	2.3"	5.7"	8.1"	9.4"

[a] These limits apply to Pu metal at $\rho = 19.6$ gm/cm^3; also to be used for alloy at reduced density.

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TABLE IV.

"SAFE" SLAB THICKNESSES FOR INDIVIDUAL SYSTEMS

Maximum Slab Thickness in Inches

	metal at full density	principally solutions $20 \leq H/X$	$400 \leq H/X$	$800 \leq H/X$
U^{235} (Refs. 5, 15, 19, 25)				
thick water reflector	0.7"	1.4"	2.5"	4.0"
nominal reflector (≤ 1" water)	1.2"	2.4"	3.6"	5.2"
minimal reflector (≤ 1/8" ss)	2.0"	3.3"	4.4"	6.1"
Pu^{239} (Refs. 5, 22, 25, 27)				
thick water reflector	0.2"[a]	1.5"	2.5"	3.3"
nominal reflector (≤ 1" water)	0.5"[a]	2.6"	3.7"	4.6"
minimal reflector (≤ 1/8" ss)	0.9"[a]	3.6"	4.8"	5.6"
U^{233} (Refs. 5, 16, 25)				
thick water reflector	0.2"	0.5"	1.9"	2.9"
nominal reflector (≤ 1" water)	0.5"	1.7"	3.2"	4.2"
minimal reflector (≤ 1/8" ss)	1.0"	2.5"	4.2"	5.1"

[a] These limits apply to Pu metal at $\rho = 19.6$ gm/cm^3; also to be used for alloy at reduced density.

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tables give critical parameters upon which the limits are based and include some supporting calculations. The mass limits include factors of safety of slightly more than 2 as a safeguard against double-batching. Capacity limits include factors of safety of at least 1-1/3, and the equivalent margins appear in dimensional limits (even with unspecified dimensions infinite).* Added to normal safety factors are allowances for uncertainties in critical data upon which the limits are based.

Specifications are given for various ranges of H/X atomic ratio ($X \equiv U^{235}$, Pu^{239}, or U^{233}), and for limited types of reflector. Although thick Be, D_2O, U, or W reflectors are more efficient than thick water,[25] the latter is considered the most effective reflector that is likely to be encountered in ordinary processing or handling operations. "Nominal reflector" refers to water no more than 1" thick. Surrounding fissionable metal systems, 1-1/2" thick graphite (or 1-1/2" thick steel) is equivalent in effect to 1" thick

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

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water (in small thicknesses water is one of the more effective reflectors). For solutions, equal thicknesses of steel and water are nearly equivalent.[7] "Minimal reflector" refers to no more than 1/8" thick stainless steel, or the same thickness of other common metal including iron, copper, aluminum, nickel, or titanium. Unless conditions are rigidly controlled, the appropriate limit for thick water reflector should be used for all applications, and, if for solutions, the limit also should be that for the greatest listed range of H/X.

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

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

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The rules also fail to apply in the rare case in which densities of fissionable material (vs H/X) exceed the values of Figures 1 and 2.[3,22] In the event that the density of fissionable material, ρ, is greater than the density ρ_o from Figures 1 or 2, mass limits of Table I should be reduced by the ratio $(\rho_o/\rho)^2$, and container volume limits of Table II by $(\rho_o/\rho)^3$. If ρ is less than ρ_o, limits must not be increased by these ratios. If ρ exceeds ρ_o, the dimensional limits of Tables III and IV should not be used.

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

Conditions Under Which Basic Limits Are Not Required. For solutions or other homogeneous hydrogenous mixtures, no further restriction is required[40] if,

1) for U^{235}: the atomic ratio $H/U^{235} \geq 2300$, which corresponds to the concentration $c(U^{235}) \leq 11$ gm/liter in aqueous (light water) solution;
2) for Pu^{239}: $H/Pu^{239} \geq 3600$, which corresponds to $c(Pu^{239}) \leq 7.8$ gm/liter in aqueous solution;
3) for U^{233}: $H/U^{233} \geq 2300$, which corresponds to $c(U^{233}) \leq 11$ gm/liter in aqueous solution.

These values contain no factor of safety; in application, a margin compatible with control errors should be maintained.

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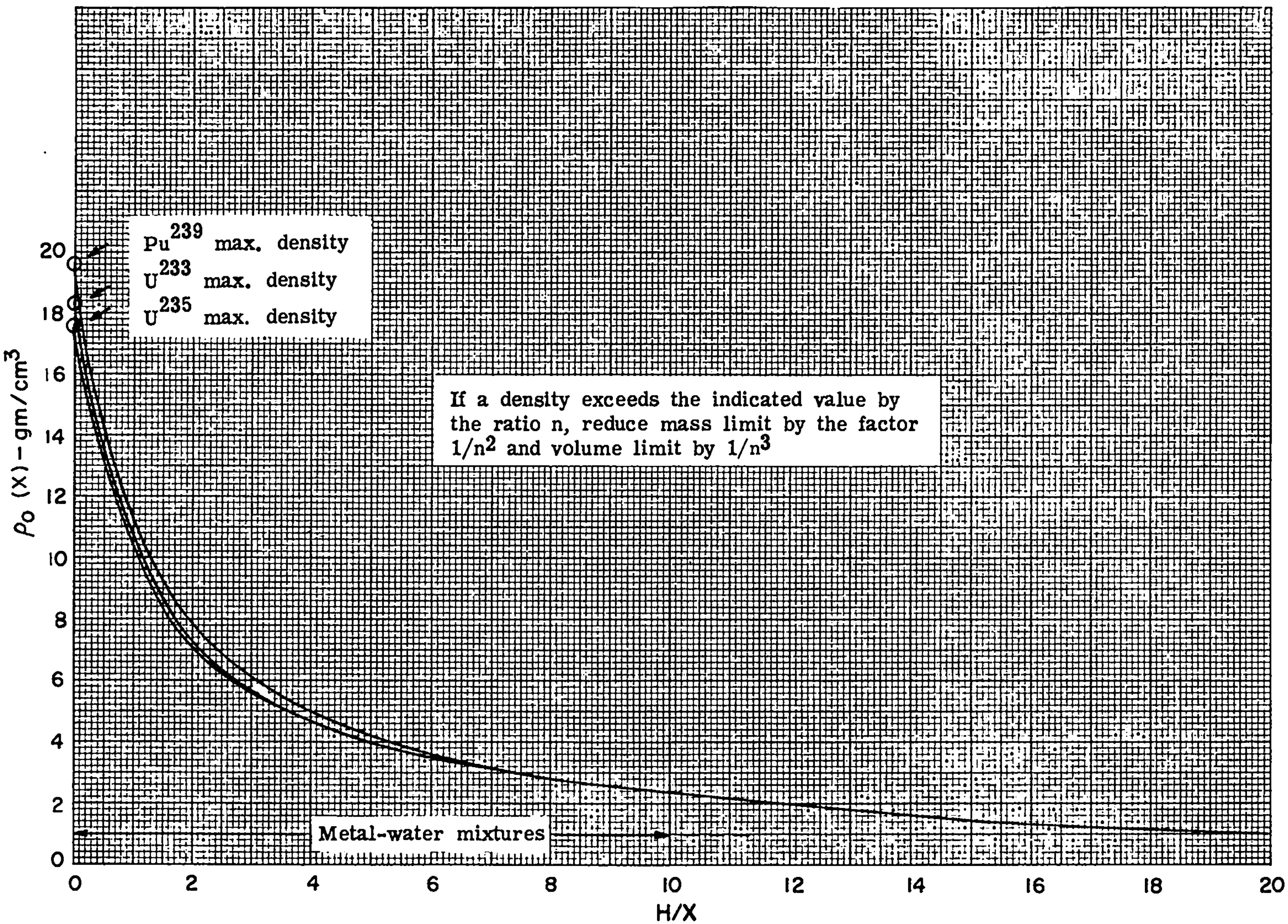

FIG. 1 Assumed densities of U^{235}, Pu^{239}, or U^{233} at $H/X \leq 20$.

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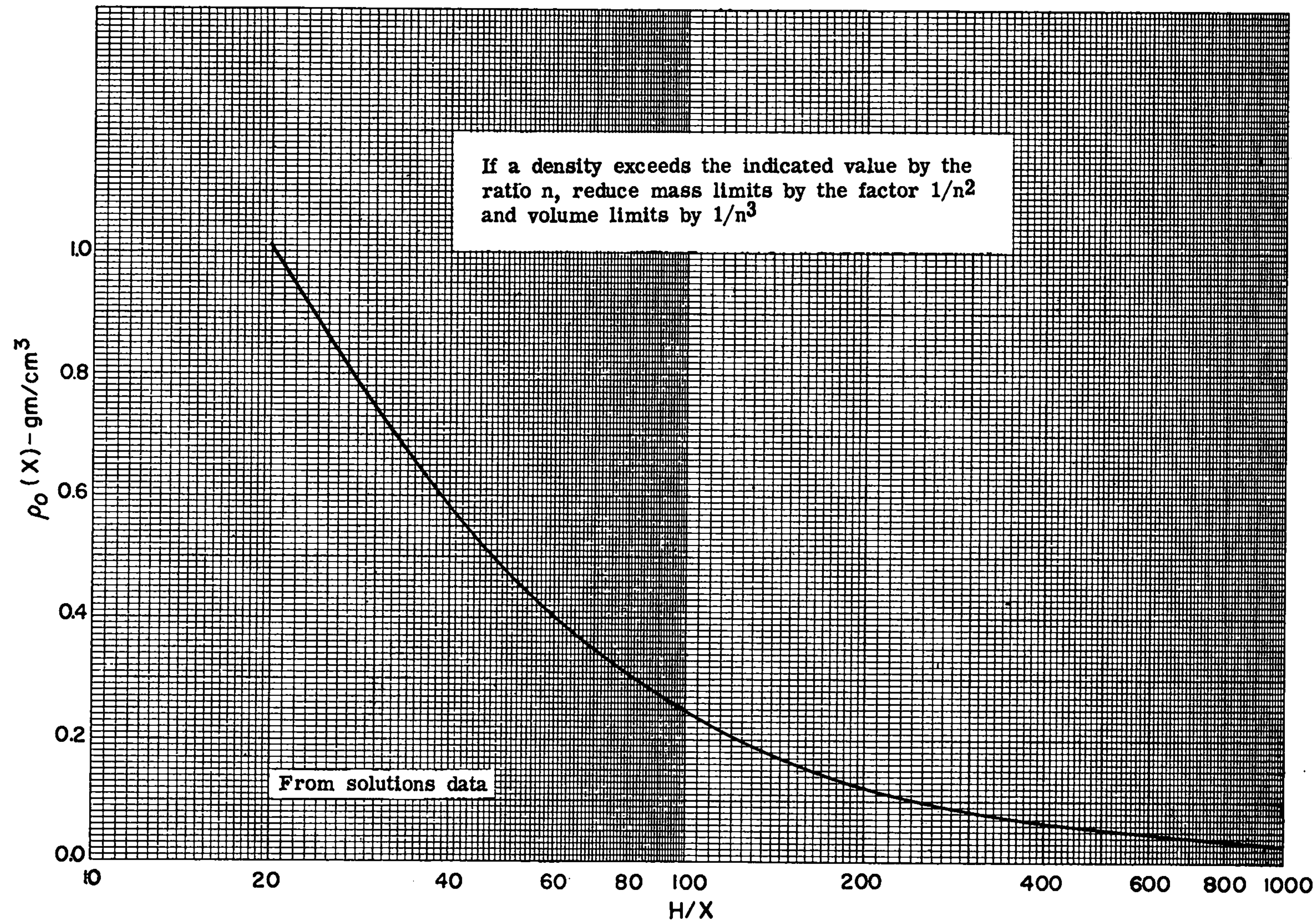

FIG. 2 Assumed densities of U^{235}, Pu^{239}, or U^{233} at $H/X \geq 20$.

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Any mass of normal or depleted uranium in aqueous (light water) solution is safe.[20] For uranium metal, or nonhydrogenous uranium compounds, there need be no further restriction if the atomic ratio $U^{235}/U^{238} \leq 0.05$.[24] This also applies to intimate mixtures of such uranium and any element for which $Z \geq 13$ provided the atomic ratio $(Z)/U^{235} \leq 100$.[27]

<u>Conditions Under Which Basic Limits May Be Increased</u>. For certain intermediate shapes of fissionable system, such as elongated or squat cylinders, mass and container capacity limits may be increased by the appropriate factor from Figure 3.[5,22,25]

For undiluted fissionable metal at density less than normal (18.8 gm/cm^3 for oralloy,* 19.6 gm/cm^3 for Pu^{239}, and 18.3 gm/cm^3 for U^{233}), the mass limit may be increased by the appropriate factor from Figure 4.[25] Factors from this figure also may be applied to solutions with uniformly distributed voids ($\leq$ 1" in one dimension), for which $H/X \geq 100$, provided "fraction of total density" is interpreted as the ratio of average density of solution plus void to the solution density.[7] Figure 5 shows factors by which mass limits may be increased if fissionable metal is

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*"Oralloy," abbreviated Oy, designates uranium in which the U^{235} content is enhanced. Oy(93) indicates uranium that is 93 w/o U^{235}.

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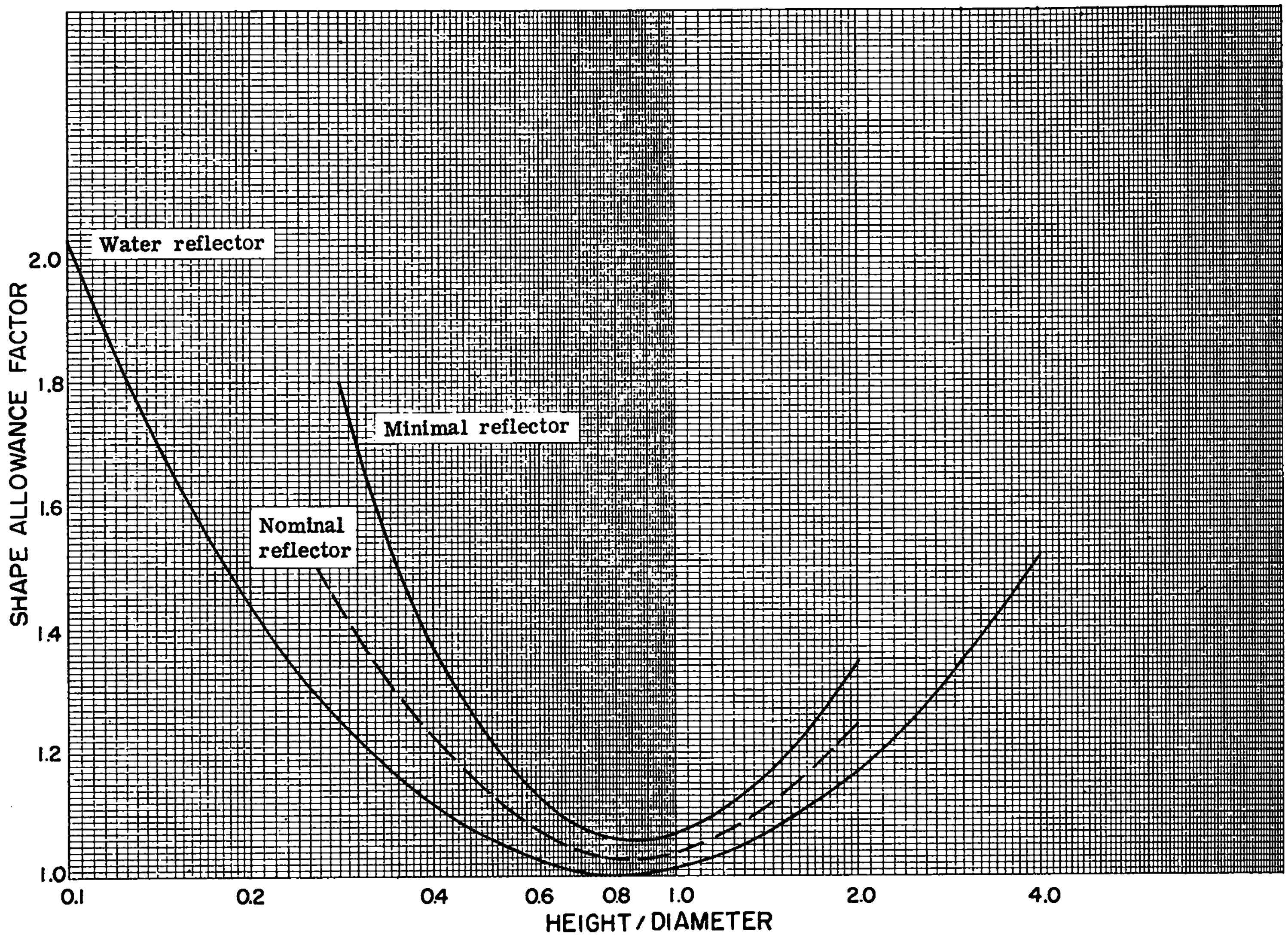

FIG. 3 Shape allowance factors for cylinders (factor by which mass and volume limits may be increased for elongated or squat cylinders).

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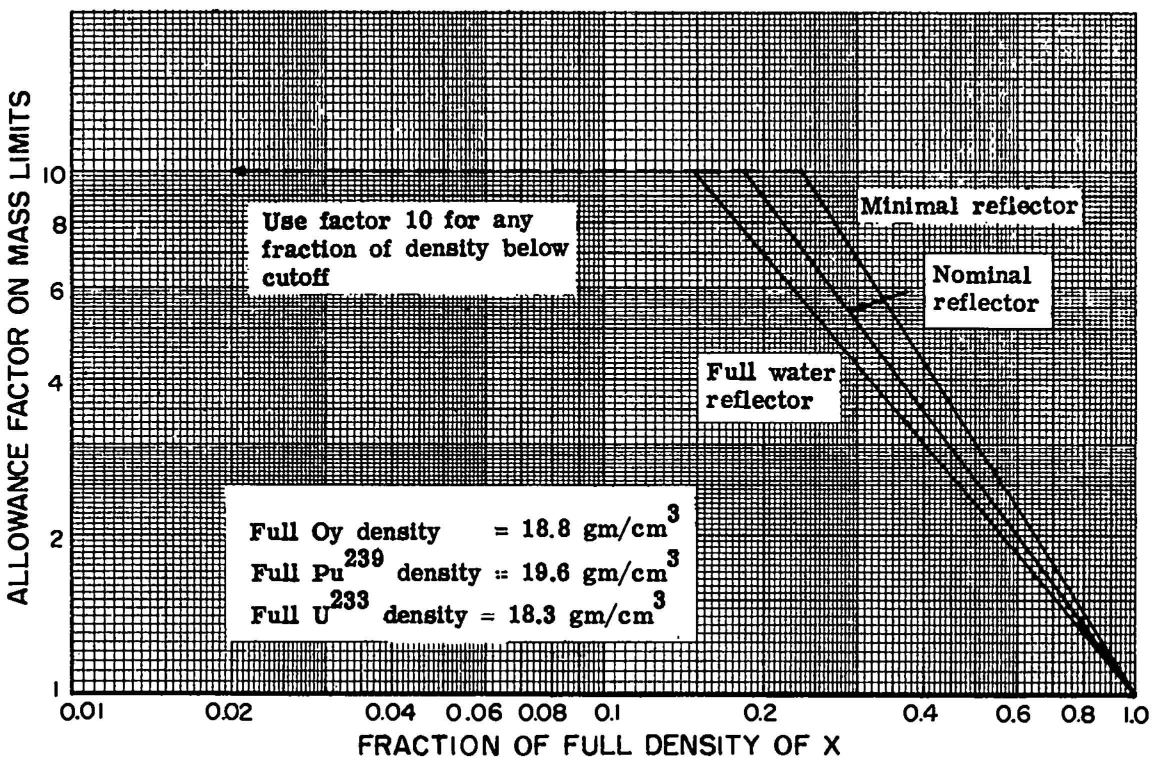

FIG. 4 Allowance factors for reduced density of oralloy Pu^{239}, and U^{233} as metal only.

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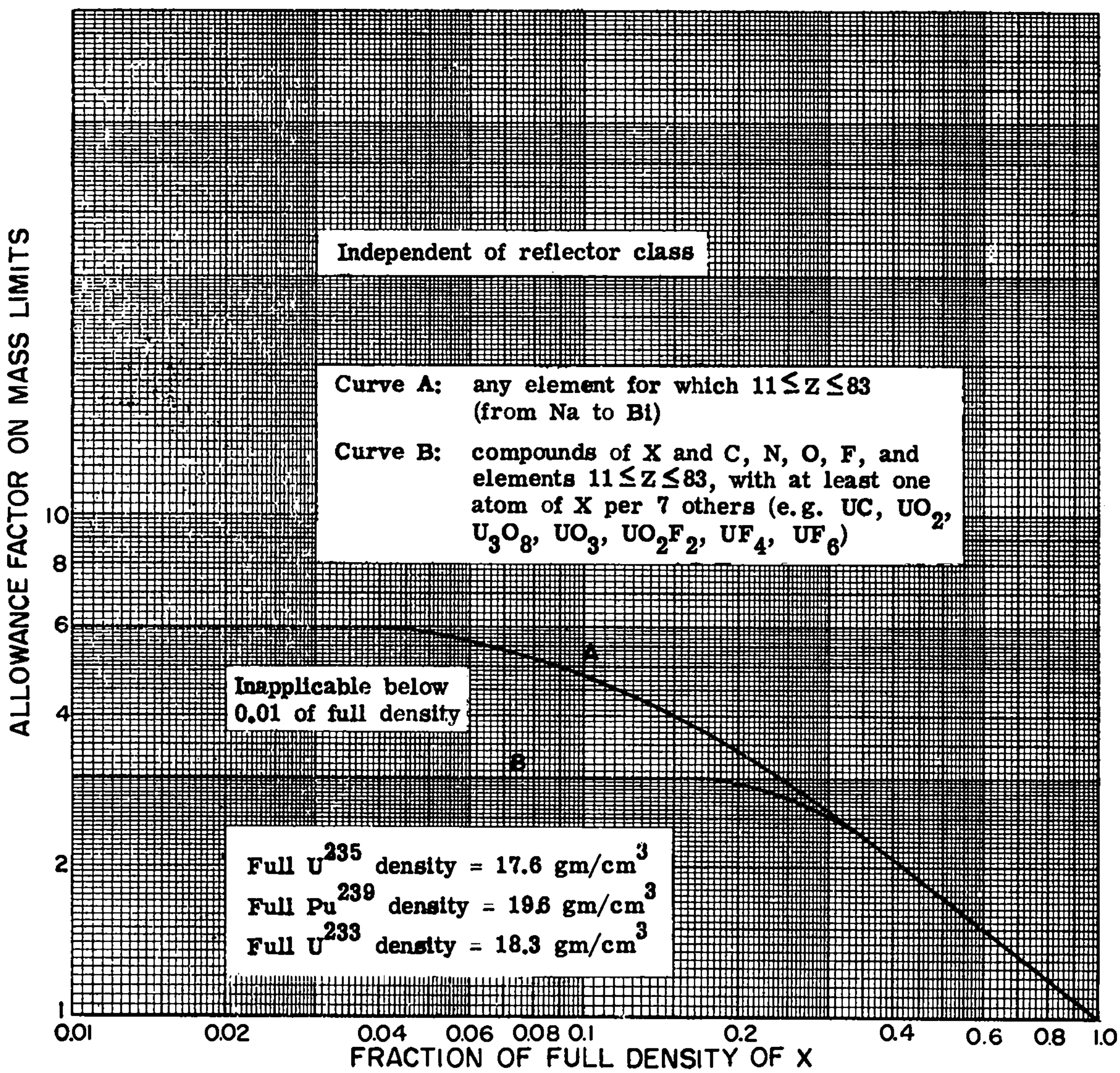

FIG. 5 Allowance factors for reduced density of U^{235}, Pu^{239}, or U^{233} mixed homogeneously with elements listed (H, D, Be excluded).

mixed uniformly with any of the listed elements.[26,27] Although intended primarily for homogeneous systems, these factors may be used for similar units of X distributed uniformly in the diluent provided one dimension of the unit does not exceed 1/8" for U^{235}, or 1/16" for Pu^{239} or U^{233}.

In the special case of undiluted uranium metal in which the U^{235} content is less than 93%, the U^{235} mass limit may be increased by the appropriate factor from Figure 6.[25] A factor for reduced density of <u>total uranium</u> (not U^{235}), from Figure 4, may be applied in addition to this concentration factor.

As stated before, the mass limits of Table I contain a factor of safety of 2 as protection against a double-batching error. (No such allowance appears in container capacity limits.) Where the possibility of over-batching is excluded, the basic mass limit may be increased by the factor 1.5.

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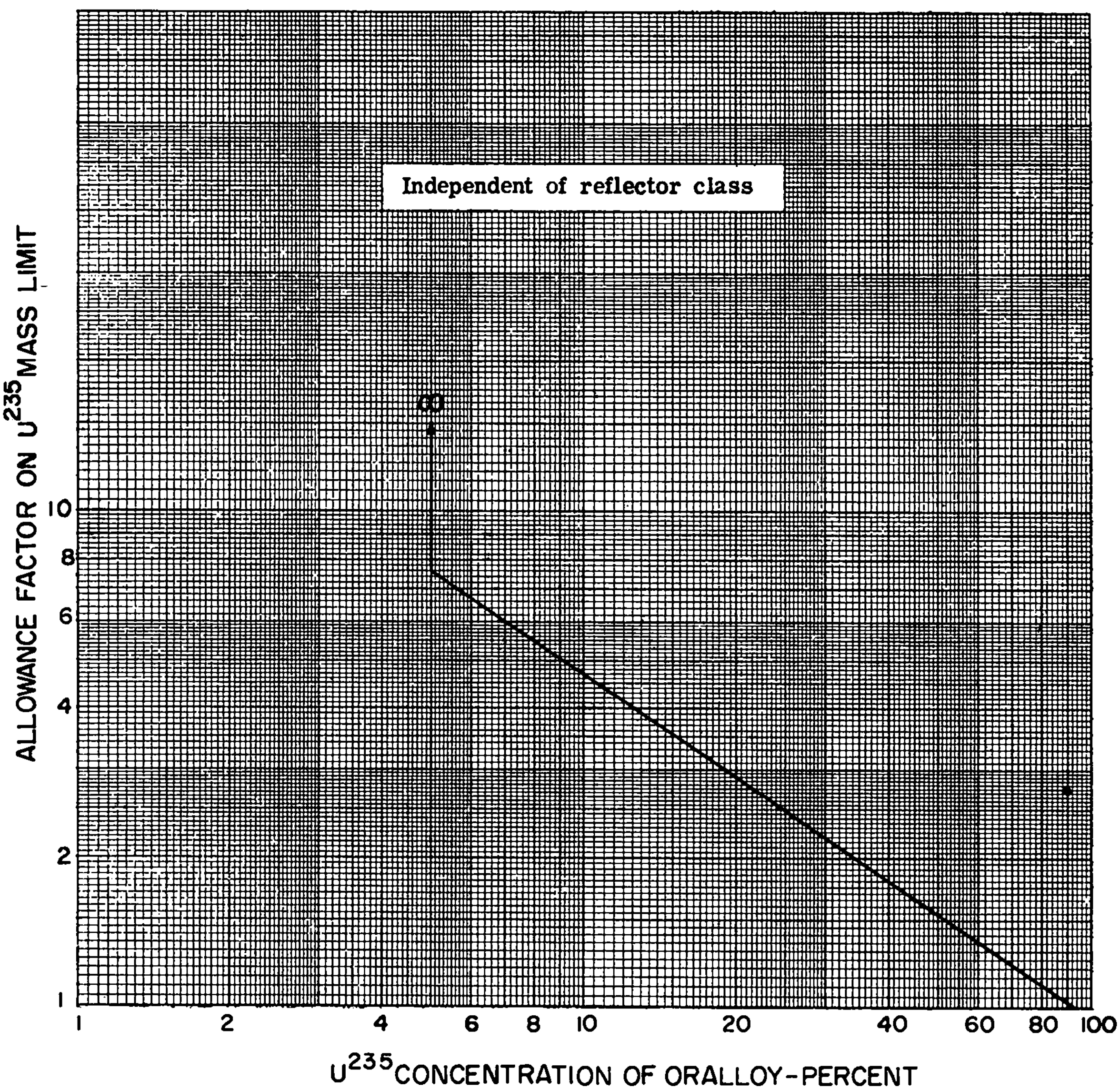

FIG. 6 Allowance factors on U^{235} mass limits for oralloy <u>metal</u> at intermediate U^{235} concentrations.

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Rules For Interacting Systems (Refs. 6, 23, 28, 29)

Maximum Storage or Transportation Units. The interaction of fissionable systems is of most concern in storage areas and transportation facilities. For these situations, it is assumed that units of carefully controlled size are in relatively light containers (nominal reflectors) which are spaced by birdcages, compartments, or specifically located anchorages. Maximum unit quantities for storage and transportation, listed in Table V, have been selected to correspond to units for which most complete interaction information is available. These units may be increased by the shape allowance factors of Figure 3, and the oralloy metal density and U^{235} concentration factors of Figures 4, 5, and 6 (but not by the allowance for perfect batch control). Storage of large units excluded by footnote (b) of Table V is considered in Part III.

Again, certain "reactor compositions," as dilute mixtures with D, Be, C, must be treated as special cases.

Rules for Storage Arrays. The storage rules of Table VI allow a factor of safety greater than 2 (in number of units) for arrays in a concrete vault that is not less than

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TABLE V.

MAXIMUM SIZES OF STORAGE OR TRANSPORTATION UNITS

	maximum unit[a]		
	U^{235}	Pu^{239}	U^{233}
metal, compounds, or mixtures, $H/X \leq 2$; mass limits:[b]	18.5 kg[c]	4.5 kg[d]	4.5 kg
hydrogenous compounds or mixtures, $2 < H/X < 20$; mass limits:[b]	4.5 kg	4.5 kg	2.5 kg
solutions, or hydrogenous mixtures, $H/X \geq 20$, in "non-safe" containers;[e] volume limits:	4.0 liters	4.0 liters	2.0 liters

(a) If density (ρ) is greater than the reference value (ρ_o) in Figure 1 or 2, reduce mass limits by the factor $(\rho_o/\rho)^2$, volume limits by $(\rho_o/\rho)^3$.

(b) Material volume of unit is not to exceed 4.5 liters.

(c) This corresponds to 20 kg of Oy ($\sim$ 93).

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

(e) For "safe" containers defined by Table III, there is no mass or volume limit for stable solutions ($H/X \geq 20$).

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TABLE VI.

LIMITS FOR STORAGE ARRAYS OF UNITS DEFINED IN TABLE V

type of array	minimum center-to-center spacing of units within array[a]	storage limit per array (number of max. storage units)[b]
isolated linear or plane array	$\geq$ 16"	no limit
isolated cubic array	36"	200
	30"	120
	24"	80
	20"	50
two associated plane arrays	30"	120/array, 240 total[c]
	24"	90/array, 180 total[c]
	20"	50/array, 100 total[c]

[a] Edge-to-edge separation of units must be at least 12".

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

[c] The same total storage limit applies to more than two associated arrays.

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9 feet in smallest dimension. Arrays that are safe in a concrete vault also will be safe in vaults of other materials such as steel, wood, or earth. For convenience, the storage rules are given in terms of number of maximum units at a given center-to-center spacing between units. A "maximum unit" may consist of a subarray of smaller units provided the total quantity is not exceeded and quantity-averaged spacing is maintained. With the requirement that edge-to-edge separation between units shall be at least 12", storage arrays as defined by Tables V and VI will be safe if fully flooded.

Two arrays are effectively isolated from one another if the arrays are completely separated by concrete at least 8" thick.[33] Two plane or cubic arrays also are considered to be isolated if the separation (minimum edge-to-edge spacing between any unit in one array and any unit in the other) is the larger of the following quantities: 1) the maximum dimension of one array; 2) 12 feet.[29] Two linear arrays are isolated regardless of length if the separation is at least 12 feet.

Parallel plane nonisolated arrays are considered to be associated if the minimum edge-to-edge spacing between units in the two arrays is at least 7-1/2 feet.

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Transportation Regulations. Table VII is a set of rules for railroad shipments of fissionable materials, which was prepared at the request of the A.E.C. Division of Production. If the assumed conditions are satisfied, these rules may be applied to transportation by other carriers. Again, maximum unit sizes are as defined in Table V. "Maximum density established by birdcage or shipping case" is based on a 20" cubic birdcage per maximum shipping unit.

The assumption underlying these rules is that birdcages or shipping cases will not be crushed in case of an accident (i.e., limits of density established by birdcage will not be exceeded), but the possibility of accidental flooding or combination of contents of two cars is admitted. "Carload limits" in Table VII allow a normal factor of safety of at least 4, of which a factor of 2 is for combination of two carloads. When flooded, individual units will be at least 20% subcritical (masswise), and requirements are such that units will not interact through intervening water.

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TABLE VII.

LIMITS FOR RAILROAD SHIPMENTS OF UNITS DEFINED IN TABLE V

	maximum density established by birdcage or shipping case[a]			normal carload limit (50 maximum shipping units except for "safe" cylinders)[b]		
	U^{235}	Pu^{239}	U^{233}	U^{235}	Pu^{239}	U^{233}
metal, compounds or mixtures, $H/X \leq 2$; mass limits:	4 kg/ft^3	1 kg/ft^3	1 kg/ft^3	925 kg/car	225 kg/car	225 kg/car
hydrogenous compounds or mixtures, $2<H/X\leq 20$; mass limits:	1 kg/ft^3	1 kg/ft^3	0.5 kg/ft^3	225 kg/car	225 kg/car	125 kg/car
solutions, or hydrogenous mixtures, $H/X \geq 20$, in "non-safe" containers[c]	0.8 liter/ft^3	0.8 liter/ft^3	0.4 liter/ft^3	225 liters/car	225 liters/car	100 liters/car

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

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

[c] For the "safe" solution cylinders of Table V, the storage conditions of Table VI may be used for transportation provided spacings are expected to be maintained in case of accident.

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PART III.

APPLICATION TO PROCESSING PLANTS

General Discussion

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

Generally, however, safe, but perhaps overconservative restrictions for plant equipment can be established in terms of the stated rules for simple, but more extreme systems. For example, an isolated cylinder of rectangular cross section will obviously be safe if the diagonal dimension does

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not exceed the diameter of a safe circular cylinder. For the purpose of such evaluations, it is necessary to establish conditions under which neighboring systems may be treated as though isolated from one another. For nonisolated systems Rules For Interacting Systems of Part II may be applied.

Effectively Isolated Systems. Two spherical or circular-cylindrical configurations of fissionable material without interconnections are considered to be isolated if the center-to-center or axis-to-axis separation is at least six times the sum of the radii of the configurations.[6,25] For irregular systems that approximate spheres or cylinders (where cross sectional dimensions differ by less than a factor of 2) volume-average radii may be used in the above criterion. Two systems completely separated by water or other material of similar hydrogen density that is at least 8 inches thick are isolated from one another. A complete concrete wall at least 8 inches thick effectively isolates one process area from another.[33]

Isolation of solution systems is not influenced by simple, right-angle piping between the systems provided the inside diameter of the intersecting pipe does not exceed one inch and provided any two pipe connections into the same vessel are separated (axis-to-axis) by at least 18 inches

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when the systems are nominally or full-water reflected and by 24 inches when reflector is minimal.[30]

Incidental Reflectors. A wall of concrete, steel, or wood (or the equivalent in columns, etc.) within six volume-average radii of the center of a vessel (as under Effectively Isolated Systems) increases minimal inherent reflection to nominal effective reflection, or nominal inherent reflection to the equivalent of full-water reflection.[39] It does not influence a system with the equivalent of a full-water reflector. Beyond six volume-average radii the effect of such a structure may be ignored. For nominally or full-water reflected systems, the effects of extraneous human body tamping may be neglected provided that the bodies in question are not in gross contact with the systems.

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

Adaptation to Standard Volumes and Pipe Sizes. In principle, the limits of Tables I, II, III, and IV of Part II might be represented as a series of curves against H/X atomic ratios. In view, however, of gaps in experimental data upon which

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these tables are based (and of the relative ease of scanning compact tables), it is believed that finer subdivisions than afforded by these tables are not presently justified. In applications to plant equipment there will be situations where the appropriate limit of Table II will fall just below the volume of a convenient standard vessel or where the "safe" dimensional limit of Table III just misses a standard pipe or tubing diameter. In such a case, it is suggested that a nuclear safety specialist help determine whether there may be safe adjustment to the size of standard equipment. It should be emphasized that linear interpolation between some of the tabulated limits in Part II will be unsafe.

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Rules For Special Systems

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

Pipe Intersections. Table VIII describes conservative uniform pipe intersections for aqueous solutions of U^{235}, Pu^{239}, and U^{233} salts.[30] These data do not apply to the metals. The examples may be extended to nonuniform intersections by the method outlined in the reference.

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

Metal Machine Turnings. Machine turnings immersed in a hydrogenous moderator should be handled in the same manner as aqueous solutions of the metal salts. Table I of Part II applies if densities are consistent with Figure 2, Part II.[42]

Special Limits for UF_6. BASIC CRITICAL MASS INFORMATION AND ITS APPLICATION TO K-25 DESIGN AND OPERATION by H. F. Henry, A. J. Mallett, and C. E. Newlon, AEC R and D report, K-1019,[20] gives safety limits for plants in which the operating material

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TABLE VIII.
CONSERVATIVE INSIDE PIPE DIAMETERS FOR UNIFORM 90° INTERSECTIONS CONTAINING FISSIONABLE SOLUTIONS ($H/X \geq 20$)

	U^{235}	Pu^{239}	U^{233}
tees:			
full water reflector	3.5"	3.2"	2.6"
nominal reflector ($\leq$ 1" water)	4.1"	4.0"	3.3"
minimal reflector ($\leq$ 1/8" ss)	4.7"	4.8"	4.0"
crosses:			
full water reflector	2.9"(a)	2.6"	2.1"
nominal reflector ($\leq$ 1" water)	3.3"	3.3"	2.7"
minimal reflector ($\leq$ 1/8" ss)	3.9"(a)	3.9"	3.3"

(a) Experiments indicate that these values are highly conservative.

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is UF_6 at a maximum uranium density of 3.2 gm/cm^3.* The limits may be applied to other uranium compounds (or certain mixtures) such as oxides, UO_2F_2, or UF_4 (for which the moderation is no greater than that of UF_6), provided uranium densities do not exceed those for UF_6 under the appropriate conditions. Tables IX and X are condensed examples of nuclear safety limits from K-1019, which are beyond the scope of Part II.

Interaction Limits for Large Systems. K-1019 also gives conservatively safe interaction criteria for spacing dimensionally large units of fissionable material which are not covered by Table V of Part II. Such units, of course, must satisfy individual safety requirements. These criteria are:

1) As seen by any unit in a system, the solid angle subtended by the other units should not exceed 8% of 4π steradians.
2) All containers should be spaced at least 1 ft apart, edge-to-edge.

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

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TABLE IX.

MASS LIMITS FOR MIXTURES OF OY(~93) AS UF_6
AND HYDROGENOUS MATERIAL, $H/U^{235} \leq 10$
(for any reflector class)

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

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TABLE X.

DEPENDENCE OF "SAFE" MASS, VOLUME, AND CYLINDER DIAMETER UPON U^{235} CONTENT OF URANIUM

(for total uranium densities that do not exceed 1.07 times the values for U^{235} in Figures 1 and 2, any H/U^{235} ratio, and thick water reflector)

U^{235} content of uranium, w/o	mass kg U^{235}	volume liters	cylinder id, in.
40	0.41	6.7	6.0
20	0.48	9.5	6.9
10	0.60	14.0	8.2
5	0.80	27.0	10.2
2	2.00	27.0	10.2
0.8	36.00	27.0	10.2
$\leq$ 0.7[1]	infinite	infinite	infinite

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Examples Of Plant Application

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

Pouring Crucible and Mold Limits for Oy(40) Metal. The problem is to suggest a safe charge weight of Oy(40) (40 w/o U^{235} - 60 w/o U^{238}) for a large pouring crucible and mold without advantageous shape. Graphite crucible and mold walls plus insulation and heating coils are sufficiently thin to be classed as nominal reflector, and there is no possibility of internal flooding.

The basic mass limit from Table I, Part II, is 15.0 kg U^{235} for nominal reflector. Figure 6 of Part II, then gives an allowance factor of 1.8 for reduction of U^{235} concentration from $\sim$ 93% to 40%. This leads to an allowable charge of 27 kg U^{235} which corresponds to 67 kg Oy(40).

Pouring Crucible and Mold Limits for a 10 w/o Oy($\sim$ 93) - 90 w/o Al Alloy. The problem is to suggest a safe charge weight of a 10 w/o Oy($\sim$ 93) - 90 w/o Al alloy for a melting crucible and mold with compact shapes. As crucible and mold

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walls, etc., exceed 2" in thickness, the equivalent of full-water reflection must be assumed. Charge is to be introduced as the alloy, and melting and casting conditions are controlled to avoid segregation. There is no possibility of flooding within the furnace.

The volume fraction of oralloy in this alloy (or the fraction of full U^{235} density) is about 0.016. From Table I, Part II, the basic mass limit is 11 kg U^{235}, and Figure 5 of Part II gives an allowance factor of 6 for aluminum dilution. Thus, the limit is 66 kg U^{235} which corresponds to about 71 kg Oy($\sim$ 93) or 710 kg of alloy.

NOTE: If the alloy were to be compounded during melting, the allowance factor would be disregarded and the limit would be 11 kg U^{235} (thick aluminum reflector is less extreme than thick water).

Pulse Column (Infinite Pipe System). The problem is to choose a safe diameter for a pulse column given the following pertinent data:

1. The column, of 3/32" thick stainless steel, is to be mounted against a concrete wall at a distance of six column radii (column is not to be recessed into a cavity).
2. There are no other interacting columns or tanks and the possibility of flooding is excluded.

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3. The concentration of U^{235} occurring in the column is not to exceed 150 grams U^{235} per liter of solution.
4. The column length can be considered infinite (5 feet or more long).

The safe diameter is 6.7", from Table III and Figure 2, Part II.

CAUTION: IT IS COMMON PRACTICE TO DESIGN A PULSE COLUMN WITH PHASE SEPARATION UNITS AT THE TOP AND BOTTOM OF THE COLUMN, WHICH ARE OF LARGER DIAMETER THAN THE COLUMN PROPER. IT IS TO BE UNDERSTOOD THAT THE 6.7" DIAMETER IS THE MAXIMUM SAFE DIAMETER FOR ALL PARTS OF THE SYSTEM.

Process Tank Without Geometric Limitation. A 200 gallon tank that is not dimensionally safe contains 100 grams of U^{235} in 150 gallons of solution, and it is desirable from a process point of view to increase the concentration to 5.0 gm U^{235}/gal (1.32 gm/liter - a safe concentration for a uniform solution of any volume). The question is how the material may be added safely.

There is a nuclear safety problem if the required U^{235} is added as a single lot of very concentrated solution (e.g., from a safe cylinder), as 650 gm U^{235} exceeds the limit for

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full-water reflector and is even less safe in a "reflector" of U^{235} solution. It is conservatively safe to introduce the material as 2 gallons of solution containing 660 gm U^{235} (8.7 gm U^{235}/liter). From Part II, we have seen that 8.7 gm U^{235}/liter is a safe concentration in a uniform solution, and it is also a safe maximum concentration in a graded solution.

Determination of a Safe Batch Size for Enriched Uranium Slugs in a Chemical Plant Dissolver. This final example illustrates the relatively sophisticated approach that some nuclear safety problems require.

It is known that natural uranium containing 0.7114% by weight U^{235} cannot be made critical in a water moderator and one may thus design a chemical plant for processing this kind of uranium with no concern for critical mass problems. Sometimes it is desirable to use slightly enriched uranium in production reactors and the question then arises of how enriched slugs may be safely processed. We consider here the following problem. Slugs of 1.36" diameter and containing 1.007% by weight of U^{235} are to be dissolved in a large tank. Large numbers of natural uranium slugs may also be undergoing dissolution in the same tank. The slugs are to be dumped into the tank; their positions with respect to one another are uncontrolled. How many 1% slugs may safely be dissolved at one time?

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

Calculations show that for this degree of enrichment, the inhomogeneous system consisting of a lattice of slugs in water will have a higher reactivity than a homogeneous solution. This results from the larger value of p, the resonance escape probability for a lattice. We thus reduce the problem to finding the highest reactivity or buckling possible in a water-uranium lattice of rods in which the lattice spacing and the rod diameter are variable (the rods up to 1.36"). Experimental measurements on lattices of this type are available.[13,21] From these, it is found that the maximum buckling obtainable with 1% uranium is about 3600×10^{-6} cm^{-2} and is found with a rod diameter of about 0.75" in a lattice with a water-to-uranium volume ratio of 2:1. Since the experiments were done with uranium clad in aluminum jackets, it is necessary to raise this value to about 4100×10^{-6} cm^{-2} for a pure uranium-water system.

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Having this number, we are in a position to specify safe numbers of slugs. A simple calculation shows that 3490 pounds of uranium will go critical if the lattice has near spherical shape and is fully reflected by water. This is equivalent to 435 slugs, each 8" long. If the possibility of double-batching in the dissolver cannot be excluded, then this number should be halved. We thus conclude that a safe batch size is about 200 slugs. Some additional safety factor is present since this specification is based on a charging slug size of 1.37 inches diameter. By the time the slugs are dissolved down to the optimum diameter, some of the uranium is in solution and some in slugs. This is a less reactive situation than if this total amount of uranium were all in the form of slugs of the optimum size.

We have not yet considered the effects which may be caused by a natural uranium reflector that may be present in the dissolver. Experiments with aluminum-uranium alloy slugs reflected with natural uranium slugs in a water system show that the critical mass is approximately halved.[41] Calculations on the present type slugs give about the same result. Thus, if natural uranium is also present in large amounts in the dissolver, the safe batch size for enriched slugs should be reduced to 100.

An alternate method of ensuring safety in this dissolver

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

[redacted]

BIBLIOGRAPHY

1. C. K. Beck, A. D. Callihan, R. L. Murray, Critical Mass Studies, Part I, Union Carbide Nuclear Company Report, A-4716 (June 1947).

2. C. K. Beck, A. D. Callihan, R. L. Murray, Critical Mass Studies, Part II, Union Carbide Nuclear Company Report, K-126 (January 1948).

3. C. K. Beck, A. D. Callihan, J. W. Morfitt, R. L. Murray, Critical Mass Studies, Part III, Union Carbide Nuclear Company Report, K-343 (April 1949).

4. J. R. Brown, B. N. Noordhoff, W. O. Bateson, Critical Experiments on a Highly Enriched Homogeneous Reactor, Westinghouse Atomic Power Division Report, WAPD-128 (May 1955).

5. A. D. Callihan, Nuclear Safety in Processing Reactor Fuel Solutions, Nucleonics 14 No. 7, p. 39 (July 1956).

6. A. D. Callihan, D. F. Cronin, J. K. Fox, R. L. Macklin, J. W. Morfitt, Critical Mass Studies, Part IV, Union Carbide Nuclear Company Report, K-406 (November 1949).

7. A. D. Callihan, D. F. Cronin, J. K. Fox, J. W. Morfitt, Critical Mass Studies, Part V, Union Carbide Nuclear Company Report, K-643 (June 1950).

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

[redacted]

[redacted]

9. A. D. Callihan, G. A. Garrett, H. F. Henry, R. L. Macklin, Assay Dependence of Critical Parameters, Union Carbide Nuclear Company Report, KS-449 (September 1954).

10. A. D. Callihan, H. F. Henry, R. L. Macklin, Safe Pipe Dimensions, Union Carbide Nuclear Company Report, KS-260 (December 1951).

11. A. D. Callihan, H. F. Henry, R. L. Macklin, U-235 Critical Mass Dependence on Moderation, Union Carbide Nuclear Company Report, KS-315 (September 1952).

12. A. D. Callihan, J. W. Morfitt, J. T. Thomas, Small Thermal Homogeneous Critical Assemblies, Paper UN-834, International Conference on the Peaceful Uses of Atomic Energy (June 1955).

13. E. D. Clayton, Physics Research Quarterly Report, Hanford Works Report, HW-42183.

14. J. K. Fox, L. W. Gilley, Preliminary Data from Critical Experiments with Aqueous Solutions, Part I, Oak Ridge National Laboratory Report, CF-55-12-6 (December 1955).

15. J. K. Fox, L. W. Gilley, Critical Parameters of a Proton Moderated and Proton Reflected Slab of U-235, Oak Ridge National Laboratory Report, CF-56-2-63 (February 1956).

16. J. K. Fox, L. W. Gilley, E. R. Rohrer, Critical Mass Studies, Part VIII, Aqueous Solutions of U-233, Oak Ridge National Laboratory Report, ORNL-2143 (August 1956).

17. L. W. Gilley, A. D. Callihan, Nuclear Safety Tests on a Proposed Ball Mill, Oak Ridge National Laboratory Report, ORNL-54-9-89 (September 1954).

18. R. Gwin, W. T. Mee, Critical Assemblies of Oralloy, Union Carbide Nuclear Company Report, Y-A2-124 (September 1953).

[redacted]

APPROVED FOR PUBLIC RELEASE

[redacted]

19. F. F. Hart, Safety Tests for Melting and Casting Oralloy, Los Alamos Scientific Laboratory Report, LA-1623 (December 1953).

20. H. F. Henry, A. J. Mallett, C. E. Newlon, Basic Critical Mass Information and Its Application to K-25 Design and Operation, Union Carbide Nuclear Company Report, K-1019, Part 3 (December 1955).

21. H. Kouts, G. Price, K. Downes, R. Sher, V. Walsh, Exponential Experiments with Slightly Enriched Rods in Ordinary Water, Paper UN-600, Int. Conf. on Peaceful Uses of Atomic Energy (June 1955).

22. F. E. Kruesi, J. O. Erkman, D. D. Lanning, Critical Mass Studies of Plutonium Solutions, Hanford Works Report, HW-24514 (May 1952).

23. E. C. Mallary, H. C. Paxton, R. H. White, Safety Tests for the Storage of Fissile Units, Los Alamos Scientific Laboratory Report, LA-1875 (February 1955).

24. J. J. Neuer, C. B. Stewart, Preliminary Survey of Uranium Metal Exponential Columns, Los Alamos Scientific Laboratory Report, LA-2023 (January 1956).

25. H. C. Paxton, Critical Masses of Fissionable Metal as Basic Nuclear Safety Data, Los Alamos Scientific Laboratory Report, LA-1958 (January 1955).

26. H. C. Paxton, Estimated Critical Masses of Diluted Oralloy, Los Alamos Scientific Laboratory Internal Report, N-2-263 (July 1956).

27. G. Safonov, Survey of Reacting Mixtures Employing U^{235}, Pu^{239}, and U^{233} for Fuel and H_2O, D_2O, C, Be, and BeO for Moderator, Rand Corporation Report, R-259 (January 1954).

[redacted]

[redacted]

28. C. L. Schuske, Neutron Multiplication Measurements of Oralloy Units in Arrays, Rocky Flats Plant Report, RFP-51 (June 1955).

29. C. L. Schuske, Neutron Multiplication Measurements of Parallel Arrays of Oralloy Units, Rocky Flats Plant Report, RFP-59 (February 1956).

30. C. L. Schuske, An Empirical Method for Calculating Subcritical Pipe Intersections, Rocky Flats Plant Report, TG 7.1 (July 1956).

31. C. L. Schuske, M. G. Arthur, D. F. Smith, Industrial Criticality Measurements on Oralloy and Plutonium, Rocky Flats Plant Report, RFP-58 (January 1956).

32. C. L. Schuske, M. G. Arthur, D. F. Smith, Criticality Experiments with Plutonium Metal Preliminary to the Design of a Melting Crucible, Rocky Flats Plant Report, RFP-63 (April 1956).

33. C. L. Schuske, M. G. Arthur, D. F. Smith, Neutron Multiplication Study of Two Plane Arrays of Oralloy Units Interacting Through Concrete, Rocky Flats Plant Report, CD56-869 (July 1956).

34. C. L. Schuske, M. G. Arthur, D. F. Smith, Neutron Multiplication Measurements on Oy Slabs Immersed in Solutions, Rocky Flats Plant Report, RFP-66 (August 1956).

35. C. L. Schuske, J. W. Morfitt, An Empirical Study of Some Critical Mass Data, Union Carbide Nuclear Company Report, Y-533 (December 1949).

36. C. L. Schuske, J. W. Morfitt, Empirical Studies of Critical Mass Data, Part II, Union Carbide Nuclear Company Report, Y-829 (December 1951).

[redacted]

37. C. L. Schuske, J. W. Morfitt, Empirical Studies of Critical Mass Data, Part III, Union Carbide Nuclear Company Report, Y-839 (January 1952).

38. A. H. Snell, Physics Division Semiannual Progress Report for Period Ending March 10, 1954, Oak Ridge National Laboratory Report, ORNL-1715 (July 1954).

39. A. H. Snell, Physics Division Semiannual Progress Report for Period Ending March 10, 1955, Oak Ridge National Laboratory Report, ORNL-1926 (September 1955).

40. J. T. Thomas, Limiting Concentrations for Fissile Isotopes, Oak Ridge National Laboratory Report, CF-55-11-104 (November 1955).

41. A. D. Callihan, D. F. Cronin, J. K. Fox, J. W. Morfitt, E. R. Rohrer, D. V. P. Williams, Critical Mass Studies, Part VI, Union Carbide Nuclear Company Report, Y-801 (August 1951).

42. J. D. McLendon, J. W. Morfitt, Critical Mass Tests on Oralloy Machine Turnings, Union Carbide Nuclear Company Report, Y-A2-71 (February 1952).

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