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# Criticality Safety Criteria for License Review of Low-Level Waste Facilities

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Manuscript Completed: November 1994  
Date Published: March 1995

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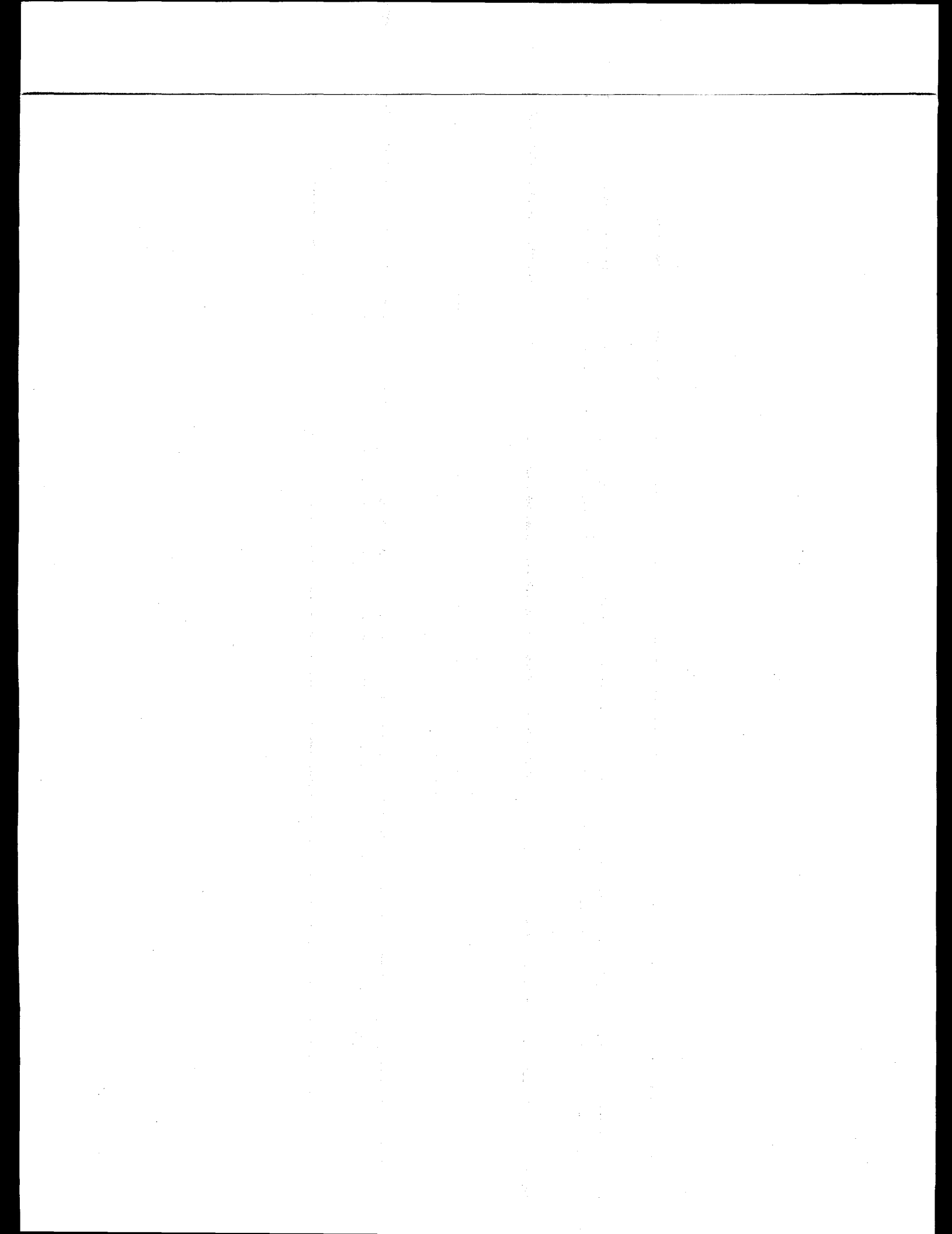
Oak Ridge National Laboratory  
Managed by Martin Marietta Energy Systems, Inc.

Oak Ridge National Laboratory  
Oak Ridge, TN 37831-6370

Prepared for  
Division of Waste Management  
Office of Nuclear Material Safety and Safeguards  
U.S. Nuclear Regulatory Commission  
Washington, DC 20555-0001  
NRC Job Code L1376

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## ABSTRACT

This report provides recommended safety criteria for U.S. Nuclear Regulatory Commission (NRC) licensed burial facilities. These criteria have been developed with accepted and consistent nuclear criticality safety evaluation techniques. Additionally, this report provides the bases for the recommended safety criteria by documenting the evaluation methods and assumptions, and by reporting the results of all single-package and array calculations. These criteria were developed with care to ensure consistency with data and practices provided in current standards on nuclear criticality safety, as well as conformity of the criteria to applicable NRC regulations.

The recommended safety criteria are expressed in terms of surface-density spacing criteria, thereby greatly simplifying the application of license conditions for nuclear criticality safety control. This approach was used by an NRC licensee at the Barnwell waste burial facility by limiting the specific controls to the fewest number of parameters consistent with good nuclear safety practice. The use of surface-density criteria can eliminate the need for numerous license amendments for variations in package contents and specifications.

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## ACKNOWLEDGMENTS

The authors gratefully acknowledge the contributions and assistance of L. M. Petrie who was consulted during the formulation of this task and the preparation of the report. The authors appreciate the efforts of R. L. Stevenson for his insight as the principal author of Ref. 1.

# 1 INTRODUCTION

The handling and burial of specified quantities of special nuclear material (SNM) at low-level-waste (LLW) facilities require a license from the Nuclear Regulatory Commission (NRC). With assistance from Oak Ridge National Laboratory (ORNL) staff, the NRC Office of Nuclear Material Safety and Safeguards, Low-Level-Waste and Decommissioning Projects Branch, has developed technical specifications for the nuclear criticality safety of  $^{235}\text{U}$  and  $^{239}\text{Pu}$  in LLW facilities. The objective of the development of these technical specifications was to establish a set of review criteria that are rigorously defensible, that can be applied uniformly to all license applications, and that conservatively ensures that buried SNM will not pose a criticality safety concern.

Since the early 1970s, the NRC and its predecessor, the Atomic Energy Commission (AEC), have used an in-house study of surface-density spacing criteria<sup>1</sup> for  $^{235}\text{U}$  as an informal basis for establishing criticality safety criteria for below-ground burial of SNM. A surface-density criterion typically specifies a fissile mass limit per package and a limiting areal density of fissile mass. Previously, the primary alternative to this approach used in licensing was to base the safety criteria on verification of the number of packages per trench, interpackage spacing, and placement of intervening material; thus, this approach leads to burial criteria that vary from license to license, depending on the respective judgments of the licensee and the NRC staff for the types of packages anticipated at the time of the license request. This alternative licensing approach resulted in the generation of numerous and differing license amendments to cover a relatively small range of variations in package contents and specifications.

The type of technical specifications for LLW burial that result from the approach used in Ref. 1 (i.e., to establish a critical criteria via a surface-density limit) were reviewed and judged to be the most suitable technical specifications for use in licensing of SNM in LLW facilities. It was judged to be most suitable for ease of understanding and application by an NRC waste burial licensee, considering current criticality safety standards and evaluation techniques. This report provides such technical specifications and licensing review criteria for LLW burial facilities for  $^{235}\text{U}$  and  $^{239}\text{Pu}$ . Additionally, this report provides the results of the computational studies that established these technical specifications.

The physical dimensions of the limit specifications,  $\text{g}/\text{ft}^2$ , were chosen to be compatible with available information to LLW burial facility personnel. The gram was selected because grams are the units provided on the NRC material transfer Form 741. Square feet was selected because most personnel working at a LLW burial facility are familiar with their building, trench, bunker, etc., dimensions in terms of square feet of floor space. If need be, the conversion to  $\text{kg}/\text{m}^2$  metric units may be accomplished by multiplying all  $\text{g}/\text{ft}^2$  values by the constant,  $0.010763 (\text{ft}^2\text{-kg})/(\text{g-m}^2)$ .

Without consideration of additional controls (e.g., intervening neutron-absorbing materials, separation of storage facilities) or extended knowledge of burial environments (e.g., neutron reflector constituents, such as concrete and/or soil and possible seasonal moisture content), surface-density criteria provided in this report should be used for guidance.

## 2 SUMMARY OF LOW-LEVEL-WASTE BURIAL LIMITS

Operational limits were determined from safety criteria and computational results provided in Section 3 and are presented below in terms of observable values, that is, LLW package fissile nuclide contents (i.e., grams of  $^{235}\text{U}$  or grams of  $^{239}\text{Pu}$  and grams of  $^{241}\text{Pu}$ ) and package "foot print" in square feet.

### 2.1 Operational Limits

Without consideration for additional burial facility conditions (e.g., intervening neutron-absorbing materials, specific maximum enrichments, specific combinations with homogeneous materials) or extended knowledge of burial environments (e.g., concrete and/or soil constituents and seasonal moisture content), the operational limits developed from the surface-density criteria methodology should be used. These basic operational limits are provided in Table 2.1. These operational limits are intended for use with "low-level wastes" consisting primarily of contaminated hydrocarbons (e.g., paper, plastic, other

organics, etc.), contaminated metals/alloys, and inorganics. Bulk carbon (graphite) is treated separately.

### 2.2 Determination of Fissile Nuclide Areal Density

Depending upon the type and orientation of the fissionable material containers (e.g., drums standing on ends or lying on sides, boxes or crates), fissile nuclide areal density should be determined according to the basic formulae shown in Figures 2.1 and 2.2. Where stacks of boxes or crates are used, the sum of the fissile material gram masses in a vertical stack of packages divided by the respective "foot print" of the package (i.e., package width times package length) determines the fissile nuclide areal density (i.e., mass per unit area). In no case may the calculated fissile nuclide areal density exceed values provided in Table 2.1. Allowable carbon areal densities are determined similarly.

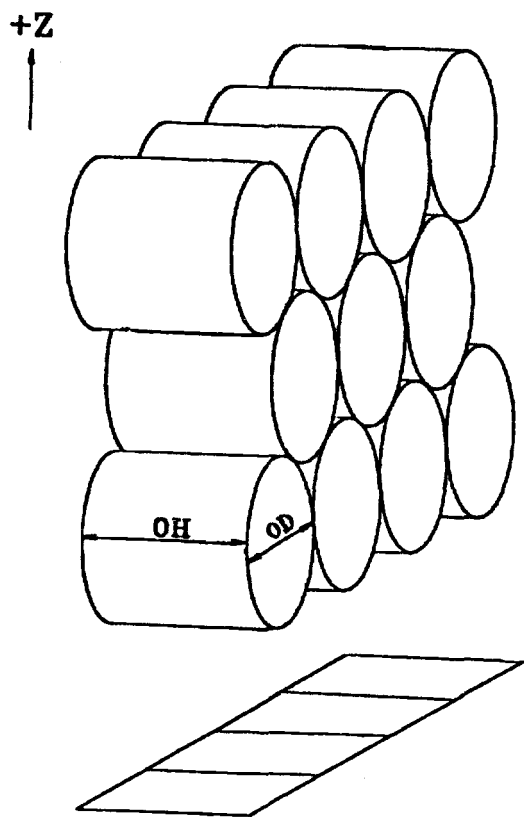
Table 2.1 Summary of operational areal density limits for fissionable material in LLW<sup>a</sup>

Fissile material type, weight percent (w/o) of fissile nuclide	Maximum mass of fissile nuclide per package	Maximum fissile nuclide areal density <sup>b</sup>	Maximum bulk carbon areal density <sup>b</sup>
$\leq 100$ w/o $^{235}\text{U}$	350 g $^{235}\text{U}$	94 g $^{235}\text{U}/\text{ft}^2$	1880 g C/ $\text{ft}^2$
$\leq 10$ w/o $^{235}\text{U}$ + $\geq 90$ w/o $^{238}\text{U}$	350 g $^{235}\text{U}$	174 g $^{235}\text{U}/\text{ft}^2$	3480 g C/ $\text{ft}^2$
$\leq 100$ w/o $^{239}\text{Pu}$	225 g $^{239}\text{Pu}$	52 g $^{239}\text{Pu}/\text{ft}^2$	c
$\leq 76$ w/o $^{239}\text{Pu}$ + $\geq 12$ w/o $^{240}\text{Pu}$ + $\leq 12$ w/o $^{241}\text{Pu}$	225 g $^{239}\text{Pu}$ + 35 g $^{241}\text{Pu}$	(51 g $^{239}\text{Pu}$ + 8 g $^{241}\text{Pu})/\text{ft}^2$	c

<sup>a</sup> For a given fissile material type all three limits (i.e., grams fissile nuclide per container, fissile nuclide areal density, and bulk carbon areal density) must be ensured.

<sup>b</sup> The areal density in  $\text{kg}/\text{m}^2$  can be obtained by multiplying the  $\text{g}/\text{ft}^2$  values by 0.010763.

<sup>c</sup> Packages with bulk carbon are outside the scope of these suggested criteria and must be considered on a case-by-case basis.



Assuming 55-gal tight-head drum

OD = 1.914 ft (22.97 in.)

OH = 2.896 ft (34.75 in.)

Given 3 layers of drums (N = 3 drums)  
 at 145 g <sup>235</sup>U/drum (M = 145 g <sup>235</sup>U/drum)  
 with no bulk beryllium or carbon

$$\frac{(N)(M)}{(OD)(OH)} = \frac{\text{g}}{\text{ft}^2}$$

$$\frac{(3 \text{ layers of drums})(145 \text{ g } ^{235}\text{U/drum})}{(1.914 \text{ ft})(2.896 \text{ ft})} = \frac{78.4 \text{ g } ^{235}\text{U}}{\text{ft}^2}$$

- M = fissile isotope mass (grams per drum)
- N = number of layers of drums
- OD = drum effective outside diameter in feet
- OH = drum effective outside height in feet

Footprint of one horizontal drum is (OD)(OH)

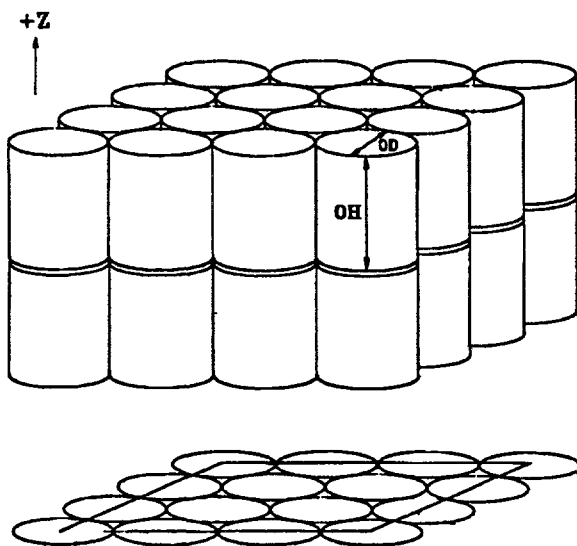
Figure 2.1 Example of an areal density determination for stacked horizontal drums

Summary

Assuming 55-gal tight-head drum

OD = 1.914 ft (22.97 in.)

OH = 2.896 ft (34.75 in.)



Given 2 layers of drums (N = 2 drums) at  
125 g <sup>235</sup>U/drum (M = 125 g <sup>235</sup>U/drum)  
with no bulk beryllium or carbon

$$\frac{(N)(M)}{(0.866)(OD)^2} = \frac{g}{ft^2}$$

$$\frac{(2 \text{ layers of drums})(125 \text{ g } ^{235}\text{U/drum})}{(0.866)(1.914 \text{ ft}^2)} = \frac{78.8 \text{ g } ^{235}\text{U}}{\text{ft}^2}$$

Footprint of one vertically positioned drum in a triangular-pitched array is  $(0.866)(OD)^2$

- M = fissile isotope mass (grams per drum)
- N = number of layers of drums
- OD = drum effective outside diameter in feet
- OH = drum effective outside height in feet

Figure 2.2 Example of an areal density determination for stacked vertical drums

### 3 REVIEW OF SURFACE-DENSITY APPROACH

In 1961, H. C. Paxton noted a relationship between the mass of fissile material per unit base area (i.e., surface density) in a critical, air-spaced plane array of discrete units and the critical mass per unit area of a uniform slab of the same material.<sup>2</sup> It was later suggested that the relationship be used to establish safe spacing criteria for planar arrays.<sup>3</sup> The resulting surface-density approach is simple: develop a limit on the fissile mass allowed per unit area (generally taken perpendicular to the axes of the arrayed units) such that a planar array of the most reactive units planned for the array will remain safely subcritical. Given the nature of long-term placement or burial of low-level waste (LLW) (i.e., the potential for package and contents settling), the surface density specifications for allowable fissile material masses per unit area must be applied to the level base area upon which the waste containers rest (e.g., the floor area of the storage area).

The surface-density study of Ref. 1 was directed at fuel fabrication plant layout and was adapted to the burial of LLW in cylindrical packages containing optimally moderated <sup>235</sup>U solutions. Container walls and liners were ignored in the calculations. The study included calculations to investigate the effects of (1) <sup>235</sup>U density, (2) fraction critical (i.e., ratio of the mass of a single unit to the bare critical mass of the same fissile material in a similar shape), (3) cylindrical geometry, (4) reflector proximity, and (5) array size. The study indicated that further work should be done to consider

other variables such as (1) isotopic composition, (2) interspersed moderation and container materials, (3) array lattice patterns, (4) reflector materials, and (5) array size. Each of the above parameters (and possibly others) should be investigated to ensure that a safe areal density value is established for all normal and abnormal circumstances that might arise in the handling and burial of fissile material at LLW facilities. Though the surface-density approach permits vertical displacement of fissile material, it must be noted that horizontal migration of the fissile material after placement in storage or burial environments is not considered. A critical configuration of fissile material can be postulated for almost any burial site if unconstrained migration of SNM is assumed.

The surface-density approach is applicable for developing safety criteria for discrete units (containers) buried in a planar array lattice. Other methods that prescribe "volume-density" limits, thus allowing multiple layers of planar arrays, have been developed and applied for storage arrays.<sup>4</sup> The volume density approach is very flexible and allows a more optimal use of land, but the burial in more than one plane could increase the probability that migration of SNM would pose a safety concern. The complexity and limited use of the volume-density approach relative to the surface-density approach eliminated it as the recommended approach to use in this study.



## 4 DEVELOPMENT OF SAFETY CRITERIA

This study was directed at the burial of LLW materials in packages which follows the normal method of handling the waste materials. Therefore, the study concentrated on planar arrays of packages. The burial of loose bulk LLW materials is outside the scope of this study.

The surface-density spacing criteria developed in this report is based on analyses that utilize state-of-the-art computational tools and data. In particular, the latest version of the well-established SCALE code system<sup>5</sup> was used, together with a cross-section library<sup>6</sup> processed from Version V of the Evaluated Nuclear Data File. The SCALE criticality safety analysis sequences (CSAS) were used to calculate the planar array spacings that provide a "critical" neutron multiplication factor ( $k_{\text{eff}}$ ) of 1.0. The CSAS module uses the BONAMI-S and NITAWL-II codes for problem-dependent resonance processing of the cross sections and the KENO V.a code to calculate the  $k_{\text{eff}}$  value using statistical Monte Carlo techniques. An automated search algorithm in the CSAS module was typically used to evaluate the critical array spacing. This code system and data library have recently been validated for use in a wide range of criticality safety analyses.<sup>7</sup>

The set of calculations used to determine the surface-density spacing criteria also considered the effect of each of the parameters discussed in Sects. 4.1-4.10 for  $^{235}\text{U}$  and  $^{239}\text{Pu}$  systems. The effect of these parameters was evaluated using calculational models of both single cylindrical units and infinite planar arrays of cylindrical units. For a selected fissile mass concentration, the single-unit mass limit fixed the volume of the cylinder. Then with this volume and a selected height-to-diameter (H/D) ratio, the dimensions of the cylinder could be established. In the planar array analyses the center-to-center spacing (or pitch) for the units was varied to determine the pitch that resulted in a calculated critical value for the system.

For all array calculations using light water or concrete as the reflector, the reflector thicknesses were taken to be 30 cm and 61 cm, respectively. For the array calculations using  $\text{SiO}_2$  (soil) as the reflector, the  $\text{SiO}_2$  was assumed to be 240 cm thick. Except as noted in

Section 4.5, there was no gap between the plane array units and the reflector. A partial listing of number densities for various mixtures used in all the analyses is given in Table 4.1.

### 4.1 Single-Package Mass Limits

Prudent application of the surface-density approach would ensure that each discrete unit (waste package) is in its most reactive configuration. The supporting analyses used in this study are based on applying a safety margin to single-package mass limits corresponding to the minimum critical mass for hydrogenous reflected and moderated spheres. Using reported critical data<sup>8</sup> (in particular, Figures 10 and 31 in Ref. 8) and a safety margin of 2.3 (to account for accidental double-batching of material plus uncertainties), the single mass limits are 350 g for  $^{235}\text{U}$  and 225 g for  $^{239}\text{Pu}$ . These limits are consistent with the single parameter limits for uniform aqueous solutions as provided in ANSI/ANS-8.1.<sup>9</sup> The study of Ref. 1 only considered light-water moderation of each package. A limited investigation was performed to determine if beryllium and/or carbon moderation or commingling would increase the single-unit reactivity and so decrease the recommended single-unit mass limits. The results are given in Sect. 4.8, which does recommend limits on the amount of carbon that may be present in waste packages containing  $^{235}\text{U}$ . Results of the beryllium studies demonstrated a reduction in allowable areal densities for both uranium and plutonium LLW. Additionally, the inclusion of bulk carbon with plutonium-contaminated LLW showed a similar reduction in allowable areal densities.

A basic requirement for the application of the surface-density technique is that the mass fraction critical be 0.3 or less. Assuming the use of the water-moderated, single-package mass limits, the fraction critical value would be 0.3 or less for each mass limit. For  $^{235}\text{U}$ (93.2), the fraction critical is approximately 0.27 and is obtained by dividing the single-package limit by the minimum critical mass (~1,300 g) of a bare (unreflected) spherical system [see Figure 4.1 (upper curve of Figure 10 in Ref. 8)]. For  $^{239}\text{Pu}$ , the fraction critical is approximately 0.24 and is obtained by dividing the single-package limit by the minimum critical

mass (~930 g) of a bare spherical system [see Figure 4.2 (upper curve of Figure 31 in Ref. 8)].

The reactivity of a single unit is reduced if either the isotope  $^{238}\text{U}$  or  $^{240}\text{Pu}$  is present within the package. This reduced reactivity can be seen in Tables 4.2 and 4.3.

## 4.2 Density Effect

Calculations were made using fissile material densities that ranged from 15 through 300 g  $^{235}\text{U}$  per liter and 10 through 300 g  $^{239}\text{Pu}$  per liter for light-water-, concrete-, and  $\text{SiO}_2$  (soil)-reflected critical planar arrays. The calculations are reported in Tables 4.4 through 4.11. Densities higher or lower than these values would decrease the reactivity of the system, as can be seen in Figures 4.3 and 4.4. The concentrations resulting in the smallest surface density ranged from 35-50 g per liter for  $^{235}\text{U}$  systems and 20-25 g per liter for  $^{239}\text{Pu}$  systems.

## 4.3 Effect of Array Unit Height

Calculations were made to demonstrate the effect that the H/D ratios of individual units in the arrays have on the reactivity of the systems. The range of values considered were H/D = 1 to H/D = 4 (in one case, 6 for low-enriched uranium). The results can be seen in Tables 4.4 through 4.11 for  $^{235}\text{U}$  and  $^{239}\text{Pu}$  critical hydrogenous systems reflected by light water, concrete, and  $\text{SiO}_2$  (soil). The optimum H/D ratio ranged between 1.0 and 2.5 for both  $^{235}\text{U}$  and  $^{239}\text{Pu}$  systems. The minimum critical value for each single unit concentration has been plotted in Figures 4.3 and 4.4 for the calculated values reported in Tables 4.4 through 4.10 (regardless of H/D ratio for which it was calculated). Thus, the seven curves in Figures 4.3 and 4.4 represent the minimum critical surface-density mass per unit area (isotopic composition vs reflector material).

## 4.4 Reflector Materials

Concrete, beryllium, or carbon (graphite) as a reflector material would increase the reactivity of a planar array (X,Y-axes) reflected with light water in

the Z-axis. However, it is not expected that beryllium or carbon will be present as reflectors in a waste burial site. Tables 4.3 through 4.4 and 4.8 and 4.9 show the results of calculations for  $^{235}\text{U}$  and  $^{239}\text{Pu}$  planar arrays reflected with light water and concrete as a function of the fissile concentration of the individual units and their H/D ratios.

Analyses also have been done to investigate whether soil can be a better reflector than water or concrete for the planar array configurations. The composition of soil can vary widely from location to location, and the moisture content varies from season to season. Therefore, worst-case soil conditions were assumed for the study, that is dry  $\text{SiO}_2$  and  $\text{SiO}_2$  with saturated moisture content. Based on a referenced upper limit,<sup>10</sup> the density of the  $\text{SiO}_2$  was assumed to be 1.9 g/cm<sup>3</sup> for dry, packed sand and gravel. A second case was calculated assuming the  $\text{SiO}_2$ , at the same density (1.9), to be water saturated. The water-saturated  $\text{SiO}_2$  reflector provided an array reactivity approaching that of the concrete reflected array. The water-saturated  $\text{SiO}_2$  results are shown in Tables 4.12 and 4.13 for  $^{235}\text{U}$  and  $^{239}\text{Pu}$  systems, respectively. The results shown in Tables 4.6, 4.7, 4.10, and 4.11 and Figures 4.3 and 4.4 for  $^{235}\text{U}$  and  $^{239}\text{Pu}$  systems, respectively, demonstrate that dry  $\text{SiO}_2$  as a reflector material yields a more reactive system than water or concrete-reflected systems. The results in Tables 4.6, 4.7, 4.10, 4.11, 4.12, and 4.13 and Figures 4.3 and 4.4 are conservative because actual soil will contain unquantifiable amounts of water moisture, organic materials, iron, and other materials that will absorb neutrons and make the array less reactive.

To qualitatively demonstrate the relative importance of evaluating specific reflector conditions, a study was performed that consisted of a series of calculations for a highly moderated infinite slab of  $^{235}\text{U}$  reflected on both sides with 2-m-thick reflectors composed of homogeneous mixtures of water, silicon dioxide, and ferric oxide in various volume percents. Results of the calculations are presented in Figure 4.5. As can be seen from the figure, a pure silicon dioxide reflector is the most restrictive condition (i.e., ~80 g $^{235}\text{U}/\text{ft}^2$ ) whereas approximately a 70 vol %  $\text{H}_2\text{O}$  and 30 vol % ferric oxide reflector is the least restrictive (~180 g $^{235}\text{U}/\text{ft}^2$ ).

## 4.5 Reflector Spacing Effect

The surface-density study of Ref. 1 indicates that the position of the reflector from the top and bottom of the array does not affect the reactivity of a large ( $1000 \times 1000 \times 1$ ) slab-like array of SNM. This assumption was verified in this study by making one calculation for a  $^{235}\text{U}$  array and a second for a  $^{239}\text{Pu}$  array (X,Y axes), which demonstrated that placement of the reflector in an infinite planar array does not affect the reactivity of the array (see Tables 4.14 and 4.15). In these calculations, the normally tight-fitting reflector in the  $\pm Z$ -axis directions was displaced 6 in. from the top and bottom of the arrays.

## 4.6 Isotopic Composition

The isotopes studied included  $^{235}\text{U}$  and  $^{239}\text{Pu}$ . The isotope  $^{233}\text{U}$  was excluded because it exists in very limited quantities outside Department of Energy (DOE) facilities. One calculation was made to demonstrate that less than fully enriched uranium (80 wt %  $^{235}\text{U}$ ) decreases the reactivity of the array (see Table 4.2). A second calculation demonstrated that the presence of  $^{240}\text{Pu}$  (20 wt %) in  $^{239}\text{Pu}$  (80 wt %) decreases the reactivity of the array (see Table 4.3).

The array calculations using  $\text{SiO}_2$  as a reflector resulted in low surface-density values when compared with water- and concrete-reflected arrays, and the radioactive material composition contains only fissile isotopes (see Tables 4.6, 4.7, 4.10, and 4.11 and Figures 4.3 and 4.4). Therefore, additional calculations were performed for low-enriched, homogeneous uranium systems containing 10 wt %  $^{235}\text{U}$  and 90 wt %  $^{238}\text{U}$ , and homogeneous plutonium systems containing 76 wt %  $^{239}\text{Pu}$ , 12 wt %  $^{240}\text{Pu}$  and 12 wt %  $^{241}\text{Pu}$ , when reflected by  $\text{SiO}_2$ . These results are reported in Tables 4.7 and 4.11 and Figures 4.3 and 4.4. These isotopic compositions are expected to bound that found in commercial nuclear activities and provide higher surface-density limits.

The mixing of  $^{235}\text{U}$  and  $^{239}\text{Pu}$  isotopes in individual units and arrays can be done safely if the limits for  $^{239}\text{Pu}$  hydrogenous systems are controlling. This situa-

tion is demonstrated in Table 4.16, where 50% of the single-unit masses for  $^{235}\text{U}$  and  $^{239}\text{Pu}$  are combined and yield a surface-density limit that is halfway between the previous individual calculations.

## 4.7 Interspersed Moderation and Container Materials

The presence of steel in these types of assumed well-moderated systems reduces  $k_{\text{eff}}$  due to thermal neutron absorption. For the burial facility, the presence of the steel containers cannot be guaranteed. The presence of 12-gauge or 1/4-in.-thick carbon-steel containers between units in arrays always resulted in less-reactive arrays (see Tables 4.14 and 4.15) because of neutron absorption in iron. The effect of interspersed moderation (1/4-in.- and 1.0-in.-thick water radially around each unit) on optimally moderated  $^{235}\text{U}$  and  $^{239}\text{Pu}$  hydrogenous array units is shown in Tables 4.14 and 4.15 to reduce the reactivity of the arrays. The presence of 1/4-in.- or 1-in.-thick lead (a neutron scatterer) shielding material between units in arrays resulted in equal or less-reactive arrays (see Tables 4.14 and 4.15). The effect of dry  $\text{SiO}_2$  (also a neutron scatterer) filling the voids between optimally spaced units resulted in equal or less-reactive arrays (see Tables 4.14 and 4.15). Wet  $\text{SiO}_2$  between units would only reduce the array reactivity because of the presence of water.

## 4.8 Carbon and Beryllium Moderators

Table 4.17 illustrates that for  $^{235}\text{U}$  systems (which were performed for a hydrogen-to-fissile nuclide atom ratio, H/X, of 744) the total mass of carbon (graphite) present in a unit (package) should not exceed 20 times the total mass of the  $^{235}\text{U}$  that may be present. Table 4.18 illustrates that for  $^{235}\text{U}$  systems, the total mass of beryllium present in a unit (package) tends to continually reduce the allowable surface density of  $^{235}\text{U}$ , thereby demonstrating the need to evaluate such containers on a case-by-case basis.

## 4.9 Array Lattice Pattern

Because the square-pitched spacing between units is optimized, it is not expected that a triangular-pitch lattice pattern could result in a significantly more reactive array than the square-pitch lattice pattern. The effect of using a triangular-pitch versus a square-pitch array lattice is shown in Table 4.19.

## 4.10 Computational Uncertainties

From Table 4.20 it can be seen that the calculational uncertainty is  $0.0530 \Delta k$ . This total uncertainty includes uncertainties for values calculated above

1.00, a statistical uncertainty of  $2\sigma$  (due to the uncertainty in the Monte Carlo calculations), cross-section uncertainties of  $0.027$  and an assumed  $0.02 \Delta k$  allowance to ensure subcriticality of the calculated array. Using this uncertainty of  $0.0530 \Delta k$ , a subcritical limit of  $0.9453$  can be determined (subcritical limit,  $k_{\text{eff}} = 0.9983 - 0.0530 = 0.9453$ , where  $k_{\text{eff}} = 0.9983$  is assumed critical). Applying this value of  $0.9453$  to a plot of Table 4.21 data (see Figure 4.6), the pitch of the array increased from  $31.148$  to  $34.5$  cm. Therefore, any calculated critical surface-density value should be reduced by  $20\%$  to ensure subcriticality.

**Table 4.1 Mixture number densities used in calculations  
(partial list)**

Mixture	Density (g/cc)	Number density (atoms/barn-cm)
Water	0.9982	H = 0.066743
		O = 0.033372
Concrete	2.3	H = 0.0085
		C = 0.0202
		O = 0.0355
		Ca = 0.0111
		Si = 0.0017
		Mg = 0.00186
		Fe = 0.000193
		Al = 0.000556
		K = 0.0000403
Na = 0.0000163		
SiO <sub>2</sub> , dry	1.9	Si = 0.0190459
		O = 0.0380919
SiO <sub>2</sub> , water saturated	2.08	Si = 0.0190459
		O = 0.0440995
		H = 0.0120153
<sup>235</sup> U(100)	0.035	<sup>235</sup> U = 8.96745-5
		H = 0.0667514
		O = 0.0333757
<sup>239</sup> Pu(100)	0.020	<sup>239</sup> Pu = 5.03834-5
		H = 0.0667514
		O = 0.0333757

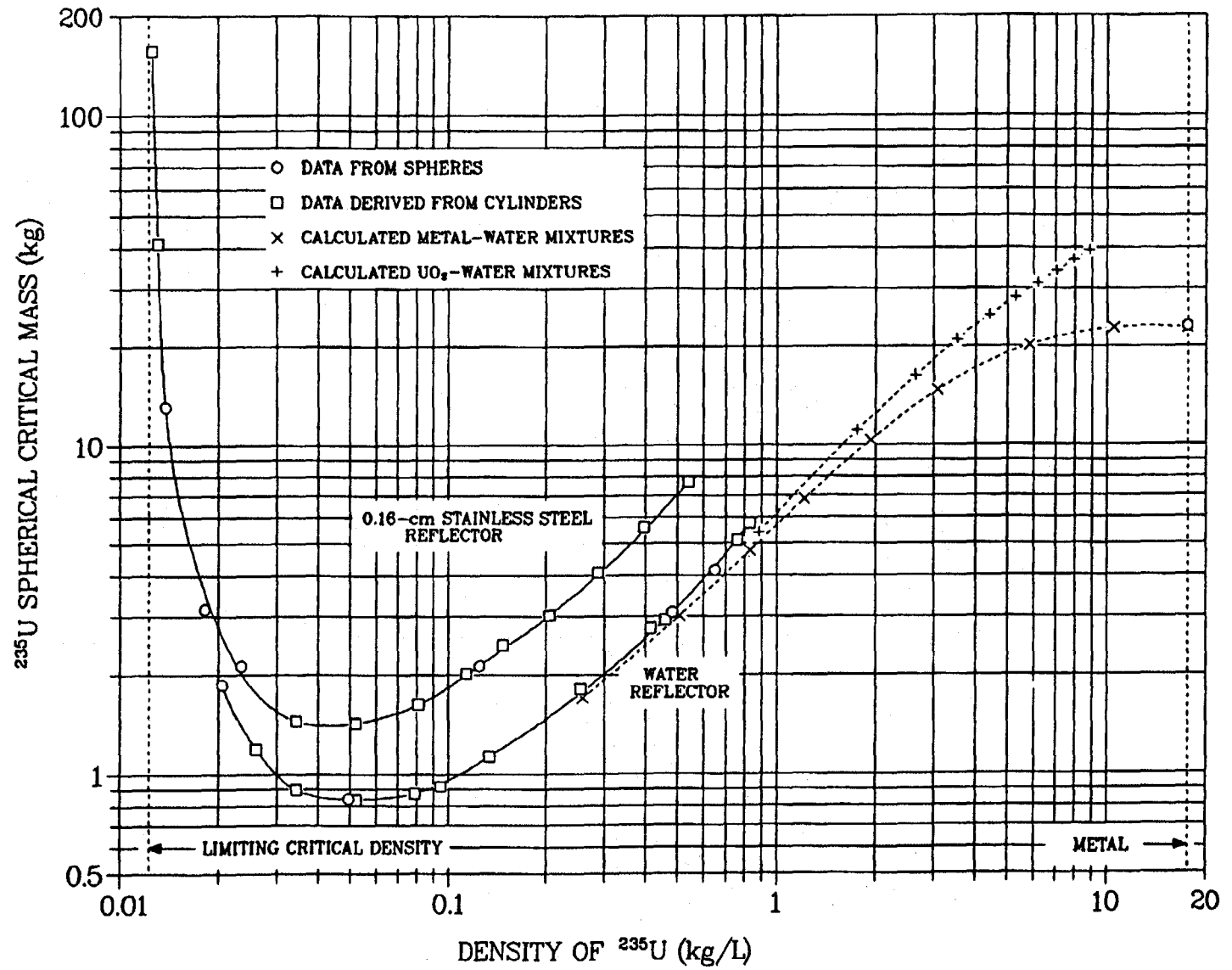


Figure 4.1 Critical masses of homogeneous water-moderated U(93.2) spheres. Solution data appear unless indicated otherwise (Taken from Figure 10 of Ref. 8)

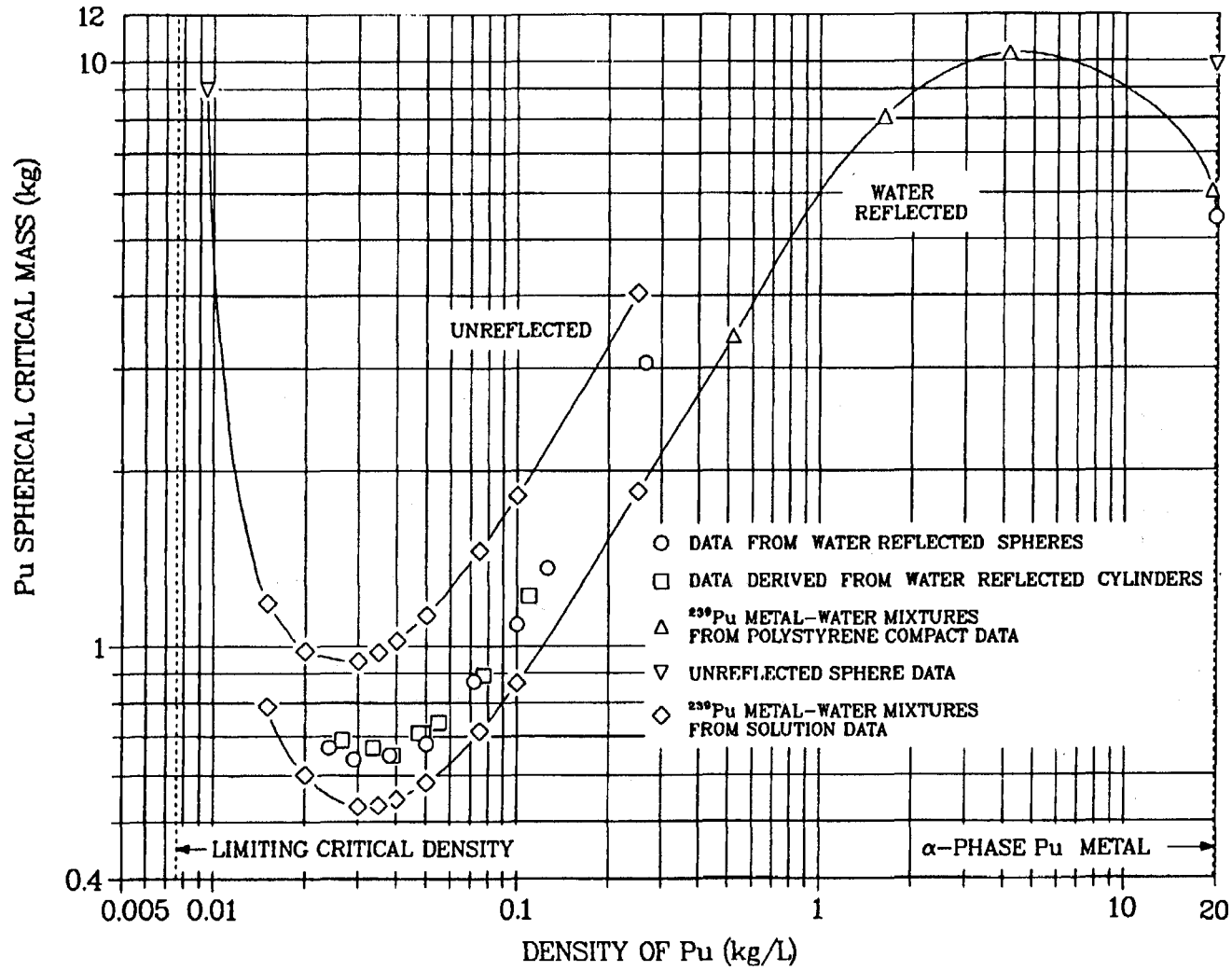


Figure 4.2 Critical masses of homogeneous water-moderated Pu spheres. Solution data appear unless indicated otherwise (Taken from Figure 31 of Ref. 8)

**Table 4.2  $^{235}\text{U}$  and  $^{238}\text{U}$  hydrogenous systems, water-reflected (Z-axis) H/D = 2.5, 350 g  $^{235}\text{U}$  per unit, H/ $^{235}\text{U}$  atom ratio = 744, infinite planar array**

Case	Pitch (cm)	$k_{\text{eff}}$	$\sigma$	$[\text{g}(^{235}\text{U})/\text{ft}^2]^a$
Base, no $^{238}\text{U}$	31.148	0.9983	0.0019	335
$^{235}\text{U}(80)$ , $^{238}\text{U}(20)$	25.07	1.0018	0.0016	517

<sup>a</sup> The areal density in kg/m<sup>2</sup> can be obtained by multiplying the g/ft<sup>2</sup> values by 0.010763.

**Table 4.3  $^{239}\text{Pu}$  and  $^{240}\text{Pu}$  hydrogenous systems, water-reflected (Z-axis) H/D = 2.5, 225 g  $^{239}\text{Pu}$  per unit, H/ $^{239}\text{Pu}$  atom ratio = 757, infinite planar array**

Case	Pitch (cm)	$k_{\text{eff}}$	$\sigma$	$[\text{g}(^{239}\text{Pu})/\text{ft}^2]^a$
Base, no $^{240}\text{Pu}$	32.532	1.0012	0.0019	198
$^{239}\text{Pu}(80)$ , $^{240}\text{Pu}(20)$	22.412	0.9955	0.0015	416

<sup>a</sup> The areal density in kg/m<sup>2</sup> can be obtained by multiplying the g/ft<sup>2</sup> values by 0.010763.



**Table 4.4  $^{235}\text{U}(100)$  hydrogenous systems, water-reflected (Z-axis),  
350  $\text{g}^{235}\text{U}$  per unit, infinite planar array**

H/D	$\text{g}^{235}\text{U}/\text{L}$	Pitch (cm)	$k_{\text{eff}}$	$\sigma$	$[\text{g}^{235}\text{U}/\text{ft}^2]^a$
1.5	100	25.844	1.0036	0.0022	487
	75	28.16	0.9990	0.0025	410
	50	30.416	1.0045	0.0022	351
	35	30.676	1.0046	0.0021	346
	25	29.484	1.0005	0.0017	374
2.0	300	16.9554	0.9996	0.0026	1131
	100	25.996	0.9999	0.0023	481
	75	28.16	0.9995	0.0022	410
	50	30.416	1.0026	0.0020	351
	35	31.218	1.0003	0.0018	334
	25	29.484	1.0043	0.0018	374
2.5	300	16.8448	1.0024	0.0023	1146
	100	25.844	0.9981	0.0022	487
	75	28.158	0.9984	0.0024	410
	50	30.416	0.9968	0.0018	351
	35	31.148	0.9983	0.0019	335
	25	29.486	1.0028	0.0016	374
	15	22.88	0.9975	0.0012	621
3.0	300	16.9998	1.0001	0.0025	1125
	100	25.592	1.0021	0.0023	496
	75	27.862	1.0046	0.0022	419
	50	30.414	0.9968	0.0022	352
	35	30.874	1.0007	0.0021	341
	25	29.44	1.0023	0.0017	375
	15	22.344	1.0008	0.0012	651
4.0	100	25.45	1.0020	0.0023	502
	75	27.666	0.9993	0.0022	425
	50	29.886	0.9977	0.0019	364
	35	30.438	1.0022	0.0017	351
	25	29.484	1.0036	0.0015	374

<sup>a</sup>The areal density in  $\text{kg}/\text{m}^2$  can be obtained by multiplying the  $\text{g}/\text{ft}^2$  values by 0.010763.

Table 4.5  $^{235}\text{U}(100)$  hydrogenous systems, concrete-reflected (Z-axis)  
 350  $\text{g}^{235}\text{U}$  per unit, infinite planar array

H/D	$\text{g}^{235}\text{U}/\text{L}$	Pitch (cm)	$k_{\text{eff}}$	$\sigma$	$[\text{g}^{235}\text{U}/\text{ft}^2]^a$
1.0	100	33.244	1.0045	0.0023	294
	75	35.574	1.0041	0.0022	257
	50	37.522	1.0048	0.0020	231
	35	37.124	1.0037	0.0020	236
	25	34.418	0.9968	0.0016	274
1.5	100	32.870	0.9992	0.0024	301
	75	35.266	1.0018	0.0023	261
	50	37.866	1.0006	0.0020	227
	35	36.944	1.0032	0.0019	238
	25	34.478	0.9999	0.0017	274
2.0	100	32.52	1.0033	0.0024	307
	75	35.028	1.0004	0.0020	265
	50	36.952	1.0037	0.0022	238
	35	37.66	0.9964	0.0018	229
	25	34.666	0.9967	0.0017	271
	15	24.582	0.9983	0.0012	538
2.5	100	32.164	1.0008	0.0022	315
	75	34.292	1.0039	0.0022	277
	50	36.634	1.0010	0.0020	242
	35	36.98	1.0005	0.0019	238
	25	34.326	1.0023	0.0015	276
	15	24.352	0.9998	0.0012	548
3.0	100	31.548	1.0045	0.0022	327
	75	33.774	1.0044	0.0021	285
	50	36.39	0.9976	0.0019	246
	35	36.848	1.0019	0.0018	239
	25	34.454	0.9972	0.0016	274
	15	23.976	0.9990	0.0014	566
4.0	100	31.23	1.0028	0.0023	333
	75	33.44	1.0038	0.0021	291
	50	35.75	1.0034	0.0019	254
	35	36.128	0.9981	0.0017	249
	25	33.754	0.9998	0.0017	285

<sup>a</sup> The areal density in  $\text{kg}/\text{m}^2$  can be obtained by multiplying the  $\text{g}/\text{ft}^2$  values by 0.010763.

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Table 4.6  $^{235}\text{U}(100)$  hydrogenous systems,  $\text{SiO}_2$  ( $\rho = 1.9$ )-reflected (Z-axis)  
 $350 \text{ g}^{235}\text{U}$  per unit, infinite planar array

H/D	$\text{g}^{235}\text{U}/\text{L}$	Pitch (cm)	$k_{\text{eff}}$	$\sigma$	$[\text{g}^{235}\text{U}/\text{ft}^2]^a$
1.0	100	43.066	1.0034	0.0027	175
	75	45.826	1.0024	0.0026	155
	50	49.716	0.9960	0.0023	132
	35	48.946	0.9995	0.0021	136
	25	43.324	1.0018	0.0018	173
1.5	100	43.288	0.9966	0.0026	174
	75	45.636	1.0033	0.0026	156
	50	48.898	1.0040	0.0024	136
	35	48.704	0.9968	0.0021	137
	25	43.288	1.0037	0.0017	174
2.0	100	42.11	1.0036	0.0029	183
	75	45.738	0.9969	0.0025	155
	50	48.404	1.0028	0.0023	139
	35	47.89	1.0000	0.0022	142
	25	43.142	1.0030	0.0018	175
	15	26.28	1.0047	0.0014	470
2.5	100	42.526	0.9965	0.0026	180
	75	45.222	0.9984	0.0024	159
	50	48.192	0.9972	0.0022	140
	35	46.916	1.0045	0.0020	148
	25	42.87	1.0012	0.0019	177
	15	26.246	1.0028	0.0012	472

<sup>a</sup> The areal density in  $\text{kg}/\text{m}^2$  can be obtained by multiplying the  $\text{g}/\text{ft}^2$  values by 0.010763.

Table 4.7  $^{235}\text{U}(10)$  plus  $^{238}\text{U}(90)$  hydrogenous systems,  $\text{SiO}_2$  ( $\rho = 1.9$ )-reflected (Z-axis)  
 $35 \text{ g}^{235}\text{U}$  per unit, infinite planar array

H/D	$\text{g}^{235}\text{U}/\text{L}$	Pitch (cm)	$k_{\text{eff}}$	$\sigma$	$[\text{g}^{235}\text{U}/\text{ft}^2]^a$
1.0	100	10.5078	0.9969	0.0023	294
	75	11.057	0.9994	0.0021	266
	50	11.4704	1.0000	0.0020	247
	35	11.5204	0.9956	0.0019	245
	25				not critical
2.0	100	10.482	0.9991	0.0023	295
	75	11.1716	0.9962	0.0020	260
	50	11.5854	1.0008	0.0018	242
	35	11.4686	0.9955	0.0018	247
	25	10.6972	0.9971	0.0016	284
4.0	100	10.4872	0.9991	0.0023	295
	75	11.0418	1.0043	0.0021	266
	50	11.5588	0.9999	0.0020	243
	35	11.401	1.0007	0.0017	250
	25	10.5782	1.0005	0.0016	290
6.0	100	10.4208	1.0044	0.0021	299
	75	11.063	0.9979	0.0021	265
	50	11.574	0.9976	0.0019	242
	35	11.4202	1.0006	0.0017	249
	25	10.535	0.9986	0.0015	293

<sup>a</sup> The areal density in  $\text{kg}/\text{m}^2$  can be obtained by multiplying the  $\text{g}/\text{ft}^2$  values by 0.010763.

Table 4.8  $^{239}\text{Pu}(100)$  hydrogenous systems, water-reflected (Z-axis)  
 225 g $^{239}\text{Pu}$  per unit, infinite planar array

H/D	g $^{239}\text{Pu}$ /L	Pitch (cm)	$k_{\text{eff}}$	$\sigma$	[g $^{239}\text{Pu}$ /ft $^2$ ] <sup>a</sup>
1.0	50	27.104	1.0042	0.0022	285
	35	30.48	0.9988	0.0021	225
	25	31.244	0.9969	0.0021	214
	20	31.354	1.0028	0.0019	213
	15	30.372	0.9999	0.0017	227
2.0	50	28.012	1.0025	0.0021	266
	35	30.882	0.9980	0.0022	219
	25	32.23	1.0039	0.0039	201
	20	32.532	1.0024	0.0021	198
	15	31.2	1.0016	0.0017	215
	10	26.288	0.9984	0.0014	302
2.5	300	13.419	1.0036	0.0025	1161
	100	21.776	1.0006	0.0024	441
	75	24.308	1.0009	0.0023	354
	50	27.87	1.0037	0.0023	269
	35	30.48	1.0049	0.0021	225
	25	32.182	0.9991	0.0021	201
	20	32.532	1.0012	0.0019	198
	15	31.17	0.9989	0.0017	215
	10	26.148	0.9983	0.0015	305
3.0	50	28.016	0.9961	0.0024	266
	35	30.48	1.0008	0.0020	225
	25	31.884	1.0044	0.0018	206
	20	32.532	0.9971	0.0018	198
	15	30.862	1.0011	0.0017	219
	10	26.094	0.9962	0.0013	307
4.0	50	27.456	1.0006	0.0024	277
	35	30.48	1.9979	0.0023	225
	25	31.532	1.0027	0.0020	210
	20	32.03	1.0027	0.0019	203
	15	30.844	1.0030	0.0020	220
	10	25.598	0.9991	0.0015	319

<sup>a</sup> The areal density in kg/m $^2$  can be obtained by multiplying the g/ft $^2$  values by 0.010763.

**Table 4.9  $^{239}\text{Pu}(100)$  hydrogenous systems, concrete-reflected (Z-axis)  
225 g  $^{239}\text{Pu}$  per unit, infinite planar array**

H/D	$\text{g}^{239}\text{Pu/L}$	Pitch (cm)	$k_{\text{eff}}$	$\sigma$	$[\text{g}^{239}\text{Pu/ft}^2]^a$
1.0	50	36.322	1.0038	0.0020	158
	35	39.82	0.9975	0.0022	132
	25	40.28	1.0045	0.0021	129
	20	39.684	1.0006	0.0019	133
	15	36.38	1.0011	0.0017	158
2.0	50	35.264	1.0011	0.0022	168
	35	38.538	0.9982	0.0021	141
	25	39.926	0.9967	0.0019	131
	20	39.05	1.0029	0.0019	137
	15	36.64	1.0017	0.0017	156
	10	28.668	1.0017	0.0013	254
2.5	100	27.918	0.9964	0.0024	268
	75	30.668	0.9952	0.0023	222
	50	34.812	0.9971	0.0023	172
	35	37.696	1.0025	0.0020	147
	25	39.094	0.9981	0.0017	137
	20	38.824	1.0008	0.0019	139
	15	35.872	1.0031	0.0016	162
10	28.564	1.0022	0.0013	256	
3.0	50	34.54	1.0022	0.0022	175
	35	37.552	0.9951	0.0021	148
	25	38.844	0.9975	0.0021	139
	20	38.40	0.9976	0.0019	142
	15	36.722	0.9961	0.0016	155
	10	28.55	1.0036	0.0013	256
4.0	50	34.13	1.0011	0.0023	179
	35	36.846	1.0020	0.0019	154
	25	38.212	1.0001	0.0020	143
	20	38.676	1.0034	0.0018	140
	15	36.042	0.9995	0.0017	161
	10	28.386	0.9995	0.0011	259

<sup>a</sup> The areal density in  $\text{kg/m}^2$  can be obtained by multiplying the  $\text{g/ft}^2$  values by 0.010763.

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**Table 4.10**  $^{239}\text{Pu}(100)$  hydrogenous systems,  $\text{SiO}_2$  ( $\rho = 1.9$ )-reflected (Z-axis)  
 225  $\text{g}^{239}\text{Pu}$  per unit, infinite planar array

H/D	$\text{g}^{239}\text{Pu}/\text{liter}$	Pitch (cm)	$k_{\text{eff}}$	$\sigma$	$[\text{g}^{239}\text{Pu}/\text{ft}^2]^a$
1.0	100	37.822	0.9973	0.0028	146
	75	41.856	1.0041	0.0028	119
	50	47.206	1.0030	0.0026	93
	35	51.490	1.0037	0.0026	79
	25	53.390	0.9996	0.0021	73
	20	52.302	0.9977	0.0019	76
	15	46.748	1.0038	0.0020	96
2.0	100	37.366	1.0038	0.0026	150
	75	41.334	1.0011	0.0028	122
	50	46.592	1.0040	0.0027	96
	35	50.652	0.9980	0.0022	81
	25	51.932	1.0039	0.0022	78
	20	51.356	0.9976	0.0019	79
	15	47.326	0.9968	0.0019	93
	10	33.528	1.0017	0.0013	186
2.5	50	46.224	1.0014	0.0026	98
	35	49.852	1.0019	0.0024	84
	25	51.478	0.9987	0.0021	79
	20	50.298	0.9995	0.0021	83
	15	46.428	1.0001	0.0019	97
	10	33.508	1.0013	0.0014	186

<sup>a</sup> The areal density in  $\text{kg}/\text{m}^2$  can be obtained by multiplying the  $\text{g}/\text{ft}^2$  values by 0.010763.

Table 4.11  $^{239}\text{Pu}(76)$  plus  $^{240}\text{Pu}(12)$  and  $^{241}\text{Pu}(12)$  hydrogenous systems,  $\text{SiO}_2$  ( $\rho = 1.9$ )-reflected (Z-axis) 225 g  $^{239}\text{Pu}$  per unit, infinite planar array

H/D	g $^{239}\text{Pu}/\text{L}$	Pitch (cm)	$k_{\text{eff}}$	[g $^{239}\text{Pu}/\text{ft}^2$ ] <sup>a</sup>	$\sigma$	[g( $^{239}\text{Pu} + ^{241}\text{Pu})/\text{ft}^2$ ] <sup>a</sup>
1.0	100	33.870	0.9968	182	0.0029	211
	75	38.318	0.9988	142	0.0026	164
	50	44.568	1.0005	105	0.0023	122
	35	49.422	1.0043	86	0.0025	100
	25	52.532	1.0050	76	0.0022	88
	20	53.912	0.9990	72	0.0021	83
	15	51.888	0.9981	78	0.0018	90
2.0	100	33.934	0.9979	182	0.0026	211
	75	38.376	0.9955	142	0.0026	164
	50	44.240	1.0046	107	0.0024	124
	35	49.346	0.9999	86	0.0022	100
	25	52.334	1.0016	76	0.0022	88
	20	52.000	1.0036	77	0.0021	89
	15	50.450	1.0026	82	0.0017	95
10	40.680	1.0024	126	0.0014	146	
2.5	50	43.750	1.0018	109	0.0023	126
	35	48.472	1.0013	89	0.0022	103
	25	51.794	0.9965	78	0.0021	90
	20	51.784	1.0005	78	0.0020	90
	15	49.866	1.0039	84	0.0019	97
	10	40.274	1.0018	129	0.0015	149

<sup>a</sup> The areal density in  $\text{kg}/\text{m}^2$  can be obtained by multiplying the  $\text{g}/\text{ft}^2$  values by 0.010763.



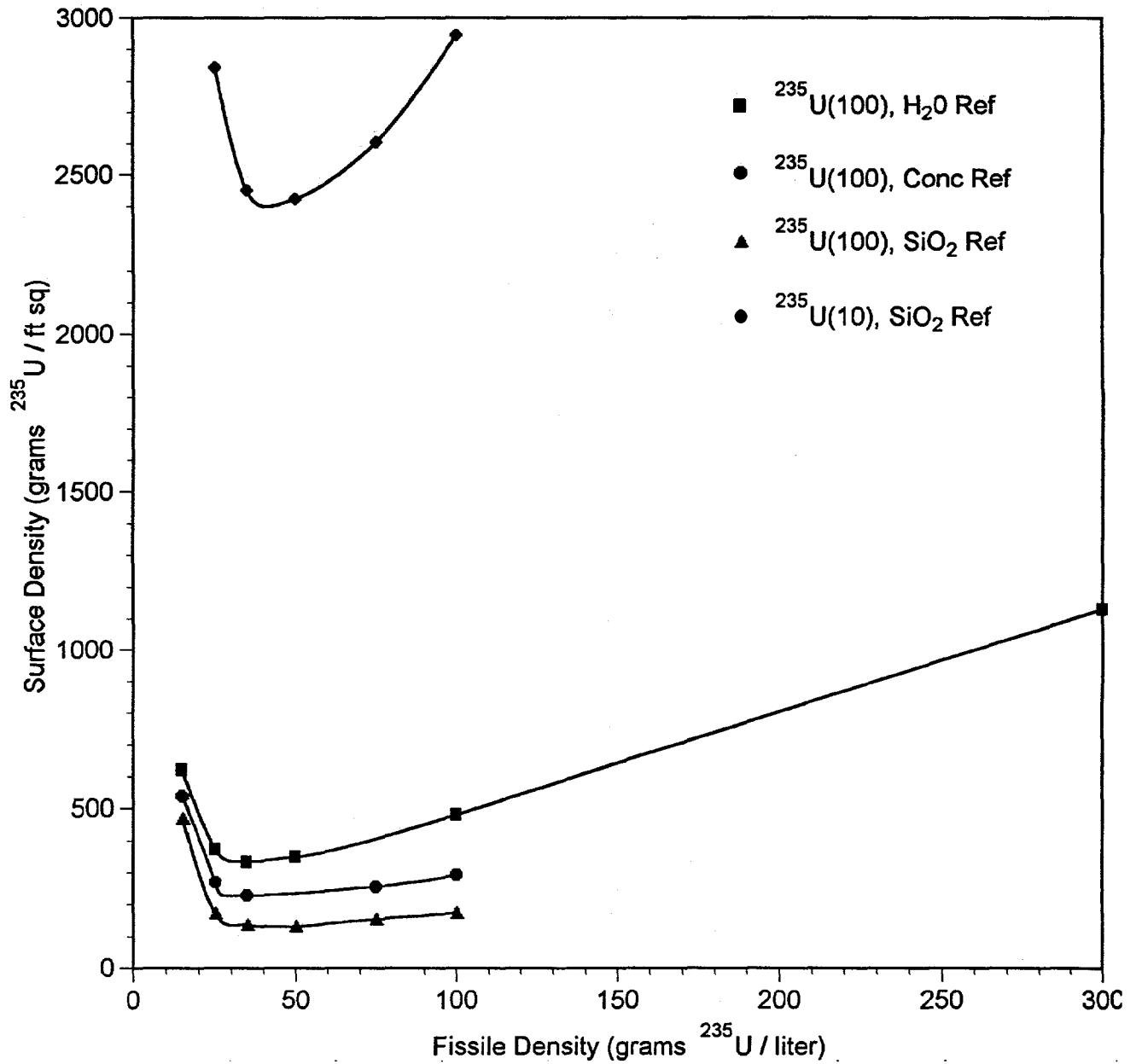


Figure 4.3 Minimum critical surface-density mass per unit area for <sup>235</sup>U units (independent of H/D ratio of single units), reflected by light water, concrete and SiO<sub>2</sub>. (Figure is based on minimum critical values taken from Tables 4.4 through 4.7.)

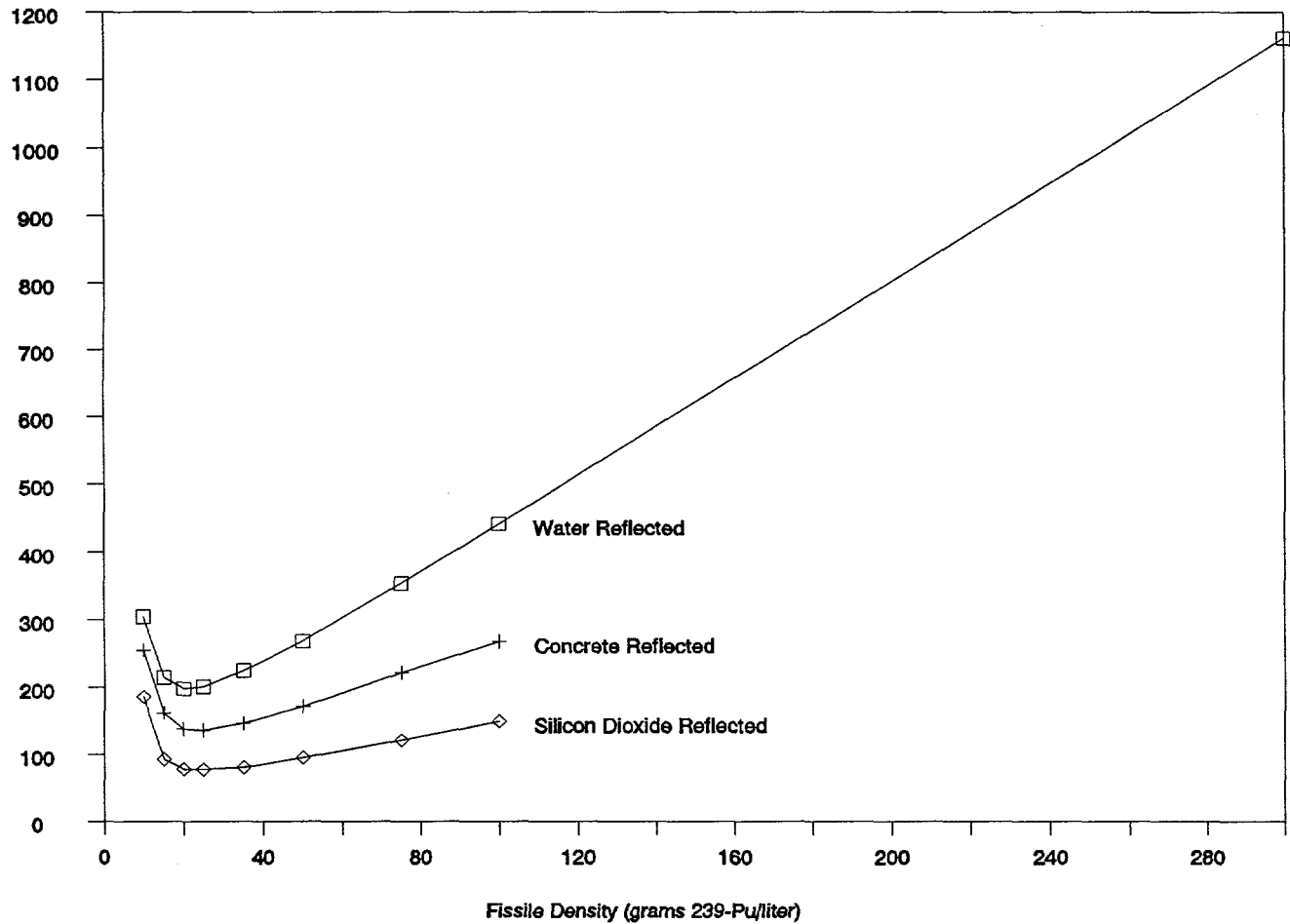


Figure 4.4 Minimum critical surface-density mass per unit area for <sup>239</sup>Pu units (independent of H/D ratio of single units), reflected by light water, concrete and SiO<sub>2</sub>. (Figure is based on minimum critical values taken from Tables 4.8 through 4.11.)

**Table 4.12**  $^{235}\text{U}(100)$  hydrogenous systems, soil ( $\text{SiO}_2$ )-reflected (Z-axis)  $H/D = 2.5$ ,  
 $350 \text{ g}^{235}\text{U}$  per unit,  $35 \text{ g}^{235}\text{U}$  per liter, infinite planar array

Reflector	Pitch (cm)	$k_{\text{eff}}$	$\sigma$	$[\text{g}^{235}\text{U}/\text{ft}^2]^a$
Base case, water	31.148	0.9983	0.0019	335
Base case, concrete	36.98	1.0005	0.0019	238
$\text{SiO}_2$ , density 1.9; no moisture	46.916	1.0045	0.0020	148
$\text{SiO}_2$ , density 1.9; water saturated	37.844	1.0030	0.0021	227

<sup>a</sup> The areal density in  $\text{kg}/\text{m}^2$  can be obtained by multiplying the  $\text{g}/\text{ft}^2$  values by 0.010763.

**Table 4.13**  $^{239}\text{Pu}(100)$  hydrogenous systems, soil ( $\text{SiO}_2$ )-reflected (Z-axis)  $H/D = 2.5$ ,  
 $225 \text{ g}^{239}\text{Pu}$  per unit,  $20 \text{ g}^{239}\text{Pu}$  per liter, infinite planar array

Reflector	Pitch (cm)	$k_{\text{eff}}$	$\sigma$	$[\text{g}^{239}\text{Pu}/\text{ft}^2]^a$
Base case, water	32.532	1.0012	0.0019	198
Base case, concrete	38.824	1.0008	0.0019	139
$\text{SiO}_2$ , density 1.9; no moisture	50.546	0.9952	0.0021	82
$\text{SiO}_2$ , density 1.9; water saturated	39.892	1.0040	0.0020	131

<sup>a</sup> The areal density in  $\text{kg}/\text{m}^2$  can be obtained by multiplying the  $\text{g}/\text{ft}^2$  values by 0.010763.

**Table 4.14**  $^{235}\text{U}(100)$  hydrogenous systems, water-reflected (Z-axis)  $H/D = 2.5$ ,  
 $350 \text{ g}^{235}\text{U}$  per unit,  $35 \text{ g}^{235}\text{U}$  per liter, infinite planar array

Case	Pitch (cm)	$k_{\text{eff}}$	$\sigma$	$[\text{g}^{235}\text{U}/\text{ft}^2]^a$
Base	31.148	0.9983	0.0019	335
1/4-in. Pb, radially	30.632	1.0024	0.0018	347
1-in. Pb, radially	30.364	1.0030	0.0020	353
1/4-in. water, radially	30.088	0.9998	0.0020	359
1-in. water, radially	22.938	0.9950	0.0019	618
12-gauge carbon steel, radially	26.118	0.9951	0.0020	476
1/4-in. carbon steel, radially	23.118	0.9980	0.0020	608
6-in. void on $\pm Z$ axes	31.2	0.9957	0.0018	334
$\text{SiO}_2$ filling void between units, dry, density 1.9	30.916	0.9986	0.0020	340

<sup>a</sup> The areal density in  $\text{kg}/\text{m}^2$  can be obtained by multiplying the  $\text{g}/\text{ft}^2$  values by 0.010763.

**Table 4.15  $^{239}\text{Pu}(100)$  hydrogenous systems, water-reflected (Z-axis)  $H/D = 2.5$ ,  
225 g  $^{239}\text{Pu}$  per unit, 20 g  $^{239}\text{Pu}$  per liter, infinite planar array**

Case	Pitch (cm)	$k_{\text{eff}}$	$\sigma$	$[\text{g}^{239}\text{Pu}/\text{ft}^2]^a$
Base	32.532	1.0012	0.0019	198
1/4-in. Pb, radially	32.532	1.0000	0.0020	198
1-in. Pb, radially	31.968	0.9958	0.0020	205
1/4-in. water, radially	31.264	1.0013	0.0019	214
1-in. water, radially	24.096	0.9980	0.0019	360
12-gauge carbon steel, radially	27.432	1.0027	0.0018	278
1/4-in. carbon steel, radially	24.704	1.0046	0.0019	343
6-in. void on $\pm Z$ axes	32.532	0.9984	0.0019	198
$\text{SiO}_2$ filling void between units, dry, density 1.9	32.532	0.9966	0.0022	198

<sup>a</sup> The areal density in  $\text{kg}/\text{m}^2$  can be obtained by multiplying the  $\text{g}/\text{ft}^2$  values by 0.010763.

**Table 4.16  $^{235}\text{U}$  and  $^{239}\text{Pu}$  hydrogenous systems, water-reflected (Z-axis)  
 $H/D = 2.5$ , 35 g  $^{235}\text{U}$  plus  $^{239}\text{Pu}$  per liter, infinite planar array**

Case	Pitch (cm)	$k_{\text{eff}}$	$\sigma$	$[\text{g}^{235}\text{U} + \text{g}^{239}\text{Pu}/\text{ft}^2]^a$
350 g $^{235}\text{U}(100)$ , no $^{239}\text{Pu}$	31.148	0.9983	0.0019	335
175 g $^{235}\text{U}(100)$ plus 112.5 g $^{239}\text{Pu}(100)$	31.52	0.9991	0.0019	269
225 g $^{239}\text{Pu}(100)$ , no $^{235}\text{U}$	30.48	1.0049	0.0021	225

<sup>a</sup> The areal density in  $\text{kg}/\text{m}^2$  can be obtained by multiplying the  $\text{g}/\text{ft}^2$  values by 0.010763.

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**Table 4.17  $^{235}\text{U}(100)$  hydrogenous and carbon systems, water-reflected (Z-axis)  
H/D = 2.5, 350 g  $^{235}\text{U}$  per unit, H/ $^{235}\text{U}$  atom ratio = 744, infinite planar array**

Carbon content	Pitch (cm)	$k_{\text{eff}}$	$\sigma$	[g $^{235}\text{U}/\text{ft}^2$ ] <sup>a</sup>
Base, no carbon	31.148	0.9983	0.0019	335
5 × mass $^{235}\text{U}$	31.266	0.9977	0.0020	333
10 × mass $^{235}\text{U}$	31.068	0.9982	0.0020	337
20 × mass $^{235}\text{U}$	31.242	1.0011	0.0019	333
40 × mass $^{235}\text{U}$	31.508	0.9983	0.0019	327
80 × mass $^{235}\text{U}$	32.02	1.0041	0.0018	317

<sup>a</sup> The areal density in kg/m<sup>2</sup> can be obtained by multiplying the g/ft<sup>2</sup> values by 0.010763.

**Table 4.18  $^{235}\text{U}(100)$  hydrogenous and beryllium systems, water-reflected (Z-axis)  
H/D = 2.5, 350 g  $^{235}\text{U}$  per unit, H/ $^{235}\text{U}$  atom ratio = 744, infinite planar array**

Beryllium content	Pitch (cm)	$k_{\text{eff}}$	$\sigma$	[g $^{235}\text{U}/\text{ft}^2$ ] <sup>a</sup>
Base, no beryllium	31.148	0.9983	0.0019	335
5 × mass $^{235}\text{U}$	31.766	1.0026	0.0020	322
10 × mass $^{235}\text{U}$	32.312	1.0035	0.0018	311
20 × mass $^{235}\text{U}$	33.480	1.0024	0.0019	290
40 × mass $^{235}\text{U}$	34.906	1.0031	0.0018	267
80 × mass $^{235}\text{U}$	37.356	0.9981	0.0019	233

<sup>a</sup> The areal density in kg/m<sup>2</sup> can be obtained by multiplying the g/ft<sup>2</sup> values by 0.010763.

**Table 4.19 Square-pitch vs triangular-pitch  $^{235}\text{U}(100)$  hydrogenous systems, water-reflected (Z-axis)  $H/D = 2.5$ ,  $350 \text{ g}^{235}\text{U}$  per unit,  $35 \text{ g}^{235}\text{U}$  per liter, infinite planar array**

Case	Pitch (cm)	$k_{\text{eff}}$	$\sigma$	$[\text{g}^{235}\text{U}/\text{ft}^2]^a$
Square-pitch	31.148	0.9983	0.0019	335
Triangular-pitch	33.471	0.9967	0.0019	335

<sup>a</sup> The areal density in  $\text{kg}/\text{m}^2$  can be obtained by multiplying the  $\text{g}/\text{ft}^2$  values by 0.010763.

**Table 4.20 Calculational uncertainties (maximum values for all calculations)**

$\Delta k_{\text{eff}}$ variance above 1.00	0.0050
$2\sigma$ (for Monte Carlo calc)	0.0080
Cross-section uncertainty <sup>7</sup>	0.0200
Allowance for subcriticality	0.0200
Total	0.0530

**Table 4.21  $^{235}\text{U}(100)$  hydrogenous systems, water-reflected (Z-axis)  $H/D = 2.5$ ,  $350 \text{ g}^{235}\text{U}$  per unit,  $35 \text{ g}^{235}\text{U}$  per liter, infinite planar array (array pitch sensitivity)**

Pitch (cm)	$k_{\text{eff}}^a$	$\sigma$
31.148	0.9983	0.0019
32.000	0.9839	0.0020
34.000	0.9549	0.0020
36.000	0.9278	0.0020
48.000	0.7974	0.0020

<sup>a</sup>Subcritical limit,  $k_{\text{eff}} = 0.9983 - 0.0530 = 0.9453$   
(based on Tables 4.19 and 4.20, were  $k_{\text{eff}} = 0.9983$  is assumed critical)

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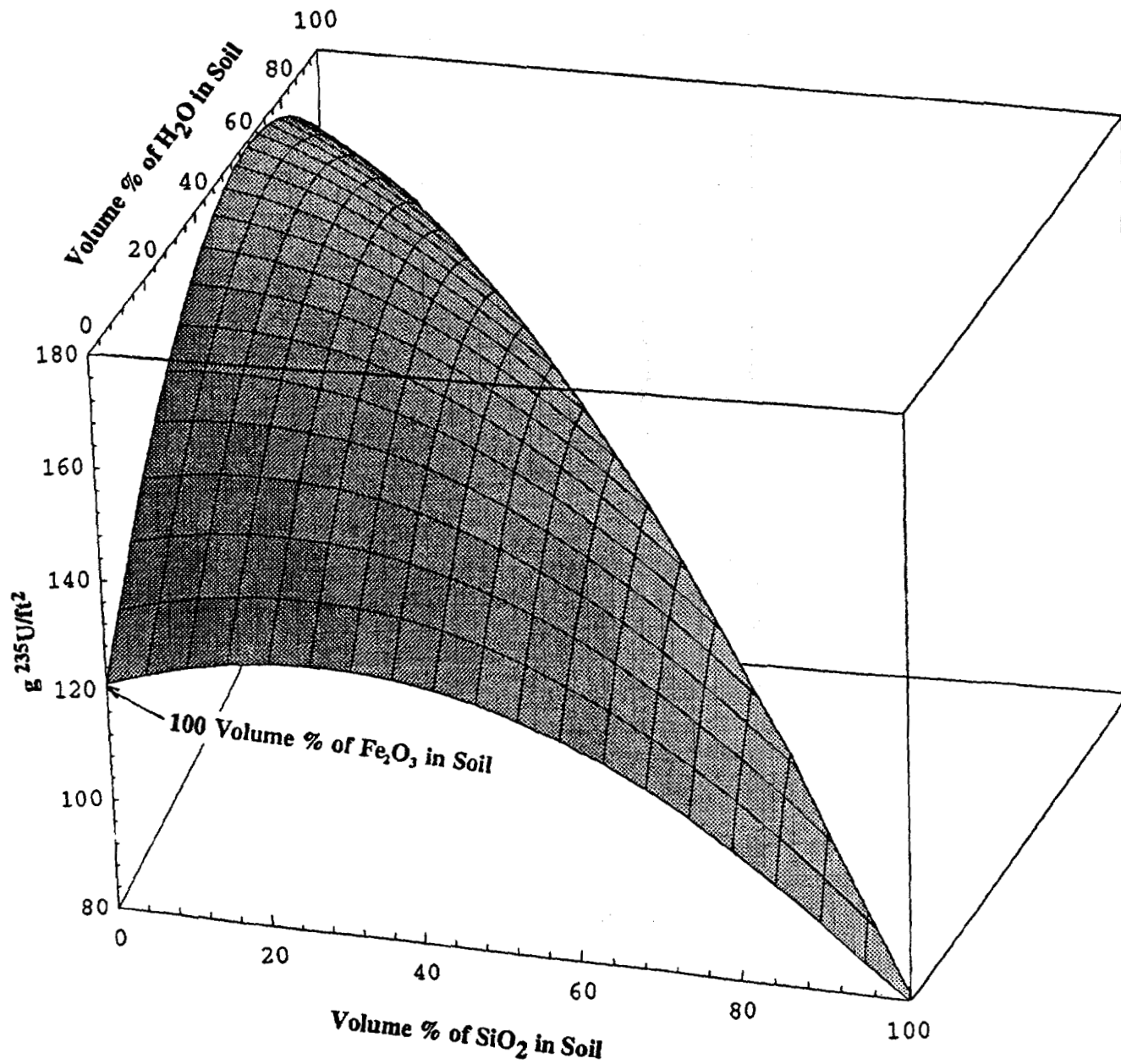
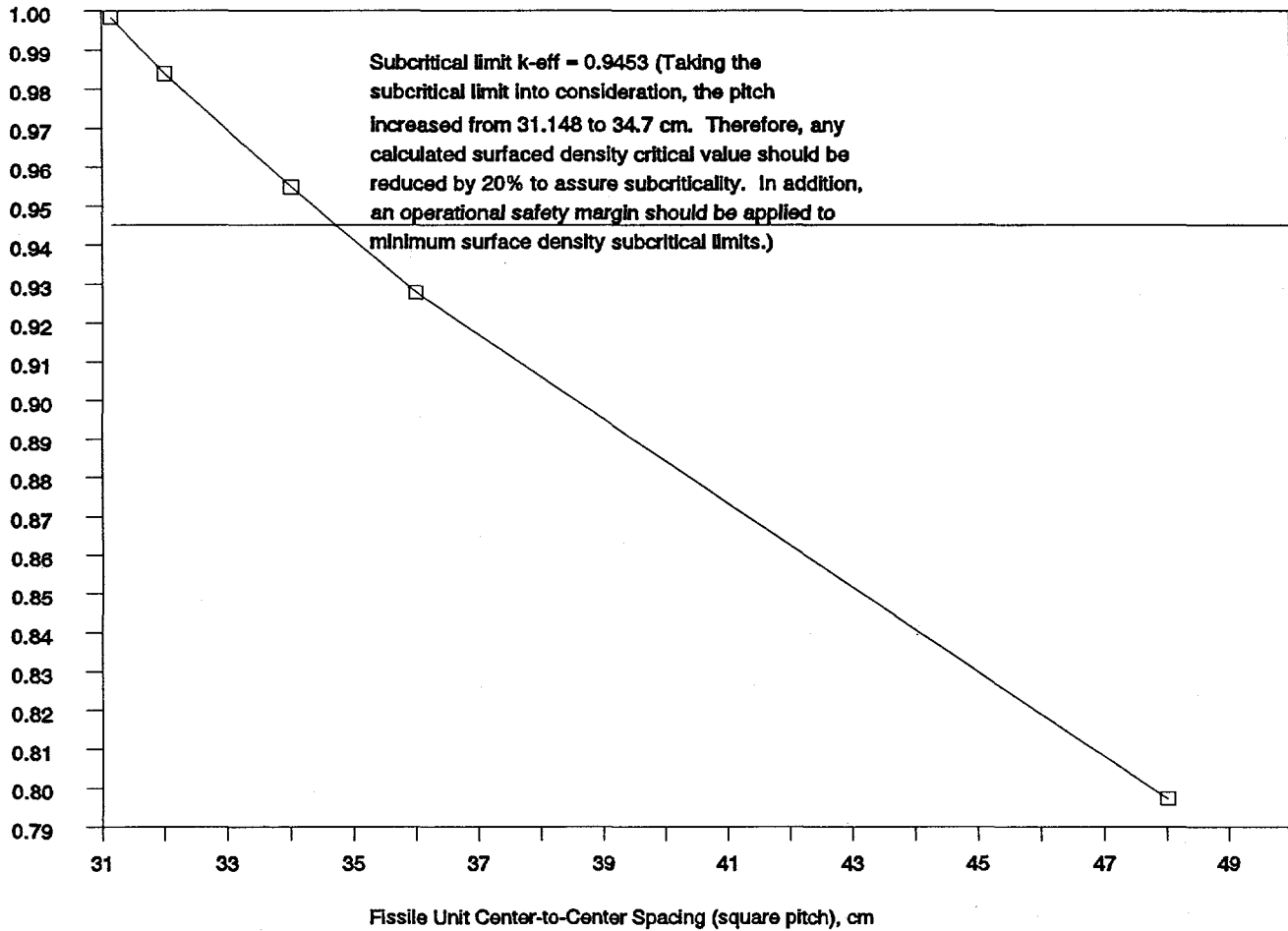


Figure 4.5 Variation of possible U(100) operational areal density limits ( $g^{235}U/ft^2$ ) vs burial trench soil composition ( $Fe_2O_3$ ,  $SiO_2$ ,  $H_2O$ )



**Figure 4.6** Array pitch sensitivity ( $k_{eff}$  vs pitch)  
 (Taken from Table 4.21,  $^{235}\text{U}(100)$  units in planar array, 35 g $^{235}\text{U}$  per liter, water reflected.)



## 5 DISCUSSION OF RESULTS

Based on the data from Tables 4.4 through 4.11, the following minimum surface-density values were calculated using the SCALE code system.<sup>5</sup> The subcritical limits were derived from the critical values by reducing the values by 20% to take into account the calculational uncertainty and applying an additional 0.02  $\Delta k$  allowance to ensure subcriticality (see Sect. 4.10).

The array calculations using SiO<sub>2</sub> as a reflector resulted in lower surface-density values than that anticipated prior to the analyses. Therefore, additional calculations with dry SiO<sub>2</sub> reflectors were performed for low-enriched, homogeneous uranium systems containing 10 wt % <sup>235</sup>U and 90 wt % <sup>238</sup>U, and homogeneous plutonium systems containing 76 wt % <sup>239</sup>Pu, 12 wt % <sup>240</sup>Pu, and 12 wt % <sup>241</sup>Pu. These isotopic compositions are expected to encompass most commercial nuclear activities and permit increased surface-density limits.

Tables 5.1 through 5.3 delineate the calculated minimum critical values, subcritical limits, and the recommended operational limits for water, concrete, and SiO<sub>2</sub> reflected planar arrays containing <sup>235</sup>U or <sup>239</sup>Pu fissile isotopes.

For LLW packages containing <sup>235</sup>U or <sup>239</sup>Pu isotopes which are buried in soil, it is recommended that the surface-density spacing criteria be based on the operational limits, delineated in Tables 5.1 through 5.4, where SiO<sub>2</sub> was assumed as the reflector. In addition, an operational safety margin should be applied to minimum-calculated subcritical surface-density limits. Frequently, an operational safety factor of 25% (decrease in fissile mass) would be applied to the subcritical limits.

However, actual soil will contain unquantifiable amounts of water moisture, organic materials, iron, and other materials which will absorb neutrons, thus making the array less reactive. Therefore, applying an operational safety factor of 10% to the SiO<sub>2</sub>-reflected subcritical limits is judged sufficient.

If the subcritical limits for hydrogenous and homogeneous systems containing <sup>238</sup>U or <sup>240</sup>Pu isotopes are used, then the LLW facility must take steps to ensure that the fissile material is essentially uniformly distributed throughout the package (this is not required for systems for which no credit is taken for the diluents).

For <sup>235</sup>U systems, the total mass of carbon (graphite) present in a package should not exceed 20 times the total mass of the <sup>235</sup>U that may be present.

The effects of interspersed moderation, lead shielding, carbon steel, and dry or moist SiO<sub>2</sub> between packages and packages on a triangular-pitch will not result in a more reactive planar array.

The calculations contain three conservative assumptions: (1) the fissile material in the waste is assumed optimally moderated, (2) the fissile material contains no absorbers, and (3) no credit is taken for the iron in the drums which is the usual method of transporting waste for disposal. It is anticipated that any iron from disintegrated containers will remain intermingled with buried LLW as iron oxide (rust).

**Table 5.1  $^{235}\text{U}(100)$  hydrogenous systems, 350 g  $^{235}\text{U}$  per unit, infinite planar array**

Reflector	Critical value [g $^{235}\text{U}/\text{ft}^2$ ] <sup>a</sup>	Subcritical limit [g $^{235}\text{U}/\text{ft}^2$ ] <sup>a</sup>	Operational limit [g $^{235}\text{U}/\text{ft}^2$ ] <sup>a</sup>
Water	334	267	200
Concrete	227	181	135
SiO <sub>2</sub> (soil)	132	105	94

<sup>a</sup> The areal density in kg/m<sup>2</sup> can be obtained by multiplying the g/ft<sup>2</sup> values by 0.010763.

**Table 5.2  $^{235}\text{U}(10)$  plus  $^{238}\text{U}(90)$  hydrogenous and homogeneous systems 35 g  $^{235}\text{U}$  per unit, infinite planar array**

Reflector	Critical value [g $^{235}\text{U}/\text{ft}^2$ ] <sup>a</sup>	Subcritical limit [g $^{235}\text{U}/\text{ft}^2$ ] <sup>a</sup>	Operational limit [g $^{235}\text{U}/\text{ft}^2$ ] <sup>a</sup>
Water	not critical	466	350
Concrete	390	312	234
SiO <sub>2</sub> (soil)	242	193	174

<sup>a</sup> The areal density in kg/m<sup>2</sup> can be obtained by multiplying the g/ft<sup>2</sup> values by 0.010763.

**Table 5.3  $^{239}\text{Pu}(100)$  hydrogenous systems, 225 g  $^{239}\text{Pu}$  per unit, infinite planar array**

Reflector	Critical value [g $^{239}\text{Pu}/\text{ft}^2$ ] <sup>a</sup>	Subcritical limit [g $^{239}\text{Pu}/\text{ft}^2$ ] <sup>a</sup>	Operational limit [g $^{239}\text{Pu}/\text{ft}^2$ ] <sup>a</sup>
Water	198	158	118
Concrete	129	103	77
SiO <sub>2</sub> (soil)	73	58	52

<sup>a</sup> The areal density in kg/m<sup>2</sup> can be obtained by multiplying the g/ft<sup>2</sup> values by 0.010763.

**Table 5.4  $^{239}\text{Pu}(76)$  plus  $^{240}\text{Pu}(12)$  plus  $^{241}\text{Pu}(12)$  hydrogenous and homogeneous systems 225 g  $^{239}\text{Pu}$  per unit, H/D = 1, 20 g Pu per liter, infinite planar array**

Reflector	Critical value [g $^{239}\text{Pu}/\text{ft}^2$ ] <sup>a</sup> or g( $^{239}\text{Pu} + ^{241}\text{Pu}$ )/ft <sup>2</sup>	Subcritical limit [g $^{239}\text{Pu}/\text{ft}^2$ ] <sup>a</sup> or g( $^{239}\text{Pu} + ^{241}\text{Pu}$ )/ft <sup>2</sup>	Operational limit [g $^{239}\text{Pu}/\text{ft}^2$ ] <sup>a</sup> or g( $^{239}\text{Pu} + ^{241}\text{Pu}$ )/ft <sup>2</sup>
SiO <sub>2</sub> (soil)	72 (83)	57 (66)	51 (59)

<sup>a</sup> The areal density in kg/m<sup>2</sup> can be obtained by multiplying the g/ft<sup>2</sup> values by 0.010763.

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(Assigned by NRC, Add Vol.,  
Supp., Rev., and Addendum Num-  
bers, if any.)

NUREG/CR-6284  
ORNL/TM-12845

2. TITLE AND SUBTITLE

Criticality Safety Criteria for License Review of Low-Level Waste Facilities

3. DATE REPORT PUBLISHED

MONTH | YEAR

March | 1995

4. FIN OR GRANT NUMBER

L1376

5. AUTHOR(S)

C. M. Hopper, R. H. Odegaarden, C. V Parks, P. B. Fox

6. TYPE OF REPORT

Technical

7. PERIOD COVERED (Inclusive Dates)

8. PERFORMING ORGANIZATION - NAME AND ADDRESS (If NRC, provide Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)

Oak Ridge National Laboratory  
Oak Ridge, TN 37831-6370

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Division of Waste Management  
Office of Nuclear Material Safety and Safeguards  
U.S. Nuclear Regulatory Commission  
Washington, DC 20555-0001

10. SUPPLEMENTARY NOTES

11. ABSTRACT (200 words or less)

This report provides recommended safety criteria for NRC licensed burial facilities. These criteria have been developed with accepted and consistent nuclear criticality safety evaluation techniques. Additionally, this report provides the bases for the recommended safety criteria by documenting the evaluation methods and assumptions, and by reporting the results of all single-package and array calculations. These criteria were developed with care to assure consistency with data and practices provided in current standards on nuclear criticality safety as well as conformity of the criteria to applicable NRC regulations.

The recommended safety criteria are expressed in terms of surface-density spacing criteria, thereby greatly simplifying the application of license conditions for nuclear criticality safety control. This approach was used by an NRC licensee at the Barnwell waste burial facility by limiting the specific controls to the fewest number of parameters consistent with good nuclear safety practice. The use of a surface-density criteria can eliminate the need for numerous license amendments for variations in package contents and specifications.

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)

criticality safety  
low-level waste

13. AVAILABILITY STATEMENT

Unlimited

14. SECURITY CLASSIFICATION

(This Page)

Unclassified

(This Report)

Unclassified

15. NUMBER OF PAGES

16. PRICE