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CRITICALITY DESIGN EVALUATION OF THE WHITE SANDS
REACTOR BUILDING STORAGE VAULT

J. S. PHILBIN AND W. E. NELSON

Sandia Laboratories

CRITICALITY DESIGN EVALUATION OF THE WHITE SANDS REACTOR BUILDING STORAGE VAULT*

by

J. S. Philbin
Sandia Laboratories
Albuquerque, New Mexico 87185

and

W. E. Nelson
Science Applications, Inc.
Albuquerque, New Mexico

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ABSTRACT

This report describes the conceptual design and criticality evaluation of a storage vault for components of the fast pulse reactor at White Sands Missile Range. Criticality calculations were performed with the KENO-IV Monte Carlo code for various storage configurations in order to investigate the coupling between the portable reactor and storage arrays of spare reactor rings or other fissile components of similar mass. Abnormal conditions corresponding to pseudo-random arrays of the fuel components, as well as a number of flooded configurations, were also evaluated to assess criticality potential for highly unlikely situations. In a normal, dry configuration, the neutron self-multiplication factor, k_{eff} , of the fully loaded 3 x 8 planar array plus the reactor is less than 0.87. A completely flooded vault was found to produce self-multiplication factors in excess of 1.2. It is interesting to note that the reactor accounts for approximately 1/3 of the overall self-multiplication factor for both the normal and abnormal configurations that were evaluated. These calculations served as a basis for design and procedural recommendations that are presented in the main body of this report in order to insure criticality safety according to recognized standards.

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CRITICALITY DESIGN EVALUATION OF THE WHITE SANDS REACTOR BUILDING STORAGE VAULT

I. INTRODUCTION

This report describes the conceptual design and a criticality evaluation of a storage vault for components of the fast pulse reactor (1, 2) at White Sands Missile Range. The reactor consists of six to eight stacked annular rings, a central safety block, and three rods of fully enriched uranium alloyed with ten weight percent molybdenum ($\rho = 17 \text{ gm/cc}$). The nominal mass per ring is 12.9 kg with inner and outer diameters of 10.16 and 20.32 cm. Rod and bolt holes penetrate through the eight ring stack. Criticality calculations were performed with the KENO IV Monte Carlo code (3) to investigate the coupling between the portable eight ring stack and a planar storage array of spare reactor rings on other fissile components of similar mass. The calculations serve as a basis for design and procedural recommendations that are meant to insure criticality safety according to recognized standards.

II. DESCRIPTION OF THE VAULT, THE STORAGE CONFIGURATIONS AND THE CALCULATIONAL MODELS

The design basis vault configuration consists of a 3 wide by 8 high planar array of reactor ring elements plus an assembled 8 ring stack on a portable stand positioned in front of the planar array. Figures 1 and 2 show the basic geometry of the vault, the planar array, and the eight ring stack. Two possible locations of the portable stand and eight ring stack are indicated in Figure 1.

Individual Ring = 1.28125" Height

Figure 1. Top View of Vault

Figure 2. End View of Vault

The cubical unit cell dimension for the storage array is 30.48 cm. Vault materials are Portland concrete for the walls, ceiling and floor and steel or Benelux 70 (Masonite) for the door. The concrete thickness is 61 cm except for the ceiling at 183 cm. The vault room is 157 cm by 122 cm by 314 cm and the array boundaries are 15.24 cm from the three concrete walls and 30.48 cm above the floor.

The initial guidance for the unit cell dimensions of the array were obtained from reference 4 and by the density analog method (5). Final evaluations were made with the KENO IV Monte Carlo code (3) using Hansen-Roach cross sections (6). This code and these cross sections and their use for criticality evaluations comprise a validated computational technique, see reference 4. Both normal storage configurations and pseudo-random arrays of the array elements and reactor stack on the floor were investigated. In the normal storage configurations, the eight ring stack was positioned at six different locations with respect to the planar array. A description of the different locations of the portable eight ring stack is given in Table 1. In the second set of calculations, all of the elements were arranged in stacks on the floor and the center-to-center spacing of the stacks was varied. In both the first and second sets of calculations, representative cases were evaluated under the unlikely assumption of the vault being completely flooded.

Atom densities for the vault materials and the reactor elements are listed in Table 2. Details of the KENO IV Monte Carlo calculations, including geometrical considerations (i.e., geometry boxes), can be found in the Appendix.

The precisions quoted in this report refer only to the statistics of these calculational techniques and do not include additional uncertainties related to cross section data, self-shielding corrections

Table 1

Locations for the Portable Eight Ring Stack

Location Number	Location Description of Eight Ring Stack
1	Midplane stack, 56.0" above floor Center of stack 18.0" from center of shelf (See Figures 1 and 2)
2	Midplane stack, 56.0" above floor Center of stack 36.0" from center of shelf (See Figures 1 and 2)
3	Stack located on floor Top view same as position 1
4	Stack located on floor Top view same as position 2
5	Stack located 6.0" off floor Top view same as position 1
6	Stack located 6.0" off floor Top view same as position 2

Table 2

Atom Densities for Vault Materials and Reactor Elements

1) Vault Materials

a) Portland Concrete (Ordinary Concrete)

O - 4.15×10^{-2} atoms/barn-cm	C - 3.80×10^{-3} atoms/barn-cm
Si - 6.00×10^{-3} "	Na - 3.00×10^{-4} "
Al - 7.00×10^{-4} "	K - 1.00×10^{-4} "
Fe - 2.00×10^{-2} "	H - 1.50×10^{-2} "
Ca - 1.16×10^{-2} "	Mg - 1.00×10^{-2} "

b) Benclex 70 (Masonite)

H - 5.51×10^{-2} atoms/barn-cm
C - 3.40×10^{-2} "
O - 2.41×10^{-2} "

2) Reactor Elements: U - 10 Mc (93.2% enriched)

U^{235} - 3.65×10^{-2} atoms/barn-cm
U^{238} - 2.63×10^{-3} "
Mo ⁹⁶ - 1.067×10^{-2} "

for the flooded cases, etc. As a result, a conservative bias has been used in determining the conditions that will properly insure that the recommended k_{eff} of 0.95 (4) is not exceeded.

III. CRITICALITY EVALUATION OF THE WSMR VAULT - NORMAL GEOMETRIES

Table 3 gives the results of the normal "array plus stack" configuration. For comparison, the abnormal condition with water present is also included. In one column the array components are assumed to be spheres of the same mass as a real ring. In the next two columns the array components are annular-shaped like the real rings. However, there has been no allowance made for the reduced average density due to rod holes or bolt holes in the second model. First, let us examine the results in columns three and four of Table 3. The calculations were done with the vault in the standard dry condition. When the eight ring stack is 91.4 cm from the array, the multiplication factor tends to be higher with the heavier annular cylinders than with the spheres but just the reverse is true at the closer location, 45.7 cm. This implies a more rapidly decreasing interaction probability between the spherical array and the stack, with separation distance, than one would expect for the annular ring array. In addition, reflection from the more distant walls and doors is more effective, i.e., $k(\text{position } 2) > k(\text{position } 1)$, only if the array is filled with the annular cylinders. These effects, which are consistent for all cases, may well be due to solid angle considerations, although this has not presently been verified. Moreover, there is statistical overlap between the sphere and cylinder models in all but one case. Therefore, to within one standard deviation, the modeling differences are not particularly important.

Table 3

WSMR Vault Criticality Evaluations

8 Ring Stack Location		K_{eff} - Array Plus Stack		
Horizontal distance from array*, cm	Height above floor, cm	<u>Storage Array Model for 14 Unit Planar</u>		<u>Vault Flooded</u>
		Spheres (12.88 kg each)	Annular Cylinders (or rings) (13.46 kg each)	Annular Cylinders (or rings) (13.46 kg each)
45.7 (18")	142.2 (56")	0.854 $\pm$ 0.007	0.844 $\pm$ 0.007	1.213 $\pm$ 0.009
91.4 (36")	142.2 (56")	0.849 $\pm$ 0.007	0.860 $\pm$ 0.007	-----
45.7 (18")	0	0.890 $\pm$ 0.007	0.878 $\pm$ 0.007	1.209 $\pm$ 0.007
91.4 (36")	0	0.877 $\pm$ 0.006	0.896 $\pm$ 0.007	-----
45.7 (18")	15.2 (6")	0.858 $\pm$ 0.006	0.848 $\pm$ 0.008	1.184 $\pm$ 0.009
91.4 (36")	15.2 (6")	0.852 $\pm$ 0.007	0.862 $\pm$ 0.008	-----

* Represents the perpendicular distance from a plane defined by the centers of the planar array and a parallel plane thru the center of the eight ring stacks.

As can be seen in Table 3, for the dry vault condition all cases are subcritical. The highest k_{eff} for this condition occurs when the eight ring stack is placed directly on the floor. This increase in k_{eff} is due to the increased ground reflection. Notice that raising the stack only six inches off the floor decreases k_{eff} to essentially the k_{eff} for the midplane location of the stack.

The cases for which the vault is completely flooded all had k_{eff} greater than one. In view of this unacceptable condition, adequate drainage and non-sealing door clearances should be incorporated in the design to insure the vault will never be in a completely flooded condition, and combustible material should be excluded from the vault thereby possibly eliminating a need for sprinklers. If sprinklers are used, however, a calculation with an appropriate water mist environment should be performed.

It should be noted that the eight ring stack accounts for approximately one-third of the total k_{eff} for the vault in either the normal or flooded condition. Thus, the vault capacity could easily be increased if the eight ring stack were stored elsewhere or disassembled and stored separately, should the need ever arise. On the other hand, as a result of increased exposures involved in disassembly, we do not recommend this action and, in fact, feel it should be discouraged.

IV. CRITICALITY EVALUATION OF THE WSMR VAULT FOR "RANDOM ARRAYS"

Criticality calculations were performed for the abnormal conditions of "random arrays" of the eight ring stack and all shelf elements located on the floor. The random arrays were intended to simulate unanticipated or accident configurations. Because of the difficulty in identifying

typical random arrays, well-defined equally spaced arrays of the eight ring stack and all the shelf elements were simulated in the calculations. The first configuration consisted of stacking all the rings two deep on the floor in a 4 x 4 matrix and varying the center-to-center spacing between the element stacks. The second array had the eight ring stack surrounded by the shelf elements (as rings) stacked three deep. The array was thus a 3 x 3 matrix with the eight ring stack in the central position. Again, the center-to-center spacing was varied between cases. The last array considered had four eight ring stacks arranged in a 2 x 2 matrix. As with the other configurations, the center-to-center spacing was varied in order to observe changes in k_{eff} . Calculations were run for dry and flooded conditions in the vault.

Tables 4, 5, and 6 contain the results of the criticality calculations for the three types of "random arrays." The lowest value of k_{eff} for any given center-to-center spacing is that associated with the elements being stacked two deep. This is to be expected since the eight ring stack contributes about one third of the value of k_{eff} and thus having the stack dismantled lowers the value of k_{eff} . The data from Tables 4, 5, and 6 are shown graphically in Figure 3. In all cases, the neutron self-multiplication factor is the largest when the random stacks are touching each other. Data from Table 6, i.e., curves E and F of Figure 3, are derived from a model where up to four reactors are stored in the vault simultaneously. This can result in configurations with k_{eff} greater than unity if the center-to-center spacing is less than 38.1 cm (15 inches).

One additional "random array" was investigated. This consisted of the eight ring stack intact and the shelf elements one layer deep equally

Table 4

"Random Array" on Floor--shelf elements stacked 2 deep on floor, eight ring stack dismantled and also stacked 2 deep on floor. Arranged in 4 x 4 array with equal center-to-center spacing.

Center-to-Center Spacing	Dry Vault	k_{eff} Flooded Vault
30.48 cm (12 inches)	0.769 $\pm$ 0.005	0.927 $\pm$ 0.007
25.40 cm (10 inches)	0.807 $\pm$ 0.005	1.049 $\pm$ 0.006
20.32 cm (8 inches)	0.921 $\pm$ 0.006	1.179 $\pm$ 0.007

Table 5

"Random Array" on Floor--one eight ring stack surrounded by shelf elements stacked three deep.

Center-to-Center Spacing	Dry Vault	k_{eff} Flooded Vault
30.48 cm (12 inches)	0.964 $\pm$ 0.006	1.220 $\pm$ 0.006
25.40 cm (10 inches)	1.011 $\pm$ 0.005	1.275 $\pm$ 0.006
20.32 cm (8 inches)	1.124 $\pm$ 0.005	1.387 $\pm$ 0.006

Table 6

"Random Array" on floor--four eight ring stacks

Center-to-Center Spacing	Dry Vault	k_{eff} Floored Vault
50.80 cm (20 inches)	----	1.211 ± 0.005
38.10 cm (15 inches)	0.999 ± 0.006	1.219 ± 0.005
30.48 cm (12 inches)	1.056 ± 0.006	----
25.40 cm (10 inches)	1.119 ± 0.006	----
20.32 cm (8 inches)	1.255 ± 0.006	----

Table 7

"Random Array" on floor--one eight ring stack surrounded by shelf elements one layer deep on floor. Dry vault.

Center-to-Center Spacing	k_{eff}
20.32 cm (8 inches)	0.942 ± 0.006
Eight ring stack removed	~ 0.650

FIGURE 3. PARAMETRIC EVALUATION OF RANDOM ARRAYS.

spaced on the floor; see Table 7. A center-to-center spacing of 20.32 cm (8 inches) resulted in k_{eff} of 0.942 ± 0.006 . No parametric variation on center-to-center spacing was done for this case because of the limited amount of extra floor space available in this configuration. Removal of the eight ring stack would result in a k_{eff} of approximately 0.650. Models represented by curve A and point G represent the only safe abnormal configurations. In the absence of water, these configurations have a self-multiplication factor less than 0.95. For criticality control, steps should be taken to insure that configurations represented by curves B, C, D, E and F are not credible configurations. Situations represented by curve E can be partially insured against by administrative procedures that do not allow more than one complete assembly being stored in the vault at full vault capacity. Situations represented by curve C, as well as any other random array, can be assured against by shelf designs or bird cages that preclude the possibility of the elements being dumped on the floor in the event of an abnormal occurrence.

Regarding the flooded cases (curves B, D, and F), as pointed out in the previous section, the vault should never be in a completely flooded condition if adequate drainage is provided and if combustibles and, therefore, sprinklers are excluded from the vault. If sprinklers are deemed necessary to satisfy other regulations, etc., a calculation with an appropriate water mist environment should be performed. Check valves should also be installed to preclude backfill from sewer lines.

V. CONCLUSIONS AND RECOMMENDATIONS

The storage vault analyzed in this report is safe from a criticality standpoint for the normal geometries and in the absence of water ingress. We recommend that adequate drainage with check valves be installed to preclude ingress in any credible situation. Combustibles should be excluded from the vault to eliminate a need for a fire protection sprinkler system.

Administrative controls should be established to limit the number of eight ring assembled stacks to no more than one when the planar array is occupied and no more than two separated by a minimum of 61 cm (2 feet) if the planar array is empty. This recommendation is based on conservative extrapolations of the results in Table 6. The total vault capacity should not exceed the capacity of the 24 unit planar array, plus a single eight ring stack unless further evaluations are carried out. However, some of the fuel can be stored in configurations similar to safe configurations analyzed in this report using 0.95 as an upper limit for a safe self-multiplication factor. Furthermore, storage compartments or bird cages, or clamping devices, that would insure a minimum separation distance between rings or fuel elements in the planar array, even if the array should be upset, is advisable. The eight ring stack accounts for approximately 1/3 of the overall self-multiplication factor for both the normal and abnormal configurations that were evaluated.

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APPENDIX

Figures A-1 through A-5 on the following pages are illustrations of the geometry boxes that were used to model the WSMR Vault. These were arrayed in a matrix three wide by three deep by nine high. The planar array of fissile units occupies one plane of the three-dimensional matrix. The outer dimensions of the array of boxes was then enclosed by a core body box (CORE BDY). Around the core body, the rest of the vault was then constructed by the use of appropriately dimensioned cuboid bodies. A listing of the geometry cards for one of the KENO-IV calculations can be found in Table A-1 at the end of this Appendix.

FIGURE A-1. SPHERICAL REPRESENTATION OF REACTOR ELEMENTS.
(a) TOP VIEW (b) FRONT VIEW

FIGURE A-2. REPRESENTATION OF THE EIGHT RING STACK SUITABLE FOR LOCATING AT THE MIDPLANE OF THE FACILITY.
 (a) TOP VIEW (b) FRONT VIEW OF TOP PART (c) FRONT VIEW OF BOTTOM PART.

FIGURE A-3. REPRESENTATION OF FULL EIGHT RING STACK (SUITABLE FOR STACKING ON THE FLOOR). (a) TOP VIEW (b) FRONT VIEW.

(a)

(b)

FIGURE A-4. REPRESENTATION OF A CYLINDRICAL EXTENT
(a) TOP VIEW (b) FRONT VIEW.

FIGURE A-5. REPRESENTATION OF EIGHT RING STACK LOCATED SIX INCHES ABOVE FLOOR. (a) TOP VIEW (b) FRONT VIEW OF TOP PART (c) FRONT VIEW OF BOTTOM PART.

Table A-1

Geometry Cards For NSM3 Vault. Position 1 on the Mixed Box Orientation Cards.

```

BOX 1
SPHERE 3 5.656 16*.
CUBOID 0 15.24 -15.24 30.48 -15.24 24.624 -5.656 16*0.
BOX 2
CYLINDER 0 5.08 22.46 0. 16*0.
CYLINDER 3 10.16 22.46 0.16*0.
CUBOID 0 15.24 015.24 30.48 -15.24 22.86 07.62 16*0.
BOX 3
CYLINDER 0 5.08 3.175 0. 16*0.
CYLINDER 3 10.16 3.175 0. 16*0.
CUBOID 0 15.24 -15.24 30.48 -15.24 30.48 0.16*0.
BOX 4
CUBOID 0 15.24 -15.24 15.24 -30.48 30.48 0. 16*0.
BOX 5
CYLINDER 0 5.08 26.035 0. 16*0.
CYLINDER 3 10.16 26.035 0.16*0.
CUBOID 0 15.24 -15.24 30.48 015.24 30.48 0. 16*0.
BOX 6
CYLINDER 0 5.08 3.254375 0.16*0.
CYLINDER 3 10.16 3.254375 0. 16*0.
CUBOID 0 15.24 -15.24 30.48 -15.24 30.48 0. 16*0.
CORE BODY 0 45.72 -45.72 68.58 -68.58 274.32 0. 16*0.
CUBOID 0 60.96 -60.96 68.58 -68.165 313.69 0. 16*0.
CUBOID 2 60.96 -60.96 68.58 -68.263 313.69 0. 16*0.
CUBOID 1 121.92 129.34 -68.165 496.57 -60.96 16*0.
4 1 3 1 1 3 1 1 2 1 0
2 2 2 1 1 1 1 1 1 0
3 2 2 1 1 1 1 2 2 1 0
6 1 3 1 3 3 1 2 9 1 1
Mixed Box Orientation Corpus

```

GEOMETRY CARDS FOR EIGHT RING STACK 6 INCHES SEE STOCK

```

BOX 2
CYLINDER 0 5.08 15.24 0. 16*0
          3 10.16 15.24 0. 16*0
CUBOID 0 15.24 -15.24 30.48 -15.24 15.24 -15.24 16*0
BOX 3
CYLINDER C 5.08 10.795 0. 16*0
          3 10.16 10.795 0. 16*0
CUBOID 0 15.24 -15.24 30.48 -15.24 30.48 0. 16*0

```

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