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A Criticality Indicator System for Storage of Fissile Materials

J. T. Thomas

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J. T. Thomas

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index. A factor of 4 is due simply to the difference in normalization.

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PREFACE

The Laboratory Director's Criticality Review Committee recognizes the advantages of providing a systematic method for controlling the potential for criticality in the handling of fissionable materials at the Oak Ridge National Laboratory. The system described herein provides a basis for the establishment of a method.

Calculation of Criticality Indicator numbers for volumes other than those listed may be effected by means of the relation

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ABSTRACT

Experimental and calculated criticality data for neutron-coupled subcritical components in reflected arrays are used as bases to formulate a system for nuclear criticality safety control in the storage of fissile materials. A criticality indexing method is described and is applied to 46 different forms of fissile materials for storage in concrete reflected arrays.

INTRODUCTION

The recurring problems of nuclear criticality safety in the routine operations of receipt, storage, and transfer of fissile materials can be minimized by the design of a system which automatically assures the maintenance of a uniform minimum margin of safety in all storage operations. Any application of a general rule for safety will entail situations which may be considered as resulting in an overly conservative limitation. The advantage, however, of relieving the burden of individual analyses far outweighs this occasionally undesirable condition.

The method must be simple, easy to apply, and have low probability of common errors leading to unwanted situations. The following model is based upon the criticality of air-spaced subcritical spherical units of fissile materials in concrete reflected arrays. Safety factors are applied to assure that the neutron multiplication factor in any storage arrangement will not exceed a k_{eff} of 0.90. The simplicity of application

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*Computing Applications Department, Computer Sciences Division.

is manifested by the minimal amount of information required; namely, the identity of the fissile material and its hydrogen moderator content, the mass of the unit, and the volume of the container. This information is sufficient to assign a unique Criticality Indicator (CI) number to the package or cell volume within a storage array and; thus, a minimal margin of safety to the storage area by limiting the total number of criticality indicators in any one storage location, to the sum of indicators that achieves a desired k_{eff} less than unity. Any smaller total number of indicators increases the margin of safety.

Theory

The criticality of air-spaced subcritical units of fissile materials arranged in cubic arrays and reflected by water has been correlated with critical experiments and with Monte Carlo calculations. The results of a study[1] of critical arrays have determined the following relationship between the mass, m, of fissile material as a unit, the center spacing, $2a_n$, of the units and the number, N, of units in the reflected array

$$\sigma(m) = \frac{nm}{(2a_n)^2}(1 - c/\sqrt{N})^2, \quad (g\text{-}cm^{-2}) \qquad (1)$$

and

$$\sigma(m) = c_2(m_o - m) \quad (g\text{-}cm^{-2}) \qquad (2)$$

where $\sigma(m)$ is a limiting surface density, c_2 is a characteristic slope of the relation between $\sigma(m)$ and m, m_o is the unreflected critical mass of the fissile material in the unit geometry, n is $N^{1/3}$, and $c = 0.55$ is a constant, characteristic of arrays.

For the same array, the unit masses of two different fissile materials satisfy the relation

$$c_2\left(\frac{m_o}{m} - 1\right) = c_2'\left(\frac{m_o'}{m'} - 1\right) \qquad (3)$$

where the primes distinguish the materials. The equation defines equivalent masses maintaining criticality in the reflected array, or maintaining a specified array k_{eff}.

The neutron multiplication factor, k_{eff}, of an array with units of mass m^* is given by

$$k_{eff} \simeq \left(\frac{m^*}{m}\right)^{1/3} \qquad (4)$$

where the mass, m, necessary for criticality satisfies Eq. (1). Any desired margin of safety may be applied to storage arrays by an appropriate reduction in the mass.

The constant c_2 is a function of the type of fissile material, the unit shape, the array shape, and the array reflector material. Each of these may be related to the array neutron multiplication factor, thus providing a measure of the influence of each on the margin of safety. Presented in Table 1 are values of c_2 determined for 46 different fissile material compositions. Also given in the table are the values of the unreflected spherical critical mass calculated by the KENO code. The m_o and c_2 values were calculated using the Hansen-Roach[2] sixteen group neutron cross section sets. Other materials of interest would require definition of the characteristic constants by calculation.

Table 1. Unreflected Spherical Critical Masses and Array Characteristic Constants for Some Fissile Materials in Water Reflected Arrays

No.	Material	Atomic Ratio[a] H/U or H/Pu	Spherical Unreflected Critical Mass[a] kg	Characteristic Constant for Criticality of Water Reflected Arrays (cm^{-2}) c_2	±
1	Metal, U(100)	0	45.68	1.806-3	0.036-3
2	Metal, U(93.2)	0	52.10	1.762-3	0.017-3
3	Oxide, U(93.2)O_2	0.4	90.24	0.854-3	0.007-3
4		3.0	63.59	0.758-3	0.008-3
5		10.0	31.43	0.778-3	0.007-3
6		20.0	17.34	0.805-3	0.004-3
7	Metal, U(80)	0	69.89	1.359-3	0.012-3
8	Oxide, U(80)O_2	0.4	111.36	0.780-3	0.006-3
9		3.0	74.08	0.713-3	0.006-3
10		10.0	36.16	0.725-3	0.006-3
11		20.0	18.67	0.779-3	0.005-3
12	Metal, U(70)	0	89.16	1.192-3	0.018-3
13	Oxide, U(70)O_2	0.4	133.39	0.723-3	0.006-3
14		3.0	83.44	0.686-3	0.006-3
15		10.0	36.89	0.735-3	0.004-3
16		20.0	19.30	0.793-3	0.004-3
17	Metal, U(50)	0	159.60	0.901-3	0.008-3
18	Oxide, U(50)O_2	0.4	207.73	0.589-3	0.005-3
19		3.0	112.82	0.594-3	0.004-3
20		10.0	55.14	0.520-3	0.006-3
21		20.0	21.48	0.777-3	0.005-3
22	Metal, U(40)	0	228.06	0.787-3	0.016-3
23	Metal, U(30)	0	379.70	0.589-3	0.007-3
24	Oxide, U(30)O_2	0.4	409.60	0.450-3	0.003-3
25		3.0	150.01	0.603-3	0.005-3
26		10.0	54.01	0.636-3	0.004-3
27		20.0	25.15	0.744-3	0.005-3
28	Metal, Pu(100)	0	9.95	4.346-3	0.112-3
29	Oxide, Pu(100)O_2	0.4	26.66	1.542-3	0.015-3
30		3.0	28.65	1.113-3	0.010-3
31		10.0	20.21	0.965-3	0.007-3
32		20.0	14.05	0.885-3	0.008-3
33	Metal, Pu(94.8)	0	10.34	4.138-3	0.091-3
34	Oxide, Pu(94.8)O_2	0.4	27.93	1.561-3	0.013-3
35		3.0	32.78	1.097-3	0.011-3
36		10.0	28.74	0.817-3	0.007-3
37	Metal, Pu(80)	0	11.69	4.261-3	0.099-3
38	Oxide, Pu(80)O_2	0.4	32.14	1.529-3	0.023-3
39		3.0	42.43	1.022-3	0.013-3
40		10.0	47.81	0.679-3	0.005-3
41	Metal, U-233	0	15.75	2.751-3	0.022-3
42	Oxide, $^{233}UO_2$	0.4	34.46	1.199-3	0.008-3
43		3.0	31.69	0.939-3	0.008-3
44		10.0	17.64	0.907-3	0.010-3
45		20.0	10.28	0.947-3	0.009-3
46	Metal U(93.2)-10 w/o Mo	0	73.06	1.305-3	0.009-3

[a]Total uranium or total plutonium.

Basis for System

A general safe mass limit for units in storage arrays is based upon the spherical shape, thereby providing limits applicable to other shapes. Given the volume of a fissile material container, package, or the cell volume a unit will occupy in the storage array and the mass fissile material, the problem is to assign a criticality indicator to the cell or package such that a storage area can be expected not to exceed a predetermined neutron multiplication factor when the allowed number of criticality indicators are present.

The development of an applicable formula to directly provide the assignment of CI to a package begins with the criticality relation. A simplifying approximation is made and its influence on the array k_{eff} examined. Next, the replacement of the water reflector about the array by concrete is described. A margin of safety, expressed in terms of k_{eff}, is introduced to complete the required equation for acceptable numbers of packages. Finally, the assignment of criticality indicators is described and a proposed system presented.

The number of units for criticality is given by a combination of Eqs. (1) and (2) as

$$N(1 - c/\sqrt{N})^6 = \left\{c_2\left(\frac{m_o}{m} - 1\right)\right\}^3 V^2 \ , \qquad (5)$$

where V is the cell volume $(2a_n)^3$. The factor $(1 - c/\sqrt{N})^6$ may be suppressed resulting in a conservative value for N, i.e., estimate N by N' as

$$N' = \left\{c_2\left(\frac{m_o}{m} - 1\right)\right\}^3 V^2 = N(1 - c/\sqrt{N})^6 < N \ . \qquad (6)$$

The influence of this approximation on the k_{eff} of the array is given by the relation

$$k_{eff}^3 = \frac{m}{m_o} + \left(\frac{N}{N'}\right)^{2/3} \left[\frac{\sqrt{N'} - c}{\sqrt{N} - c}\right]^2 \left(1 - \frac{m}{m_o}\right) ,$$

where primes denote the reduced N values and m is the mass for criticality in the N-unit reflected array. The reduction in k_{eff} is dependent upon the unit mass. Typical results for m/m_o equal to 0.1 and 0.8 are given in Table 2. The loss in k_{eff} is greatest for small m and provides a reasonable additional margin of safety for the more strongly neutron coupled systems of units with low mass values.

Table 2. Resulting Array k_{eff} When N is Reduced to N' Units[a] in a Reflected Cubic Array

N	N'	m/m_o = 0.1	m/m_o = 0.8
64	41.7	0.948	0.989
216	171.8	0.965	0.994
512	441.0	0.984	0.996
1000	900.1	0.989	0.997
2500	2339.5	0.993	0.998

a) $N(1 - c/\sqrt{N})^6 = N'$

Consideration of replacing the water reflector by a concrete reflector may be conservatively accomplished by the equivalence relation utilizing the characteristic constants for concrete. The constants $c_2 \equiv c_c(t)$ have been evaluated for U(93.2) metal with various concrete thicknesses and the ratios $c_c(t)/c_w$ for U(93.2) have been shown to be applicable to other fissile materials.[3] Substitution of the expression

$$\frac{c_c(t)}{c_w}\left(\frac{m_o}{m} - 1\right) \text{ for } \left(\frac{m_o}{m} - 1\right) ,$$

where c_w is c_2 for a water reflector, into the criticality relation (5) leads to

$$N' = \left\{c_2 \frac{c_c(t)}{c_w}\left(\frac{m_o}{m} - 1\right)\right\}^3 V^2 .$$

The final relation to the specification of the number of allowed packages, N(k), utilizes Eq. (4) to eliminate the need to determine the mass necessary for criticality and assures the same minimum margin of safety is used in all assignments of the CI. The general relation to be used for a mass m in a cell volume, V, is thus

$$N(k) = \left\{c_2 \frac{c_c(t)}{c_w}\left(k^3 \frac{m_o}{m} - 1\right)\right\}^3 V^2 . \quad (7)$$

The CI for each unit will be defined as

$$\rightarrow \quad CI = \frac{1000}{N(k)} \quad (8)$$

where N(k) is the number of units in a reflected cubic array corresponding to a chosen k_{eff}. The total of 1000 indicators, therefore, represents a limit for any storage area.

There is no undue penalty in establishing the CI as applicable to concrete reflection 16 inches in thickness. With this assumption, $c_c(16) = 1.085 \times 10^{-3}\ cm^{-2}$, $c_w = 1.762 \times 10^{-3}\ cm^{-2}$, and taking $k = 0.9$, i.e., a 0.1 margin of safety in k,

$$N(0.9) = \frac{1}{11}\left\{c_2\left(\frac{m_o}{m} - 1.37\right)\right\}^3 V^2 . \quad (9)$$

The expression should be limited in the cell volume to which it may be applied. Storage arrangements based upon Eq. (9) satisfy the requirements of the ANSI Standard[4] N16.5 (1975). The assignment of CI under this system permits the intermixing of packages of different fissile materials.

Example of Relations

Consider a 56.8 liter package (15 gal.). Suppose it contained 2.0 kg U-233 as a dry oxide (H/U less than 0.4). The CI would be assigned in the following manner. From Table 1, U-233 at an H/U of 0.4 has m_o = 34.46 kg U and $c_2 = 1.199 \times 10^{-3}\ cm^{-2}$; therefore,

$$N(0.9) = \frac{1}{11}\left\{1.199 \times 10^{-3}\left(\frac{34.46}{2} - 1.37\right)\right\}^3 (56.8 \times 10^3)^2$$

and

$$N(0.9) = 2017$$

with

$$CI = \frac{1000}{2017} = 0.5 \ .$$

Suppose it were desired to use the package with the same CI for another material, say $U(30)O_2$ with $3 < H/U < 10$, what mass of U(30) may be placed in the package? The constants for $U(30)O_2$ from Table 1 are

$$c_2 = 0.636 \times 10^{-3}\ cm^{-2}$$

and

$$m_o = 54.01\ kg\ U(30) \ .$$

Substituting into Eq. (3), one has

$$0.636\left(\frac{54.01}{m'} - 1\right) = 1.199\left(\frac{34.46}{2} - 1\right)$$

and

$$m' = 1.71 \text{ kg U(30)} .$$

Relationship Between Criticality Indicator and Transport Index

The Code of Federal Regulations requires that a Transport Index (TI) be assigned to packages to control the accumulation of packages during shipment. A 50-unit rule is employed to limit the number of packages; i.e., the sum of Transport Indices in a shipment or temporary storage location should not exceed 50. The TI is determined by requiring that five times the number allowed, N_A, in a shipment arranged in a water reflected cubic array be subcritical, and by assigning the index using the relation,

$$TI = \frac{50}{1/5\ N_A} = \frac{250}{N_A} .$$

The evaluation of effects of packaging materials leads, in general, to larger N_A or could result in a significant increase in mass over that based upon air-spaced units in water reflected arrays.

A comparison of CI with TI depends upon a number of factors:

1) Normalizing quantity used,

2) Margin of safety employed,

3) Reflector material,

4) Volume of package, and

5) Mass of units.

The normalization quantity is for convenience and is chosen to distinguish the two systems.

The margin of safety is specific in the case of CI assuring no storage array will exceed a defined k_{eff}. In the case of TI, however, only arbitrary subcriticality is required and is satisfied by any demonstrated value of k_{eff} less than unity. Neglecting the effects of packaging materials, the margin of safety inherent in the factor of 5 is clearly dependent upon the mass of the unit and may be estimated by the expression that produced Table 2. For example, an m/m_o of 0.8 would result in a Δk of approximately -0.02 for N_A, while an m/m_o of 0.1 gives -0.18 for Δk. The reflector condition, the volume of the package, and the mass of the units directly affect the number of units for criticality and hence the assignments of CI and TI.

It is clear that a non-uniform margin of safety exists in transportation because of arbitrary subcriticality. A direct comparison of CI and TI is almost without meaning. Ignoring the effects of packaging on the neutron multiplication factor, Eq. (6) could be used to determine the N_A to be used in the assignment of TI, since its application results in subcriticality as substantiated by Table 2. Set

$$5N_A = N' = \left\{c_2\left(\frac{m_o}{m} - 1\right)\right\}^3 V^2$$

and with

$$N(0.9) = \frac{1}{11}\left\{c_2\left(\frac{m_o}{m} - 1.37\right)\right\}^3 V^2$$

make a comparison with, say, $m_o/m = 3$ for the same volume package. Then

$$\frac{CI}{TI} = \frac{1000}{250}\,\frac{N_A}{N(0.9)} = 4\left(\frac{2}{1.63}\right)^3 11 = 81 \ .$$

The criticality indicator is, thus, 81 times larger than the transport index. A factor of 4 is due simply to the difference in normalization. There is a factor of $4.3 = (c_w/c_c)^3$ due to the difference in reflector condition. Finally, there is the difference in the assured margin of safety, since the N(k) results in a negative k of at least 0.1 while the $5N_A$ may have a negligible amount. This factor also is dependent on the mass of the unit. The combined effect of m and k gives a factor of about 4.7. As an illustration of the mass influence, were the ratio m_o/m taken as 4 instead of 3, the factor would be about 3.6.

Margin of Safety

In addition to the prescribed margin of safety ($\Delta k_{eff} = -0.1$) suggested, there are other considerations in any practical storage operations which inherently will provide a greater margin. Some of these are

- Non-spherical shape of fissile materials typically handled.
- Utilization of package volume for the evaluation of CI rather than the actual space the package will occupy in a storage arrangement.
- Arrangements of packages in other than cubic arrays and presence of aisles.
- Possible presence of thermal insulation and other packaging materials containing the fissile materials.
- The walls and ceilings of storage areas only approximate a close-fitting reflector about the storage arrangement.

The contribution to Δk_{eff} of each of these could be evaluated for particular situations. The changing situation in operations, however, make it preferable to regard these as additional assurance the minimum margin will not be breached.

A Criticality Indicator System

A Criticality Indicator number for various cell sizes may be assigned to any fissile material listed in Table 1 or others for which m_0 and c_2 are known. Eq. (9) with the adoption of the normalizing quantity of 1000 may be directly applied. There are inherent advantages, however, to tabular values which may be used directly as needs dictate.

Definition of equivalent masses for the materials of Table 1 is made in Table 3. The heading of each column of Table 3 identifies the fissile material. Listed in each column are mass values of the fissile material beginning initially with a value equivalent to 4 kg U(93.2) and increasing in steps equivalent to 1.0 kg U(93.2). Any row of the table identifies equivalent mass units of the different materials any of which in the same package would have the same CI. The mass of fissile material in the package of concern is identified in the table by the alphabetic key at the margins. If the mass is a value between two table entries, the larger mass value is used.

Table 4 assigns the Criticality Indicator to the package. Each column represents the volume of a package beginning with 18.9 liters (5 gals) and increasing in steps of 18.9 liters. The rows of Table 3 correspond to the alphabetic key of Table 3. The mass and volume of the packages represent then the rows and columns of the table, respectively. The intersection of each row and column gives the CI to be assigned the package.

Calculation of Criticality Indicator numbers for volumes other than those listed may be effected by means of the relation

$$CI(X) = CI(0) \left(\frac{V(0)}{V(X)}\right)^2$$

where CI(0) and V(0) are any corresponding pair of values for an alphabetic key determined for the fissile material.

The Criticality Indicator shall not be applied to volumes less than 16 liters nor to containers of extreme shape, i.e., containers having an aspect ratio greater than 3.

The sum of the CI for any storage area or vault shall not exceed 1000. The assigned CI should be no greater than 50 or less than 0.1 for a single package.

All other fissionable materials or storage conditions should be referred to the Criticality Review Committee.

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Table 3. Mass in Kilograms of Total Uranium or Total Plutonium Contained in Package or Storage Cell

Material	U(100)	U(93.2)	$U(93.2)O_2$				U(80)	$U(80)O_2$				U(70)	
H/U or H/Pu	0	0	0.4	3	10	20	0	0.4	3	10	20	0	
A	3.6	4.0	3.5	2.2	1.1	0.6	4.2	4.0	2.4	1.2	0.7	4.7	A
B	4.5	5.0	4.4	2.8	1.4	0.8	5.3	5.0	3.1	1.5	0.8	6.0	B
C	5.4	6.0	5.4	3.4	1.7	1.0	6.4	6.1	3.7	1.8	1.0	7.2	C
D	6.3	7.0	6.3	4.0	2.0	1.1	7.5	7.2	4.4	2.1	1.2	8.5	D
E	7.2	8.0	7.3	4.6	2.3	1.3	8.6	8.3	5.1	2.4	1.4	9.7	E
F	8.1	9.0	8.3	5.2	2.7	1.5	9.7	9.4	5.8	2.8	1.6	11.0	F
G	8.9	10.0	9.3	5.9	3.0	1.7	10.8	10.6	6.5	3.1	1.8	12.3	G
H	9.8	11.0	10.4	6.6	3.3	1.9	12.0	11.8	7.2	3.5	2.0	13.7	H
I	10.7	12.0	11.4	7.3	3.7	2.1	13.1	13.0	8.0	3.9	2.2	15.0	I
J	11.6	13.0	12.5	8.0	4.0	2.3	14.3	14.3	8.8	4.2	2.4	16.4	J
K	12.5	14.0	13.6	8.7	4.4	2.5	15.4	15.6	9.6	4.6	2.6	17.8	K
L	13.4	15.0	14.8	9.4	4.8	2.7	16.6	16.9	10.4	5.0	2.8	19.1	L
M	14.3	16.0	16.0	10.2	5.1	2.9	17.8	18.3	11.3	5.4	3.1	20.6	M
N	15.2	17.0	17.2	11.0	5.5	3.1	19.0	19.7	12.1	5.8	3.3	22.0	N
O	16.0	18.0	18.4	11.8	5.9	3.4	20.2	21.1	13.0	6.3	3.5	23.5	O
P	16.9	19.0	19.6	12.6	6.4	3.6	21.4	22.6	14.0	6.7	3.8	24.9	P
Q	17.8	20.0	20.9	13.4	6.8	3.8	22.7	24.1	14.9	7.2	4.1	26.4	Q
R	18.7	21.0	22.3	14.3	7.2	4.1	23.9	25.6	15.9	7.6	4.3	28.0	R
S	19.6	22.0	23.6	15.2	7.7	4.3	25.2	27.2	16.9	8.1	4.6	29.5	S

Table 3 (continued)

2

Material	$U(70)O_2$				U(50)	$U(50)O_2$				U(40)	U(30)	$U(30)O_2$	
H/U or H/Pu	0.4	3.0	10.0	20.0	0	0.4	3.0	10.0	20.0	0	0	0.4	
A	4.4	2.6	1.2	0.7	6.5	5.6	3.1	1.3	0.8	8.2	10.3	8.5	A
B	5.6	3.3	1.6	0.9	8.2	7.1	3.9	1.7	1.0	10.3	13.0	10.8	B
C	6.8	4.0	1.9	1.1	10.0	8.7	4.7	2.0	1.2	12.5	15.8	13.2	C
D	8.0	4.6	2.2	1.3	11.7	10.2	5.6	2.4	1.4	14.8	18.7	15.6	D
E	9.2	5.5	2.6	1.5	13.5	11.9	6.5	2.8	1.6	17.1	21.7	18.1	E
F	10.5	6.3	3.0	1.7	15.4	13.6	7.4	3.2	1.8	19.5	24.8	20.7	F
G	11.8	7.1	3.3	1.9	17.3	15.3	8.4	3.6	2.0	21.9	27.9	23.4	G
H	13.2	7.9	3.7	2.1	19.2	17.1	9.3	4.0	2.3	24.4	31.2	26.2	H
I	14.6	8.7	4.1	2.3	21.2	18.9	10.3	4.5	2.5	26.9	34.5	29.1	I
J	16.0	9.6	4.5	2.5	23.2	20.8	11.4	4.9	2.7	29.5	38.0	32.1	J
K	17.5	10.4	4.9	2.7	25.2	22.7	12.4	5.4	3.0	32.2	41.5	35.1	K
L	19.0	11.3	5.3	3.0	27.3	24.7	13.5	5.9	3.3	34.9	45.2	38.3	L
M	20.5	12.3	5.8	3.2	29.5	26.8	14.7	6.4	3.5	37.7	49.0	41.6	M
N	22.1	13.2	6.2	3.5	31.7	28.9	15.8	6.9	3.8	40.6	52.9	45.1	N
O	23.7	14.2	6.7	3.7	33.9	31.2	17.0	7.4	4.1	43.5	57.0	48.7	O
P	25.4	15.2	7.1	4.0	36.2	33.4	18.3	8.0	4.3	46.5	61.1	52.4	P
Q	27.2	16.3	7.6	4.2	38.6	35.8	19.6	8.6	4.6	49.6	65.4	56.2	Q
R	28.9	17.4	8.1	4.5	41.0	38.3	20.9	9.2	4.9	52.8	69.9	60.2	R
S	30.8	18.5	8.6	4.8	43.4	40.8	22.3	9.8	5.2	56.1	74.6	64.4	S

Table 3 (continued)
3

Material	$U(30)O_2$			Pu(100)	$Pu(100)O_2$				Pu(94.8)	$Pu(94.8)O_2$			
H/U or H/Pu	3.0	10.0	20.0	0	0.4	3.0	10.0	20.0	0	0.4	3.0	10.0	
A	4.2	1.6	0.9	1.7	1.8	1.4	0.9	0.6	1.7	1.9	1.6	1.1	A
B	5.3	2.0	1.1	2.1	2.3	1.8	1.1	0.7	2.1	2.4	2.0	1.3	B
C	6.4	2.4	1.3	2.4	2.7	2.2	1.3	0.9	2.4	2.9	2.5	1.6	C
D	7.6	2.9	1.5	2.8	3.2	2.6	1.6	1.0	2.8	3.4	2.9	1.9	D
E	8.8	3.3	1.8	3.1	3.7	2.9	1.8	1.2	3.1	3.9	3.3	2.2	E
F	10.0	3.8	2.0	3.4	4.1	3.3	2.1	1.3	3.4	4.4	3.8	2.5	F
G	11.3	4.3	2.3	3.7	4.6	3.7	2.3	1.5	3.7	4.9	4.2	2.9	G
H	12.6	4.8	2.6	4.0	5.1	4.1	2.6	1.7	4.0	5.4	4.7	3.2	H
I	13.9	5.3	2.8	4.2	5.5	4.6	2.8	1.8	4.3	5.9	5.1	3.5	I
J	15.3	5.8	3.1	4.5	6.0	5.0	3.1	2.0	4.5	6.4	5.6	3.8	J
K	16.8	6.3	3.4	4.7	6.5	5.4	3.4	2.2	4.8	6.9	6.1	4.2	K
L	18.2	6.9	3.7	5.0	7.0	5.8	3.7	2.4	5.0	7.4	6.6	4.5	L
M	19.8	7.4	4.0	5.2	7.5	6.3	3.9	2.6	5.3	7.9	7.1	4.9	M
N	21.3	8.0	4.3	5.4	7.9	6.7	4.2	2.7	5.5	8.4	7.6	5.3	N
O	23.0	8.6	4.6	5.6	8.4	7.2	4.5	2.9	5.7	8.9	8.1	5.7	O
P	24.6	9.3	4.9	5.8	8.9	7.6	4.8	3.1	5.9	9.4	8.6	6.0	P
Q	26.4	9.9	5.2	6.0	9.4	8.1	5.1	3.3	6.1	9.9	9.2	6.4	Q
R	28.2	10.6	5.6	6.2	9.9	8.6	5.5	3.6	6.3	10.5	9.7	6.9	R
S	30.0	11.3	5.9	6.4	10.4	9.0	5.8	3.8	6.5	11.0	10.3	7.3	S

Table 3 (continued)

4

Material H/U or H/Pu	Pu(80) 0	Pu(80)O_2 0.4	Pu(80)O_2 3.0	Pu(80)O_2 10.0	U-233 0	U-233O_2 0.4	U-233O_2 3.0	U-233O_2 10.0	U-233O_2 20.0	U(93.2) + 10 U/O M_o 0	
A	2.0	2.2	2.0	1.5	1.2	1.8	1.3	0.7	0.4	4.2	A
B	2.4	2.7	2.5	1.9	2.2	2.3	1.7	0.9	0.6	5.3	B
C	2.8	3.3	3.0	2.3	2.7	2.9	2.1	1.1	0.7	6.4	C
D	3.2	3.8	3.5	2.7	3.1	3.3	2.4	1.3	0.8	7.5	D
E	3.6	4.4	4.0	3.1	3.5	3.8	2.8	1.5	0.9	8.7	E
F	3.9	4.9	4.6	3.6	3.9	4.3	3.2	1.7	1.0	9.8	F
G	4.3	5.5	5.1	4.0	4.3	4.8	3.6	1.9	1.2	10.9	G
H	4.6	6.1	5.7	4.5	4.6	5.3	4.0	2.1	1.3	12.1	H
I	4.9	6.6	6.3	4.9	5.0	5.8	4.4	2.4	1.4	13.3	I
J	5.2	7.2	6.9	5.4	5.4	6.4	4.8	2.6	1.6	14.4	J
K	5.5	7.8	7.5	5.9	5.7	6.9	5.2	2.8	1.7	15.6	K
L	5.8	8.3	8.1	6.4	6.1	7.4	5.6	3.0	1.8	16.8	L
M	6.0	8.9	8.7	7.0	6.4	8.0	6.1	3 3	2.0	18.1	M
N	6.3	9.5	9.3	7.5	6.8	8.5	6.5	3.5	2.1	19.3	N
O	6.6	10.1	9.9	8.1	7.1	9.1	7.0	3.9	2.3	20.5	O
P	6.8	10.7	10.6	8.7	7.4	9.7	7.4	4.0	2.4	21.8	P
Q	7.0	11.3	11.3	9.2	7.8	10.3	7.9	4.3	2.6	23.1	Q
R	7.3	11.9	11.9	9.9	8.1	10.8	8.4	4.5	2.7	24.4	R
S	7.5	12.5	12.6	10.5	8.4	11.4	8.9	4.8	2.9	25.7	S

Table 4. Criticality Indicator Corresponding to the Volume of a Storage Cell or Package and the Contained Mass

Criticality Indicator (CI)

Gallons -	5.0	10.0	15.0	20.0	25.0	30.0	
Liters -	18.9	37.9	56.8	75.7	94.6	113.6	
A	3.5	0.9	0.4	0.2	0.1	0.1	A
B	7.6	1.9	0.8	0.5	0.3	0.2	B
C	14.4	3.6	1.6	0.9	0.6	0.4	C
D	25.1	6.3	2.8	1.6	1.0	0.7	D
E	41.3	10.3	4.6	2.6	1.7	1.1	E
F		16.3	7.2	4.1	2.6	1.8	F
G		24.8	11.0	6.2	4.0	2.8	G
H		36.8	16.3	9.2	5.9	4.1	H
I			23.8	13.4	8.6	5.9	I
J			34.0	19.1	12.2	8.5	J
K			48.0	27.0	17.3	12.0	K
L				37.7	24.1	16.8	L
M					33.5	23.2	M
N					46.1	32.0	N
O						44.0	O
P							P
Q							Q
R							R
S							S

Gallons -	35.0	40.0	45.0	50.0	55.0	60.0	
Liters -	132.5	151.4	170.3	189.3	208.2	227.1	
A	0.1	0.1	0.1	0.1	0.1	0.1	A
B	0.2	0.1	0.1	0.1	0.1	0.1	B
C	0.3	0.2	0.2	0.1	0.1	0.1	C
D	0.5	0.4	0.3	0.3	0.2	0.2	D
E	0.8	0.6	0.5	0.4	0.3	0.3	E
F	1.3	1.0	0.6	0.7	0.5	0.5	F
G	2.0	1.5	1.2	1.0	0.8	0.7	G
H	3.0	2.3	1.8	1.5	1.2	1.0	H
I	4.4	3.3	2.6	2.1	1.8	1.5	I
J	6.2	4.8	3.8	3.1	2.5	2.1	J
K	8.8	6.7	5.3	4.3	3.6	3.0	K
L	12.3	9.4	7.4	6.0	5.0	4.2	L
M	17.1	13.1	10.3	8.4	6.9	5.8	M
N	23.5	18.0	14.2	11.5	9.5	8.0	N
O	32.3	24.8	19.6	15.8	13.1	11.0	O
P	44.3	34.0	26.8	21.7	18.0	15.1	P
Q		46.6	36.8	29.8	24.6	20.7	Q
R				40.9	33.8	28.4	R
S					46.6	39.2	S