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MODELS FOR THE SAFE STORAGE OF
FISSILE METAL

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Prepared under Contract AT(29-1)-1106
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Albuquerque Operations Office
U. S. Atomic Energy Commission

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MODELS FOR THE SAFE STORAGE OF FISSILE METAL

Sidney J. Altschuler and C. Lee Schuske

Abstract. Two models are described for calculating critically safe storage configurations for uranium (93.4 percent uranium 235) and plutonium (96 percent plutonium 239, 4 percent plutonium 240) metal. The first model deals with conventional arrays in air of fissile units surrounded by concrete walls. The model uses the concepts of surface density and unit surface-to-volume ratio to define safe-array parameters.

The second model makes use of thick internal moderators (i.e., water), enclosing each storage unit in an array. These arrays are also surrounded by concrete walls. The internal moderators partially isolate adjacent storage units from one another and thus, in some cases, permit extremely high surface densities and vault loading. A discussion of the models is preceded by a calculational analysis of many factors that influence the models, such as the shape and density of the unit and the degree of reflection of arrays of units.

Given also are examples to illustrate the effective use of the models.

DEFINITIONS

Loading. The loading is the total mass of fissile metal which can be safely stored in a vault. It equals the product of the usable area and the surface density. For mixtures of material of different sizes, shapes, and compositions, the loading equals the sum of the products of the safe surface density for each type of material and the usable area occupied.

Usable Area. Includes the largest surface area, whether wall or floor, of the rectangular parallelepiped constituting the storage facility minus corrections to allow for aisle space.

Surface Density. Refers to the mass of an array of units divided by the area over which distributed (units are kilograms per square foot).

Surface-to-Volume Ratio. Defined as the quotient of the unit surface area and its fissile volume.

Surface. Refers to the surface of a single unit from which neutrons may escape the unit. It is the smallest surface area which encloses the unit. This does not include reentrant surfaces, such as holes.

Volume. The volume is the space occupied by the mass of fissile metal in a single unit when calculated at maximum theoretical density (18.7 grams per cubic centimeter for enriched uranium and 19.7 grams per cubic centimeter for plutonium).

INTRODUCTION

Methods are needed for determining critically safe storage arrays for fissile metal. The methods should be simple and applicable to the wide variety of unit shapes that occur in practice. The methods described herein closely satisfy both requirements.

The first method involves correlating the surface density of the array, defined as the mass of fissile material per unit floor area, with the surface-to-volume ratio of the individual units in the array. The correlation of the surface density with surface-to-volume ratios dates to about 1957 from earlier work (unpublished) done by C. Lee Schuske. Figure 1 contains the original experimental data. Since 1957, several authors have explored this method.^{1,2,3} The current report significantly advances the previous work and provides guidance for use of the first method.

The second method makes use of water as an internal moderator to partially isolate adjacent units in the storage arrays. Much higher surface densities can be developed for storage structures of this type.

¹H. C. Paxton. *Correlations of Experimental and Theoretical Critical Data*. LAMS-2537. May 15, 1961. Page 11; and———. *Criticality Control in Operations with Fissile Material*. LA-3366. Los Alamos Scientific Laboratory, Los Alamos, New Mexico. January 15, 1966. Page 39.

²T. Gutman. "A Surface-Density Evaluation of Critical Array Data." *Nuclear Applications*, 2:121. 1968.

³R. L. Stevenson and R. H. Odegarden. "Studies of Surface Density Spacing Criteria Using KENO Calculations." *Transactions of the American Nuclear Society*, 12:890. November 30, 1969.

FIGURE 1. Original Experimental Data of Critical Surface Density and Unit Surface-to-Volume Ratio.

In addition to the discussion of the storage models and examples, presented also is a comparison of the calculational method used in deriving these models with pertinent experimental arrays. A calculational study follows of the factors, such as unit shapes and densities and array reflection, that influence the storage models.

Because of the requirements for fire protection, the discussion relates also to effects on the neutron multiplication factor (k_{eff}) of water sprays.

DESCRIPTION OF CALCULATIONS AND RESULTS

A series of KENO⁴ calculations has been made to supplement the existent experimental data.^{5,6,7} The cross sections used were the Hansen-Roach B set,⁸ with the exception of calcium and silicon which were obtained from G. E. Whitesides of Oak Ridge. All nuclides except hydrogen were treated as isotropic scatterers. The plutonium used in all calculations for the storage models was 96 percent plutonium 239 (²³⁹Pu) and 4 percent plutonium 240 (²⁴⁰Pu) with unit densities ranging from 4.43 to 19.7 grams per cubic

centimeter (g/cm³). The enriched uranium was 93.4 percent ²³⁵U and 6.6 percent ²³⁸U with densities from 5.46 to 18.7 g/cm³. The concrete composition used in these calculations was 02-A given in the handbook, *Reactor Physics Constants*.⁹

The calculations data are presented in five basic parts. The first part is a comparison between KENO results and experimental data. The comparisons are

⁴G. E. Whitesides and N. F. Cross. *KENO, A Multigroup Monte Carlo Criticality Program*. CTC-5. Computing Technology Center Nuclear Division, Union Carbide Corporation, Oak Ridge, Tennessee. September 10, 1969.

⁵H. F. Finn and N. L. Pruvost. "Livermore Plutonium Array Program." *Proceedings of the Livermore Array Symposium*. CONF-680909. Lawrence Radiation Laboratory, Livermore, California. September 23-25, 1960.

⁶C. L. Schuske, C. L. Bell, G. H. Bidinger, and D. F. Smith. *Industrial Criticality Measurements on Enriched Uranium and Plutonium, Part II*. RFP-248. Rocky Flats Division, The Dow Chemical Company, Golden, Colorado. January 10, 1962.

⁷J. T. Thomas. "Critical Arrays of U (93.4) Metal Cylinders." ORNL-3499. *Neutron Physics Division Annual Progress Report*, 158-62. Oak Ridge National Laboratory, Oak Ridge, Tennessee. December 10, 1963.

⁸*Reactor Physics Constants*. Second Edition. ANL-5800. Argonne National Laboratory, Argonne, Illinois. 1963. Pages, 558-576.

⁹*Ibid.* Pages 659-660.

TABLE I. Comparison of Calculations with Experimental Results.

Number of Array Units	Description of Experiments	$k_{\text{eff}} \pm \sigma$ (KENO)	Footnote Reference
3 X 3 X 3	3-kilogram plutonium metal units	0.993 $\pm$ 0.009	5
4 X 4 X 4	3-kilogram plutonium metal units, 1.27-centimeter (cm) moderators	0.988 $\pm$ 0.009	
4 X 4 X 4	3-kilogram plutonium metal units, 2.55-cm moderators	1.019 $\pm$ 0.008	
4 X 4 X 6	2.03-kilogram plutonium metal units in steel cans on a large concrete slab	0.999 $\pm$ 0.011	6
^a 5 X 5 X 3	2.03-kilogram plutonium metal units in steel cans on a large concrete slab	0.973 $\pm$ 0.008	
^b 5 X 5 X 4	2.03-kilogram plutonium metal units in steel cans on a large concrete slab	1.037 $\pm$ 0.010	
2 X 2 X 2	~21-kilogram uranium (93.2) cylinders in 0.635-cm lucite box	1.006 $\pm$ 0.010	7
2 X 2 X 2	~21-kilogram uranium (93.2) cylinders in 1.27-cm lucite box	0.990 $\pm$ 0.008	

^aThe system was subcritical at an approximate multiplication of 40.

^bThe KENO calculation was used to bracket the critical value; the experiment indicated that this assembly would be super critical.

^cCalculations based on ~11,000 neutron histories.

given in Table I and Figures 1 and 4. The experimental data are critical data, except the 1957 material and the data given under Footnote 6.

The second part of the calculational data shows how to develop the relationship between the critical surface density, SD, and the surface-to-volume ratio, s/v , of the individual arrayed units for several variables. These variables are the shape of a stored unit, the density of the unit, and the degree of reflection of an array of units. Concrete was used as the reflector in all cases. All curves can be represented by the following empirical relationship:

$$SD = SD_0 - a \exp \left\{ -b \left[\left(\frac{s}{v} \right) - \left(\frac{s}{v} \right)_0 \right] \right\}$$

SD = critical surface density

SD₀ = surface density for an infinite slab

$\frac{s}{v}$ = surface-to-volume ratio
of individual units

a, b, $\left(\frac{s}{v} \right)_0$ = constants

The primary purpose for the curve fitting was to determine if all of the curves were of the same form and to determine if any of the parameters could be simply calculated and had physical significance. The surface density, SD₀, is for an infinite slab of the fissile material and is independent of the fissile unit shape and density. It is dependent on the degree of reflection; for example, whether the array is bare, reflected on one surface, or on both surfaces. All other constants [a, b, $(s/v)_0$] do not have simple physical significance.

The third part concerns the development of a safe-storage model for conventional arrays in air surrounded by concrete walls.

The fourth part concerns the development of a safe-storage model that assumes a water moderator which partially isolates one interacting storage unit from another.

The final part includes a discussion of special internally moderated systems, where the moderator is concrete or Plexiglas, and comparisons are made with the water-moderated systems.

CALCULATIONAL RESULTS RELATING SURFACE DENSITY AND UNIT SURFACE-TO-VOLUME RATIO

Bare Planar Arrays:

Figure 2 shows the critical surface density versus individual unit surface-to-volume ratio curves for large arrays of uranium and plutonium bare spheres and cubes. Figure 3 shows this relationship for right circular cylinders with height-to-diameter (H/D) ratios of 2, 4, and 8.

The surface-to-volume ratio at zero surface density is that for a single critical unit. It is the largest single unit of interest and has the lowest surface-to-volume ratio. Since such a unit is critical by itself, the surface density equals zero when its mass is averaged over an infinite area.

The limiting maximum surface density, for large arrays, occurs for an infinite slab. All other critical surface densities, regardless of unit shape, are less than this value. For all units, the highest value of surface density occurs when the units touch. This accounts for the abrupt ending of the curves for spheres and not for cubes.

Semireflected Planar Arrays:

Figure 4 shows the surface density versus surface-to-volume ratio relationship for semireflected arrays of plutonium and uranium spheres and cubes. These arrays are placed upon a 6-inch (15.24 centimeters) thick, 20 by 20-meter concrete slab which, in this case, is much larger than the array itself.

Also plotted in Figure 4 are the original points by C. L. Schuske which are shown in Figure 1 also. The agreement between the calculated and the experimental points for uranium pieces is good. The plutonium points were only estimates.

As the amount of reflection for each unit is increased, the size of a single critical unit will decrease. The curves will shift downward and to the right. Critical conditions will occur at lower surface densities and higher surface-to-volume ratios; i.e., smaller units separated by larger distances.

Sandwiched Planar Arrays:

Figure 5 shows the critical surface density versus surface-to-volume ratio for cubes sandwiched between

FIGURE 2. Critical Surface Density and Unit Surface-to-Volume Ratio for Unreflected, Nearly Infinite Square Lattice Arrays. (Values on curves are weights of units in kilograms.)

FIGURE 3. Critical Surface Density and Unit Surface-to-Volume Ratio of Unreflected, Nearly Infinite Square Lattice Arrays of Right Circular Cylinders. (Values on curves are weights of units in kilograms.)

FIGURE 4. Critical Surface Density and Unit Surface-to-Volume Ratio for a Nearly Infinite Square Lattice Array on a Concrete Slab. (Values on curves are weights of units in kilograms.)

two 6-inch thick concrete slabs. To minimize edge leakage, the arrays have been made large. Twenty meters was chosen as a large practical limit.

From Figures 2, 4, and 5, it appears that the curves for uranium units, particularly *cubes*, tend to be flatter above the *knee* than those for plutonium.

The Effects of Reflection on Slab Thickness:

This section was included as an observation that surface density (SD_0) (see previous section) is approximately a linear function (within 2σ) of reflection for large arrays. Previous work¹⁰ confirms this linear relationship.

Figure 6 gives the relationship between critical slab thickness and the number of slab sides reflected by concrete.

Planar Arrays in Storage Facilities:

A third and the most common storage condition would be in a vault with walls, floor, and ceiling of concrete.

¹⁰ R. E. Rothe, C. L. Schuske, and E. E. Hicks. "The Criticality of a Uranium Solution Slab under Various Reflector Conditions." *Nuclear Applications and Technology*, 7:505-512. December 1969.

This case is not realistically described by the semi-reflected or sandwiched arrays. Since the sandwiched case is an extreme one and gives conservative results, the vault size chosen was large; i.e., 20 by 20 by 3 meters. The value was selected in order to obtain some contrast with the sandwiched case. The storage facility chosen is not so large as to be totally impractical. The critical surface density versus surface-to-volume ratio relationships for this storage facility are shown in Figure 7, along with those for sandwiched cubes to allow comparison.

A series of calculations was performed to gain insight on the effect of vault height on k_{eff} . A fixed floor loading was assumed for each of the three data values given in Figure 8.

Three-Dimensional Arrays in Vaults:

A number of calculations were done to investigate the effect on k_{eff} of redistributing spherical fissile units from a critical planar array on the vault floor into three-dimensional arrays. The systems investigated were 7- and 21-kilogram (kg) uranium spheres, 4.3-kg plutonium cubes, and 0.04, 0.28, 2.23, 3.54, and 5.28-kg

FIGURE 5. Critical Surface Density and Unit Surface-to-Volume Ratio for a Nearly Infinite Square Lattice of Cubes Sandwiched between Two Concrete Slabs. (Values on curves are weights of units in kilograms.)

plutonium spheres. In approximately cubic lattices, none of these systems was more reactive than when in a planar array on the floor of the vault.

The requirement for uniform spacing in three dimensions is not a stringent one, as is shown in Table II. The lattice spacings for these arrays in the z direction will differ from those in the x or y directions by as much as 20 percent, while k_{eff} is essentially constant. Figures 9 and 10 show the variation of k_{eff} with lattice spacing in the z direction. Even when several units are stacked upon each other, k_{eff} does not exceed 1.08.

Reduced Density:

A series of calculations was performed on arrays of low density cubes. The data for the specific densities (ρ) are presented in Figure 11. The curves have the typical shapes observed in previous sections.

Water Sprinklers:

Under current consideration is the installation of water sprinkler systems as a fire control method in fissile material handling facilities.

Calculations indicate that a sprinkler flow of 100 gallons per 100 square feet per minute has a negligible effect on an array reactivity. The flow rate is approximately a factor of four higher than for a standard sprinkler.¹¹

Variation of Multiplication Factor (k_{eff}) with Vault Size:

Table III contains a brief study of k_{eff} as a function of the internal vault dimensions. The surface densities have been held constant. It can be seen, as expected, that k_{eff} decreases when dimensions are decreased from a 66.8 by 66.8 by 9.8-foot structure to a 10 by 10-foot structure.

STORAGE MODEL FOR ARRAYS IN AIR

Basic Assumptions:

The graph of the critical surface density (SD) of an array versus the surface-to-volume ratio (s/v) of an individual fissile unit has a form independent of unit

¹¹C. Yao and A. S. Kalelkar. "Effect of Drop Size on Sprinkler Performance." *Fire Technology*, 254-268. 1970

FIGURE 6. Critical Slab Thickness and Number of Reflected Sides.

shapes, degree of reflection, or unit densities. This relationship is used to develop a safe-storage model, one for plutonium and one for enriched uranium, for a variety of unit shapes, masses, and densities. Five assumptions were used:

1. A concrete storage structure with internal dimensions of 66.8 by 66.8 by 9.8-feet with one-foot thick concrete¹² walls was chosen as the maximum size that could be accommodated by the storage

¹²ANL-5800. *Loc. cit.*

FIGURE 7. Critical Surface Density and Unit Surface-to-Volume Ratio in Square Lattice Arrays. (Values on curves are weights of units in kilograms.)

FIGURE 8. Height of Vault versus k_{eff} Values. (A 20 by 20-meter by vault height with a slab of 0.8-centimeter plutonium on the floor and 6-inch thick concrete floor, walls, and ceiling.)

model. [Larger structures could be constructed using this model, if sub-divided by an isolation thickness¹³ of concrete (~ one foot) into individual adjacent structures no greater than 66.8 by 66.8 by 9.8 feet.] Any structure smaller than these dimensions would also be acceptable. See Table III for k_{eff} as a function of vault size.

2. All containers or shelving must provide positive protection against double batching. If this cannot be accomplished, reduce masses accordingly.

3. Sprinkling of storage facility with water is permitted provided the flow rate does not exceed 100 gallons per 100 square feet per minute. If more water is needed, verification calculations would be needed.

4. Finely divided or compressed metal turnings must be protected against internal moderation because of sprinkler action or other water sources.

5. All storage configurations permitted by the model are far subcritical ($k_{eff} + 4\sigma \leq 0.90$).

¹³C. L. Schuske. *Neutron Multiplication Measurements of Parallel Arrays of Orallloy Units*. RFP-59. Rocky Flats Division, The Dow Chemical Company, Golden, Colorado. February 6, 1956.

Rules Defining the Model:

1. Maximum individual cube, sphere, or equilateral cylinder masses permitted for full density are 22.0 kg for enriched uranium and 5.0 kg for plutonium.
2. The maximum permissible masses of single cubes, spheres, or equilateral cylinders of reduced density are given in Figure 12 and discussed as Item 1, following the rules (see Table IV also).
3. Any single storage unit must be subcritical when fully water-flooded. For guidance, use Equations 1 and 2 in Item 2 following the rules.
4. Maximum individual masses permitted, regardless of density, are 65 kg for enriched uranium and 30 kg for plutonium.
5. Any enriched uranium mass that exceeds 40.0 kg must not exceed a surface density of 6.0 kilograms per square foot (kg/ft^2) in a storage array. Any plutonium unit mass that exceeds 15.0 kg must not exceed a surface density of $3.0 \text{ kg}/\text{ft}^2$ in a storage array.
6. Spacing of storage positions for individual units must be selected in such a manner as to distribute units nearly uniformly throughout the structure. See Table II for guidance. A 20 percent deviation in vertical spacing from uniform spacing is permissible.

TABLE II. Variation of k_{eff} with Distance between Units.

Array Size in Storage Units	Unit Radius (R) (centimeters)	Unit Mass (M) (kilograms)	Lattice Spacing ($l_x = l_y$) (l_z) (centimeters)		$k_{\text{eff}} \pm \sigma$ (sigma)	Notes and Comments	Identifying Figure	
Uranium (93.4) Metal Spheres:								
56 X 56 X 1	6.50	21.28	36.36	—	0.999 ± 0.009	Spheres in a plane array on floor of vault	Plotted as Figure 9 (Page 10)	
28 X 28 X 4			72.72	75.0	0.995 ± 0.012	Spheres evenly spaced		
↓			↓	↓	36.4	1.010 ± 0.012		Spheres in contact
					19.0	1.036 ± 0.014		
			13.0	1.073 ± 0.012				
116 X 116 X 1	4.50	7.06	17.55	—	1.005 ± 0.009	Spheres in a plane array on floor of vault	Plotted as Figure 10 (Page 11)	
41 X 41 X 8			49.66	37.5	0.989 ± 0.013	Spheres evenly spaced		
44 X 44 X 7			46.28	42.9	1.000 ± 0.010	Spheres evenly spaced		
48 X 48 X 6			42.42	50.0	0.984 ± 0.015	Spheres evenly spaced		
↓			42.42	19.0	1.020 ± 0.015	Spheres in contact		
		42.42	9.0	1.065 ± 0.015				
Plutonium Metal Spheres and Cubes:								
1252 X 1252 X 1	0.75	0.0348	1.60	—	0.982 ± 0.014	Spheres <

FIGURE 9. Vertical Lattice Spacing versus k_{eff} Values. (Array size of 28 by 28 by 4 for 21.28-kilogram spheres of 93.4 percent uranium 235.)

TABLE III.- Variation of k_{eff} with Vault Size. (All vaults have one-foot thick concrete walls.)

Unit Diameter (D) (centimeters)	Unit Height (H) (centimeters)	Unit Mass (M) (kilograms)	Surface Density (SD) (kilograms per square foot)	Inside Vault Dimensions (feet)	k _{eff} ± σ (sigma)
Plutonium Metal:					
12.0	3.15	7.02	2.04	66.8 × 66.8 × 9.8	0.873 ± 0.009
				16.7 × 16.7 × 9.8	0.851 ± 0.008
				9.3 × 9.3 × 9.8	0.848 ± 0.007
7.05	6.5	5.00	1.01	66.8 × 66.8 × 9.8	0.842 ± 0.011
				17.8 × 17.8 × 9.8	0.857 ± 0.010
				8.9 × 8.9 × 9.8	0.842 ± 0.007
4.8	19.0	6.77	2.55	66.8 × 66.8 × 9.8	0.853 ± 0.010
				9.8 × 9.8 × 9.8	0.770 ± 0.011
Uranium (93.4) Metal:					
38.0	3.104	65.13	6.44	66.8 × 66.8 × 9.8	0.845 ± 0.012
				19.1 × 19.1 × 9.8	0.814 ± 0.008
12.3	11.3	24.8	3.20	66.8 × 66.8 × 9.8	0.867 ± 0.010
				16.7 × 16.7 × 9.8	0.859 ± 0.009
				11.1 × 11.1 × 9.8	0.846 ± 0.011
7.818	46.0	40.9	2.97	66.8 × 66.8 × 9.8	0.747 ± 0.010
				11.1 × 11.1 × 9.8	0.690 ± 0.008

FIGURE 10. Vertical Lattice Spacing versus k_{eff} Values. (Array size of 48 by 48 by 6 for 7.06-kilogram spheres of 93.4 percent of uranium 235.)

FIGURE 11. Effect of Varying the Density of Units on the Relationship between Critical Surface Density and Surface-to-Volume Ratio of Nearly Infinite Square Lattice Arrays on a Concrete Slab.

7. Plutonium and enriched uranium can be stored in the same structure provided that the different materials are approximately alternately mixed.¹⁴

8. Aisles and material transfer routes must be subtracted from the total floor area on which material can be stored because these aisles will also contain material during transfer. Total vault capacity can be maximized by minimizing aisle area.

The aisle correction is done as follows —

Step 1: Assume that all aisles extend from floor to ceiling. Calculate the volume occupied by aisles.

¹⁴ C. Lee Schuske and Donald C. Coonfield. *Mixtures of Plutonium and Enriched Uranium in Slab Geometry*. RFP-1489. Rocky Flats Division, The Dow Chemical Company, Golden, Colorado. August 10, 1971.

Step 2: Assume all storage units permitted by the model are uniformly distributed about the total vault volume.

Step 3: Subtract the number of units occupied by the aisle volume, Step 1, from the total number in Step 2.

9. Units of different shapes and masses can be stored in the same structure provided that the safe surface densities are observed for each individual unit. This is more easily accomplished, if sections of the structure are set aside for dissimilar masses and shapes rather than randomly storing of the units. The rule is based on the concepts of coupled reactors.¹⁵

¹⁵ R. Avery. "Coupled Fast-Thermal Power Breeder," *Nuclear Science and Engineering*, 3:129-144. 1958; ———, "Theory of Coupled Reactors," P/1858. Proceedings of International Conference in Geneva, Switzerland. Volume 12. 1958. Pages 182-191; and R. Avery et al. "Coupled Fast-Thermal Power Breeder Critical Experiment," P/2160. Volume 12. 1958. Pages 151-165.

TABLE IV. Vault Calculations for Reduced Density.

Array Size in Storage Unit	Unit Diameter (D) (centimeter)	Unit Height (H) (centimeter)	Unit Mass (M) (kilogram)	Density Ratio (ρ/ρ_0)	Surface Density (SD) (kilograms per square feet)	$k_{eff} + \sigma$	$(k_{eff} \pm 1\sigma)$	Notes
30 X 30 X 1	7.05	6.5	5.00	1.00	1.01	0.842 ± 0.011	0.886	^a Plutonium
67 X 67 X 1	9.07	8.38	5.00	0.4686	5.03	0.823 ± 0.013	0.875	^a Plutonium
25 X 25 X 1	11.8	10.87	21.99	1.00	3.08	0.833 ± 0.010	0.873	^a Uranium
45 X 45 X 1	14.12	13.04	21.99	0.5822	9.98	0.840 ± 0.013	0.892	^a Uranium
30 X 30 X 1	7.05	6.5	5.00	1.00	1.01	0.842 ± 0.011	0.886	^a Plutonium
11 X 11 X 1	22.56	20.8	36.85	0.225	1.00	0.689 ± 0.009	0.725	^b Plutonium
19 X 19 X 1	22.56	20.8	36.85	0.225	2.98	0.779 ± 0.012	0.827	^b Plutonium
25 X 25 X 1	22.56	20.8	36.85	0.225	5.17	0.878 ± 0.014	0.934	^{b,c} Plutonium
25 X 25 X 1	11.8	10.87	21.99	1.00	3.08	0.833 ± 0.010	0.873	^a Uranium
11 X 11 X 1	30.2	27.83	108.80	0.295	2.95	0.727 ± 0.011	0.814	^b Uranium
20 X 20 X 1	30.2	27.83	108.80	0.295	9.75	0.863 ± 0.010	0.903	^{b,c} Uranium
21 X 21 X 1	38.0	3.104	65.13	1.00	6.44	0.845 ± 0.012	0.893	^b Uranium
12 X 12 X 1	76.0	6.208	216.22	0.415	6.98	0.842 ± 0.010	0.882	^b Uranium

^aComplies with rules of model.

^bNot acceptable according to model; violates Rule No. 3

^cNot acceptable according to model; does not meet Rule No. 4, surface density is too high.

The calculations for b and c were to gain insight on the latitude of safe values of k_{eff} permitted by the model.

^dThe equation gives the relationship of maximum mass (M_0) to density (ρ_0) of a single unit to other unit masses and densities.

10. Figure 13 and Table V can be used to calculate safe-storage configurations ($k_{eff} + 4\sigma \leq 0.90$) provided that Rules 1 through 9 are used.

Item 1. Reduced Density. The data on reduced density units required for application of Rule 2 of the model are provided in Figure 12. A test of Figure 12 has been made and reported in Table IV.

Caution: Some common sense is also required in applying data in the figure. The density correction applies to a uniform density change, not a change brought about by averaging out; for example, a hole drilled in a unit.

Item 2. Safe Individual Storage Units with Full Water Reflection. The lower limit for surface-to-volume ratio is set by the requirement that a single unit be safe when water-reflected. In the works by Gwin and

Mee¹⁶ and by Goodwin and Schuske¹⁷ equations are given of hyperbolas for critical cylinders of uranium and plutonium metal reflected by hydrogenous material. For the current report, these equations have been modified by reducing their asymptotes. The critical diameter of an infinitely long cylinder was decreased 10 percent. The critical thickness of an infinite diameter cylinder was decreased 15 percent. The remaining constant was then adjusted to correspond to a cylinder of optimum height-to-diameter ratio whose mass was about 15 percent lower than the critical value. The plutonium equation was also adjusted for the difference in density between those reported by Gwin and Goodwin to high density.

¹⁶ R. Gwin and W. T. Mee. *Critical Assemblies of Uranium 235*, Y-A2-124. Radiation Control Group. Y-12 Plant. Oak Ridge, Tennessee. September 8, 1953.

¹⁷ A. Goodwin, Jr. and C. L. Schuske. "Plexiglas and Graphite Moderated Plutonium Assemblies." Parts A and B. Reactor Science and Technology. *Journal of Nuclear Energy*, 15:120-129. 1961.

FIGURE 12. Relationship between the Mass of a Single Unit and the Density Assuming an Inverse Power Law of 4/3.

The resulting equations are:

1. $(D - 3.623)(H - 0.433) = 20.80$ for plutonium
2. $(D - 6.606)(H - 1.564) = 48.35$ for enriched uranium

Where, H and D are the height and diameter of the cylinder in centimeters.

Calculational Verification of the Model:

The purpose of this section is to provide a measure of the safety inherent in the model. Most of the test data presented in Table V represent cases where unit dimensions, mass, and surface density are in excess of those permitted by the model.

The test data provide a designer with knowledge of the safety factors involved in the model, as well as suggest some latitude for storage facility design. All cases tested are subcritical ($k_{eff} < 0.95$). Any specific data in Table VI where $k_{eff} + 4\sigma \leq 0.90$ may be used for design considerations.

Example 1 - Two-Layer Array of Annular Cylinders:

The unit is an annular cylinder of plutonium [$(\rho) \rho = 15.6 \text{ g/cm}^3$] with dimensions $R_1 = 2 \text{ cm}$, $R_2 = 4 \text{ cm}$, $H = 10.2 \text{ cm}$ (mass = $\sim 6 \text{ kg}$). Find the horizontal center-to-center spacing for a two-layer array of these units.

$$s \text{ (surface)} = 2 \pi R_2^2 + 2 \pi R_2 H = 356.88 \text{ centimeters}^2$$

$$v \text{ (volume)} = \pi(R_2^2 - R_1^2)H \times \frac{\rho}{\rho_{\max}} = 304.50 \text{ centimeters}^3$$

$$\frac{s}{v} = 1.17 \text{ centimeters}^{-1}, \text{ safe SD} = 3 \text{ kilograms per square foot}$$

R_1 = inside radius of annular cylinder

R_2 = outside radius of cylinder

ρ = density of plutonium.

H = height of cylinder

FIGURE 13. Permissible Values from Model for Arrays in Air.

TABLE V. Specifications for Model.

Fissile Material	Range of Surface-to-Volume Ratio (s/v) (centimeters ⁻¹)	Safe Surface Density (SD) (kilograms per square foot)
Uranium (93.4) (18.7 grams per cubic centimeter)	0.000 to 0.487	0.0
	0.488 to 0.649	3.0
	0.650 to 0.749	6.0
	> 0.750	10.0
Plutonium metal (19.7 grams per cubic centimeter)	0.000 to 0.822	0.0
	0.823 to 0.969	1.0
	0.970 to 1.099	2.0
	1.100 to 1.449	3.0
	> 1.450	5.0

Therefore: 12 kg (two 6-kg units) require 4 square feet of area, or 2-foot centers are required for an array two layers high.

The KENO calculation gave $k_{eff} \pm \sigma = 0.761 \pm 0.012$ for ~ 11,000 histories.

STORAGE MODEL FOR ARRAYS IN WATER

Greatly increased storage densities and resulting economies can be achieved if moderators are used inside the vault to decrease interaction between the individual units. The model described in this section makes use of water as the moderator.

Basic Assumptions:

Each plutonium storage unit is placed in a bucket which has a 7.5-inch inner diameter and a 10-inch inner height. Each bucket is surrounded by a water jacket 3 inches thick. The enriched uranium containers have 10-inch inner diameter (D) and 13.5-inch inner height (H) and are surrounded by 3 inches of water. All array calculations were based on an *in-contact* 20 by 20 by 20-array of these containers.

All arrays are surrounded by 12-inch thick concrete walls.

Rules:

1. A storage unit is to be subcritical when fully water reflected.
2. The following equations may be used for guidance. Other shaped units must follow Rule No. 1.

For uranium:

$$(D - 6.24) (H - 1.47) = 41.8$$

For plutonium:

$$(D - 3.42) (H - 0.40) = 17.6$$

3. All containers must provide positive protection against double batching.

4. Low density fissile materials, such as metal turnings, etc., must be protected against internal moderation by sprinklers or other sources of water.

5. A means of assuring that the water jackets are full is required. (Jelled water should be used to minimize loss of water in jackets from possible small leaks.)

6. Water sprinklers may be used to control fires.

Calculational Verification of Storage Model for Arrays in Water:

Table VII contains a calculational verification of arrays of several units taken from the equations in Rule No. 2, assuming a 20 by 20 by 20-array of these units. One foot of concrete surrounded the arrays.

Larger unit shapes, such as tall thin cylinders or thin slabs, could be stored in this manner if the inside dimensions of the buckets are increased proportionally.

TABLE VI. Results of Calculations to Test Model.

Array Size in Storage Units	Unit Diameter (D) (centimeters)	Unit Height (H) (centimeters)	Unit Mass (M) (kilograms)	Surface-to-Volume Ratio (s/v) (centimeters ⁻¹)	Surface Density (SD) (kilograms per square foot)		Multiplication Factor (k _{eff} ± σ)	k _{eff} + 4σ	Comments
					Permitted by Model	Of Actual Array			
Plutonium Metal									
30 X 30 X 1	7.05	6.5	5.00	0.875	1.0	1.01	0.842 ± 0.011	0.886	Permitted
^b 29 X 29 X 1	7.2	6.6	5.29	0.859	1.0	1.00	0.868 ± 0.012	0.916	Not permitted
^b 36 X 36 X 1	7.2	6.6	5.29	0.859	1.0	1.54	0.901 ± 0.010	0.941	Not permitted
54 X 54 X 1	6.626	—	3.00	0.905	1.0	1.96	0.767 ± 0.007	0.794	^a Safe but not permitted
45 X 45 X 1	7.584	—	4.50	0.7911	1.0	2.00	0.895 ± 0.013	0.947	Not permitted
41 X 41 X 1	4.8	19.0	6.77	0.939	1.0	2.55	0.853 ± 0.010	0.893	Safe but not permitted
36 X 36 X 1	12.0	3.15	7.02	0.968	2.0	2.04	0.873 ± 0.009	0.909	Not permitted
36 X 36 X 1	12.0	3.25	7.24	0.948	2.0	2.04	0.889 ± 0.012	0.937	Not permitted
40 X 40 X 1	15.0	2.4	8.36	1.100	3.0	3.00	0.862 ± 0.010	0.902	Not permitted
44 X 44 X 1	20.0	1.83	11.36	1.29	3.0	4.93	0.888 ± 0.010	0.928	Not permitted
43 X 43 X 1	21.5	1.717	13.28	1.350	3.0	5.50	0.882 ± 0.008	0.914	Not permitted
63 X 63 X 1 slab 21.2 X 21.2	1.016	9.00	2.157	5.0	8.00	0.936 ± 0.016	1.000	Not permitted	
36 X 36 X 10	4.5	cube	1.80	1.333	3.0	5.21	0.868 ± 0.015	0.928	Not permitted
41 X 41 X 1	24.0	1.50	13.34	1.498	5.0	5.02	0.875 ± 0.010	0.915	Not permitted
^b 34 X 34 X 1	32.0	1.2	19.01	1.792	3.0	4.92	0.827 ± 0.011	0.871	^a Safe but not permitted
^b 39 X 39 X 1	32.0	1.2	19.01	1.792	3.0	6.48	0.891 ± 0.013	0.943	Not permitted
25 X 25 X 1	52.0	0.863	36.11	2.394	5.0	5.06	0.813 ± 0.016	0.877	^a Safe but not permitted
Uranium (93.4) Metal									
25 X 25 X 1	11.8	10.87	21.99	0.523	3.0	3.08	0.833 ± 0.010	0.873	Permitted
^b 24 X 24 X 1	12.3	11.3	24.8	0.502	3.0	3.20	0.867 ± 0.010	0.907	Not permitted
^b 27 X 27 X 1	12.3	11.3	24.8	0.502	3.0	4.06	0.886 ± 0.009	0.922	Not permitted
18 X 18 X 1	7.818	46.0	40.9	0.555	3.0	2.97	0.747 ± 0.010	0.787	Permitted
^c 26 X 26 X 1	26.5	4.0	40.81	0.651	6.0	6.18	0.862 ± 0.011	0.906	Not permitted
^c 13 X 13 X 4	26.5	4.0	40.81	0.651	6.0	6.18	0.841 ± 0.012	0.889	Safe but not permitted
22 X 22 X 1	32.0	3.773	56.5	0.655	6.0	6.13	0.882 ± 0.008	0.914	Not permitted
^b 22 X 22 X 1	32.0	3.8	56.54	0.651	6.0	6.13	0.897 ± 0.009	0.933	Not permitted
^b 24 X 24 X 1	32.0	3.8	56.54	0.651	6.0	7.30	0.910 ± 0.010	0.950	Not permitted
^b 28 X 28 X 1	32.0	3.8	56.54	0.651	6.0	9.93	0.948 ± 0.011	0.992	Not permitted
21 X 21 X 1	34.0	3.62	60.78	0.670	6.0	6.01	0.879 ± 0.013	0.931	Not permitted
^{b,c} 21 X 21 X 1	38.0	3.104	65.13	0.750	6.0	6.44	0.845 ± 0.012	0.893	Safe but not permitted
^c 12 X 12 X 3	38.0	3.104	65.13	0.750	6.0	6.30	0.805 ± 0.010	0.845	Safe but not permitted
^b 26 X 26 X 1	38.0	3.104	65.13	0.750	6.0	9.87	0.903 ± 0.009	0.939	Not permitted
^{b,c} 17 X 17 X 1	46.0	3.02	92.9	0.749	6.0	6.02	0.870 ± 0.010	0.910	Not permitted
^c 12 X 12 X 2	46.0	3.02	92.9	0.749	6.0	6.00	0.869 ± 0.010	0.909	Not permitted
^b 22 X 22 X 1	46.0	3.02	92.9	0.749	6.0	10.07	0.927 ± 0.012	0.975	Not permitted

^aSafe but not permitted indicates that this system is not permitted by the model but does comply with $k_{eff} \pm 4\sigma \leq 0.90$.

^bShows effect of varying surface density.

^cShows effect of rearranging units.

Vault is 12-inch thick concrete, 66.8 by 66.8 by 9.8 feet inside dimensions.

TABLE VII. Verification of Model for Units in Water-Jacketed Buckets.
(The 20 by 20 by 20 array is enclosed by a 12-inch thick concrete vault.)

Material	Unit Diameter (D) (centimeters)	Unit Height (H) (centimeters)	Unit Mass (M) (kilograms)	$k_{eff} \pm \sigma$	$k_{eff} + 4\sigma$	Notes
Plutonium	18.732	1.81	9.83	0.853 ± 0.009	0.889	Safe but not permitted
	18.732	1.555	8.44	0.814 ± 0.009	0.850	Permitted
	4.51	24.24	7.94	0.812 ± 0.009	0.848	Safe but not permitted
	7.046	6.509	5.00	0.883 ± 0.009	0.919	Not permitted
	6.54	6.042	4.00	0.803 ± 0.008	0.835	Permitted
Uranium	11.8	10.87	21.99	0.876 ± 0.008	0.904	Safe but not permitted
	11.03	10.19	18.01	0.831 ± 0.009	0.867	Permitted
	25.08	4.18	38.20	0.907 ± 0.009	0.943	Not permitted
	25.08	3.689	33.72	0.886 ± 0.008	0.918	Permitted
	8.11	33.71	32.22	0.838 ± 0.008	0.870	Safe but not permitted

NOTE: Jacket is 3-inch thick water, 0.063-clad iron inside and out.
Plutonium bucket is 7.5-inch, inside diameter and 10-inch inside height.
Uranium bucket is 10-inch inside diameter, and 13.5 inside height.

Example 1 – A Cubic Array In Contact:

This example makes use of the annular cylinder unit used on Page 14, i.e., plutonium metal ($\rho = 15.6 \text{ g/cm}^3$) with dimensions $R_1 = 2 \text{ cm}$, $R_2 = 4 \text{ cm}$, $H = 10.2 \text{ cm}$ (mass ~ 6 kg). A unit was placed upright on the bottom of a 7.5-inch inside diameter, 10-inch inside height, and 3-inch thick bucket of water. The walls of the bucket were 0.063-inch iron, inside and out. The bucket had a top of similar material and thickness. The covered buckets were then placed in contact with each other in a 20 by 20 by 20-array, which was in turn enclosed by 12 inches of concrete.

A KENO calculation for this case gave a $k_{eff} \pm \sigma = 0.762 \pm 0.012$ for ~ 11,000 histories. The $k_{eff} \pm \sigma = 0.860 \pm 0.011$ for a single water flooded unit.

SPECIAL STORAGE ARRAYS USING INTERNAL MODERATORS

This section contains calculated storage arrays where Plexiglas, concrete, and water are used as internal

moderators. These cases are not arrived at by the previous two models, but are presented to provide a comparison of the effectiveness of the three moderators.

Table VIII, *Plutonium Units in Plexiglas Buckets*, lists the results of a series of calculations made to simulate a possible storage facility. The plutonium units are placed on the bottom of the bucket which has an inside diameter of 7.5 inches and an inside height of 10 inches. The center-to-center spacing of the buckets is 29 inches. Calculations show that the presence or absence of 0.063-stainless cladding of the buckets inside and out does not change k_{eff} appreciably.

Cladding may be necessary for fire safety. Plexiglas buckets, two inches thick, provide sufficient isolation for 5-kg units to be stored on 29-inch centers. This amounts to a surface density of about 14 kg/ft^2 . If the Plexiglas bucket is made 3 inches thick and provided with 3-inch thick tops, sufficient decoupling is provided to allow them to be placed in contact with each other and still be safely subcritical while containing a 5-kg unit of plutonium metal. The safe-surface density is then 70 kg/ft^2 .

TABLE VIII. Plutonium Units in Plexiglas Buckets.

Array Size in Storage Units	Unit Mass (M) (kilograms)	Plexiglas Bucket Thickness (inches)	Spacing and Notes	$k_{eff} \pm \sigma$
124 X 8 X 14	3	2	No tops or clad	0.798 ± 0.009
1	3	2	No tops or clad	0.740 ± 0.010
124 X 8 X 14	6	2	No tops or clad	0.987 ± 0.009
1	6	2	No tops or clad	0.891 ± 0.008
124 X 8 X 14	5	2	No tops or clad	0.902 ± 0.015
1	5	2	No tops or clad	0.844 ± 0.009
124 X 8 X 14	5	2	No tops	0.896 ± 0.010
1	5	2	No tops	0.849 ± 0.011
124 X 8 X 14	5	3		0.861 ± 0.009
124 X 8 X 14	5	3	In contact	0.882 ± 0.012
1	5	3		0.869 ± 0.009
124 X 8 X 14	3	3		0.798 ± 0.009
124 X 8 X 14	3	3	In contact	0.841 ± 0.014

NOTE: Vault is 6-inch thick concrete; internal dimensions are 300 feet long by 20 feet wide by 34 feet high. The 3-kg units are 3.32-cm radius spheres, other units have cylinders with H/D = 1. Single unit in array is placed in vault corner for maximum reactivity. Buckets are spaced 29 inches center-to-center, except when in contact with each other. All buckets have tops and are clad inside and out with 0.063 inches of iron, except where noted.

TABLE IX. Plutonium Units in Concrete Buckets.

Array Size in Storage Units	Unit Mass (M) (kilograms)	Concrete Bucket Thickness (inches)	Spacing and Other Notes	$k_{eff} \pm \sigma$
124 X 8 X 14	5	3		0.927 ± 0.012
1	5	3		0.859 ± 0.009
124 X 8 X 14	4	3		0.880 ± 0.007
124 X 8 X 14	3	3	In contact	0.890 ± 0.008
124 X 8 X 14	3	2	In contact	1.028 ± 0.009

NOTE: All buckets have tops and are clad inside and out with 0.063 inches of iron. Buckets are spaced 29 inches center-to-center, except when in contact with each other. The 3-kg units are 3.32-cm radius spheres, other units are cylinders with height-to-diameter ratio of one. Vault is 6-inch thick concrete, 300 feet long by 20 feet wide by 34 feet high inner dimensions. Single unit in array is placed in vault corner for maximum reactivity.

Table IX, *Plutonium Units in Concrete Buckets*, presents the results of replacing the Plexiglas buckets with concrete ones because of economy and increased fire safety. Three inches of concrete is not as efficient at neutronic isolation as the same thickness of Plexiglas.

TABLE X. Buckets in Edge-to-Edge Contact.

Unit Mass (M) (kilograms)	Bucket Material	$k_{eff} \pm \sigma$	Notes and Comments
2.5	Concrete	1.062 ± 0.011	Buckets fit around unit with no space between them. Bucket is filled by unit.
2.0	Concrete	0.977 ± 0.011	
4.0	Plexiglas	0.976 ± 0.012	
3.0	Plexiglas	0.889 ± 0.007	
3.0	Water	0.875 ± 0.012	Buckets are 7.5 inches inner diameter and 10-inch inner height. Units do not fill bucket but rest on the bottom of the bucket.
3.0	Plexiglas	0.758 ± 0.012	
3.0	Water	0.739 ± 0.010	
5.0	Water	0.883 ± 0.009	
3.0	Concrete	0.817 ± 0.009	

NOTE: The 12-inch thick concrete vault surrounds the 20 by 20 by 20-array of 3 inches thick, 0.063-inch iron clad (inside and out) buckets, in contact with each other, with tops. The units are right circular cylinders of optimum height-to-diameter ratio (H/D) (0.9238).

Plutonium metal units of slightly less than 4 and 3 kg respectively may be safely arrayed and *in contact*, in concrete buckets, under the same conditions as stated above for Plexiglas.

Table X lists the results of calculations of in contact arrays of buckets of concrete, Plexiglas, or water. The arrays are cubic, 20 by 20 by 20, and surrounded on all six surfaces by 12 inches of concrete with no intervening space. The plutonium metal units are cylinders with the optimum height-to-diameter (H/D) ratio = 0.9238, rather than spheres or equilateral cylinders, H/D = 1.

The conclusion to be drawn from the table is that, if the buckets fit tightly around the units with no intervening space, only Plexiglas and water buckets are safe and then only for 3-kg units. If the buckets are standardized to some reasonable size (i.e., the 7.5-inch inner diameter and 10-inch inside height used previously), 3-kg units in Plexiglas, concrete, or water buckets all have a large margin of safety.

Thus, hydrogenous materials can be used effectively in high density storage configurations.