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**CRITICALITY ASSESSMENT OF BASKET DESIGNS
FOR USE IN THE MH-1A SHIPPING CASK**

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ABSTRACT

An analytical study is made of a proposed stainless steel basket to be used in the MH-1A cask for the shipment of National Bureau of Standards reactor fuel elements. The use of B_4C in the basket as a primary control for the prevention of criticality is shown to be effective but not necessary. A basket fabricated of 0.635-cm-thick stainless steel provides a sufficient margin of subcriticality.

INTRODUCTION

The National Bureau of Standards (NBS) operates a research reactor utilizing fuel elements characterized as aluminum-plate type. Each element contains 310g of ^{235}U in the form of U_3O_8 clad by aluminum. There are two sets of 17 fuel bearing plates per element separated axially by ~ 15 cm. At the end of a life cycle in the reactor and after an appropriate decay period, the fuel elements are transported from the reactor site in the MH-1A shipping cask. The cask may be described as a cuboidal cavity having dimensions $37.5 \times 43.2 \times 132$ cm surrounded successively by a 1.27 cm thickness of stainless steel, 19.4 cm thickness of lead, and a 1.27 cm thickness of stainless steel. A basket, fabricated of stainless steel, is used as an insert in the cask to maintain the fuel element configuration. There are 16 channeled compartments available to receive the fuel-bearing portions sectioned from the elements. The capacity of the basket is 64 fuel element sections (32 fuel elements). A proposed design for the basket considers the use of B_4C as a primary control to prevent nuclear criticality during transport. The B_4C , as a Boral cruciform, divides the basket into quadrants in which only the stainless steel separates the sectioned elements. This study was undertaken at the request of the NBS to examine credible loadings of the cask and to characterize the efficiency of and necessity for the B_4C as a primary control. The method of evaluation was analytical utilizing the validated combination of the KENO Monte Carlo criticality program¹ and the Hansen-Roach 16 group cross section sets.² The neutron multiplication factor was calculated for various fuel element section configurations submerged, with and without the basket; initial and depleted ^{235}U loadings; and various loaded cask configurations.

CALCULATIONAL METHOD

The reliability of the k_{eff} computed by the combination of the KENO IV Monte Carlo criticality program and the Hansen-Roach cross section sets for aluminum-plate-type elements has been documented.^{3,4} Briefly, critical experiments performed at the Oak Ridge Critical Experiments Facility using fuel elements of the Oak Ridge Research Reactor (ORR) and SPERT-D fuel elements were reported^{5,6} in 1958 and 1965, respectively. The results of test calculations of appropriate experiments are reproduced in the Appendix. The conclusion of the analyses was that at most a negative bias of $0.02 \pm 1\sigma$ in k_{eff} could be expected and would imply that systems calculated to have a k_{eff} of 0.98 should be regarded as having a potential for criticality.

The present study used the KENO V Monte Carlo Code which extends the capability and options of the KENO IV code. Various calculations of close packed 4x4 arrangements of NBS fuel elements reported in the results to follow gave k_{eff} values comparable to the similar ^{235}U loaded ORR and HFBR* fuel elements given in Table A.3 of the Appendix. This is taken as confirmation that the geometry description and mathematical relations were being properly executed in the code and that the calculated k_{eff} 's would have the same bias as determined by the test calculations of the experiments.

The sectioned NBS fuel elements are described from as-built specifications** with respect to dimensions of plates, fuel loading, and assembled fuel element. The only minor approximation made in the description is the representation of the fuel plates as being flat rather than having the slight curvature as fabricated. This approximation is not discernible in the calculation of k_{eff} .

CALCULATED DATA

Submerged Basket

Operations in the pool area of the facility may involve the stainless steel basket out of the cask. Various loadings of the basket with sectioned elements were considered. A typical description of the geometry representation is presented in Table 1. Unit 1 of the table is a fuel bearing plate and describes half the water channel on either side of the plate, a portion of the end plate of the fuel element and stainless steel of the basket, and one-half the thickness of the stainless steel forming the grid of the basket. Units 2 and 3 are the aluminum end plates of the fuel element. A compartment containing a fuel element is described by assembling one aluminum plate (Unit 2) followed by 17 fuel bearing plates (Unit 1) and finally an aluminum plate (Unit 3). A 2x2 arrangement of compartments forms a quadrant of the loaded basket. The core boundary entry of the table (Unit 4) gives the dimension of the quadrant. The second region of the reflector adds the additional thickness of stainless steel to the outside faces of the basket and to the cruciform dividing the basket into quadrants. The +x and -y faces have a spectral reflector condition completing the 4x4 arrangement and representing the entire basket. The basket is reflected by a 30 cm thickness of water. The second reflector option given (Unit 4) describes the B₄C loading of the cruciform. The height of the basket is always the same as the height of stacked sectioned elements.

* Elements in use at the Brookhaven National Laboratory.

** Private communication from Mr. F. Sherman, Texas Instruments, Inc., Attleboro, MA.

Table 1. Basic Geometry Input for Fuel Elements in Submerged Basket

Region	Media Bias For ID	Geometry Description For Those Units Utilized In This Problem
		----- Unit 1 -----
1 Cuboid	1	+x = 3.1763 -x = -3.1763 +y = 3.8100E-02 -y = -3.8100E-02 +z = 13.937 -z = -13.937
2 Cuboid	1	+x = 3.3426 -x = -3.3426 +y = 6.3500E-02 -y = -6.3500E-02 +z = 16.310 -z = -16.310
3 Cuboid	1	+x = 3.3426 -x = -3.3426 +y = 2.1080 -y = -2.1080 +z = 16.310 -z = -16.310
4 Cuboid	1	+x = 3.8100 -x = -3.8100 +y = 2.1080 -y = -2.1080 +z = 16.310 -z = -16.310
5 Cuboid	1	+x = 4.4088 -x = -4.4088 +y = 2.1080 -y = -2.1080 +z = 16.310 -z = -16.310
6 Cuboid	1	+x = 4.5676 -x = -4.5676 +y = 2.1080 -y = -2.1080 +z = 16.310 -z = -16.310
		----- Unit 2 -----
1 Cuboid	2	+x = 3.3426 -x = -3.3426 +y = 8.0000E-02 -y = -8.0000E-02 +z = 16.310 -z = -16.310
2 Cuboid	3	+x = 3.3426 -x = -3.3426 +y = .42000 -y = -.42000 +z = 16.310 -z = -16.310
3 Cuboid	2	+x = 3.8100 -x = -3.8100 +y = .42000 -y = -.42000 +z = 16.310 -z = -16.310
4 Cuboid	3	+x = 4.4088 -x = -4.4088 +y = 1.2658 -y = -1.2658 +z = 16.310 -z = -16.310
5 Cuboid	4	+x = 4.5676 -x = -4.5676 +y = 1.4246 -y = -1.4246 +z = 16.310 -z = -16.310
		----- Unit 3 -----
1 Cuboid	2	+x = 3.3426 -x = -3.3426 +y = 8.0000E-02 -y = -8.0000E-02 +z = 16.310 -z = -16.310
2 Cuboid	3	+x = 3.3426 -x = -3.3426 +y = .23730 -y = -.23730 +z = 16.310 -z = -16.310
3 Cuboid	2	+x = 3.8100 -x = -3.8100 +y = .23730 -y = -.23730 +z = 16.310 -z = -16.310
4 Cuboid	3	+x = 4.4088 -x = -4.4088 +y = .23730 -y = -.23730 +z = 16.310 -z = -16.310
5 Cuboid	4	+x = 4.5676 -x = -4.5676 +y = .23730 -y = -.23730 +z = 16.310 -z = -16.310
		----- Unit 4 External to Lattice 1 -----
Reflector		
1 Core Boundary	0	+x = 9.1352 -x = -9.1352 +y = 10.471 -y = -10.471 +z = 50.265 -z = -50.265
2 Cuboid	28 4	+x = 9.3600 -x = -9.3600 +y = 10.629 -y = -10.629 +z = 50.265 -z = -50.265
		----- Unit 4 External to Lattice 1 -----
Reflector		
1 Core Boundary	0	+x = 9.1352 -x = -9.1352 +y = 10.471 -y = -10.471 +z = 50.265 -z = -50.265
2 Cuboid	30 5	+x = 9.3600 -x = -9.3600 +y = 10.471 -y = -10.471 +z = 50.265 -z = -50.265
3 Cuboid	28 4	+x = 9.3600 -x = -9.3600 +y = 10.629 -y = -10.629 +z = 50.265 -z = -50.265

**Table 2. Materials and Cross Section Sets Used in
Calculation of Submerged Basket**

**Mixing Table
Number of Scattering Angles = 1**

Entry	Mixture	Nuclide	Density
1	1	92503	1.40190E-03
2	1	92504	3.07730E-04
3	1	92842	9.15900E-05
4	1	92843	3.21800E-05
5	1	13100	5.31900E-02
6	1	8100	4.88910E-03
7	2	13100	6.02300E-02
8	3	502	1.00000E+00
9	4	200	1.00000E+00
10	5	5100	3.96300E-02
11	5	6100	9.98820E-03
12	5	26100	1.87960E-04
13	5	14100	1.06780E-04
14	5	13100	3.46810E-02

Cross Sections Read From The AMPX Working Library On Unit 4

200	Type 304 Stainless Steel	7.9G/CC	Contains C,CR,MN,FE,NT,SI
502	DE/E Water	0.9982G/CC	H=.066742 O=.033371
5100	BORON		Hansen Roach
6100	CARBON		Hansen Roach
8100	OXYGEN		Hansen Roach
13100	ALUMINUM		Hansen Roach
14100	SILICON		XSDRN
26100	IRON		Hansen Roach
92503	U-235-3R	SIG P = 60	Hansen Roach
92504	U-235-4R	SIG P = 100	Hansen Roach
92842	U-238	SIG P = 900	Hansen Roach
92843	U-238	SIG P = 1000	Hansen Roach

The medium numbers appearing in Table 1 represent the material description contained in each region and these are presented in Table 2.

The calculated neutron multiplication factors for the loaded basket are given in Table 3. Three configurations of sectioned elements are depicted in the diagrams below the table. The cruciform separating the basket into quadrants, the $+x$ and $-y$ faces of the diagrams, was considered as either solid stainless steel or as a B_4C core with a stainless steel cladding. Note that the total thickness of the cruciform is 0.768 cm, which includes a 0.45 cm thick core. The effects of various combinations of element location in compartments, number of tiers of elements and type of cruciform were explored.

The first entry of the table, for example, represents the basket loaded with 48 sections (3 in each of 16 compartments) centered in the compartments with a stainless steel cruciform. The second entry is the same except the cruciform contains the B_4C . These two results indicate the B_4C produces a Δk_{eff} of about 0.13. The sectioned full elements are displaced toward the center of the basket in the following two entries and produce an increase in the calculated k_{eff} for the stainless steel cruciform while the B_4C cruciform shows no change.

Entries 5 through 8 again compare the type of cruciform but also show the effect of removing the stainless steel between elements in a quadrant and the doubling of the number of tiers (96 sectioned elements). There is little axial coupling between tiers in the basket as shown by the entries 5 and 6. The coupling is not detectable when the B_4C cruciform is present (entries 7 and 8). Comparison of entries 1 and 5 indicate the stainless steel in the quadrants of the basket may be associated with a Δk_{eff} of about 0.10.

The clustering of elements in the quadrants of the basket produce the k_{eff} 's shown as entries 9 and 10. These are about the same as the first two entries and suggest a diminished B_4C effectiveness. The last entry is a fully loaded basket with elements in the most reactive configuration. This result, with fresh fuel elements, produces an acceptable margin of subcriticality.

An additional calculation was performed in which the top and bottom tiers were as diagram (c) of Table 3, while the second and third tiers were as diagram (b). The k_{eff} was 0.896 ± 0.005 .

Table 3. Neutron Multiplication Factor of Submerged Basket For Various Fuel Element Configurations And Basket Materials

case	Basket Loading and Description*			Calculated	
	$n_x \times n_y \times n_z$	element configuration	+x,-y	k_{eff}	$\pm\sigma$
1	4 x 4 x 3	(a)	(i)	0.854	0.005
2	4 x 4 x 3	(a)	(ii)	0.720	0.004
3	4 x 4 x 3	(b)	(i)	0.901	0.005
4	4 x 4 x 3	(b)	(ii)	0.715	0.005
5	4 x 4 x 3 [†]	(a)	(i)	0.959	0.004
6	4 x 4 x 6 [†]	(a)	(i)	0.978	0.005
7	4 x 4 x 3 [†]	(a)	(ii)	0.804	0.005
8	4 x 4 x 6 [†]	(a)	(ii)	0.802	0.004
9	4 x 4 x 3	(c)	(i)	0.836	0.005
10	4 x 4 x 3	(c)	(ii)	0.736	0.005
11	4 x 4 x 4	(b)	(i)	0.928	0.005

Two Conditions For +x and -y Faces

(i) Stainless steel 0.225-cm-thick

(ii) 0.159-cm-thick stainless steel followed by 0.225-cm-thick B₄C

[†] The stainless steel cross removed from quadrants of basket.

Effect of ^{235}U Content

Typical safety analyses of shipping spent fuel elements are based upon an evaluation of the transport casks loaded with fresh fuel elements. This practice ignores the presence of fission products and the diminished ^{235}U content of spent fuel. While fission products could be represented in the analysis, there is not general consensus of the make-up composition with respect to quantity, cross sections, and distribution among the fission products produced. This element of randomness is not present in the representation of ^{235}U content. It follows that the characterization of spent fuel as fresh fuel of reduced ^{235}U loading will result in calculated k_{eff} 's which approximate expected values of actual loadings as unachievable upper bounds.

The ^{235}U content of the sectioned fuel elements was reduced to 85, 75, 65, and 50 wt % of the initial value. The associated atom number densities are given in Table 4. The k_{eff} of 4x4 arrangements of sectioned elements, closely packed, having the description presented in Table 5 was calculated for 1, 2 and 4 tiers. These arrays are submerged and there is no stainless steel present. The calculated k_{eff} 's are given in Table 6. Comparison of these values with the appropriate entries of Table 3 shows an increased axial coupling for sectioned elements outside of the stainless steel basket. The calculation of the 4x4x2 array having the initial loading may be compared to the similar calculations of the ORR and HFBR fuel elements given in Table A3 of the Appendix. The ^{235}U surface densities of the ORR, NBSR and the HFBR fuel elements is 0.80, 0.86 and 1.06 g $^{235}\text{U}/\text{cm}^2$, respectively; however, there is little difference in the outside dimensions of the fuel elements and, hence, in the total volumes of the 4x4 arrays.

Normalizing the calculated k_{eff} 's of Table 6 to the initial loading value and averaging the ratios, it is possible to obtain a factor for the reduction of calculated k_{eff} 's of fuel element arrangements as a function of percent reduction of the initial loading. The result is presented in Fig. 1 and the factor may be applied to any of the calculated results of this study.

Table 4. Materials Description And Cross Sections Used
In Calculations With Reduced ^{235}U Content In
NBSR Fuel Elements

Mixing Table
Number of Scattering Angles = 1

Entry	Mixture	Nuclide	Density	Wt % of ^{235}U
1	1	92503	1.40190E-03	100
2	1	92504	3.07730E-04	
3	1	92842	9.15900E-05	
4	1	92843	3.21800E-05	
5	1	13100	5.31900E-02	
6	1	8100	4.88910E-03	
7	2	13100	6.02300E-02	
8	3	502	1.00000E+00	85
9	4	200	1.00000E+00	
10	6	92503	8.46020E-04	
11	6	92504	6.07180E-04	
12	6	92842	1.23770E-04	
13	6	13100	5.31900E-02	
14	6	8100	4.88910E-03	
15	7	92503	4.69820E-04	75
16	7	92504	8.12380E-04	
17	7	92841	1.96570E-05	
18	7	92842	1.04110E-04	
19	7	13100	5.31900E-02	
20	7	8100	4.88910E-03	
21	8	92503	9.38370E-05	65
22	8	92504	1.01750E-03	
23	8	92841	4.01650E-05	
24	8	92842	8.36050E-05	
25	8	13100	5.31900E-02	
26	8	8100	4.88910E-03	
27	9	92504	6.66650E-04	50
28	9	92505	1.88170E-04	
29	9	92841	7.09430E-05	
30	9	92842	5.28280E-05	
31	9	13100	5.31900E-02	
32	9	8100	4.88910E-03	

Table 4. (cont.)

Cross Sections Read From The AMPX Working Library On Unit 4

200	Type 304 Stainless Steel 7.9G/CC Contains C,CR,MN,FE,NI,SI		
502	DE/E Water 0.9982G/CC H=.066742 O=.033371		
8100	OXYGEN		Hansen Roach
13100	ALUMINUM		Hansen Roach
92503	U-235-3R	SIG P = 60	Hansen Roach
92504	U-235-4R	SIG P = 100	Hansen Roach
92505	U-235-5R	SIG P = 200	Hansen Roach
92841	U-238	SIG P = 800	Hansen Roach
92842	U-238	SIG P = 900	Hansen Roach
92843	U-238	SIG P = 1000	Hansen Roach

Table 3. Geometry Description Used In Assemblies Of Sectioned
MSR Fuel Elements Closely Packed And Submerged

Region	Media For	Size ID	Geometry Description For Those Units Utilized In This Problem							
----- Unit 1 -----										
1 Cuboid	1	1	+x = 3.1763	-x = -3.1763	+y = 3.8100E-02	-y = -3.8100E-02	+z = 13.957	-z = -14.280		
2 Cuboid	2	1	+x = 3.3426	-x = -3.3426	+y = 6.3500E-02	-y = -6.3500E-02	+z = 16.510	-z = -16.510		
3 Cuboid	3	1	+x = 3.3426	-x = -3.3426	+y = .21080	-y = -.21080	+z = 16.510	-z = -16.510		
4 Cuboid	2	1	+x = 3.8100	-x = -3.8100	+y = .21080	-y = -.21080	+z = 16.510	-z = -16.510		
----- Unit 2 -----										
1 Cuboid	2	1	+x = 3.3426	-x = -3.3426	+y = 8.0000E-02	-y = -8.0000E-02	+z = 16.510	-z = -16.510		
2 Cuboid	3	1	+x = 3.3426	-x = -3.3426	+y = .42000	-y = -.22730	+z = 16.510	-z = -16.510		
3 Cuboid	2	1	+x = 3.8100	-x = -3.8100	+y = .42000	-y = -.22730	+z = 16.510	-z = -16.510		
----- Unit 3 -----										
1 Cuboid	2	1	+x = 3.3426	-x = -3.3426	+y = 8.0000E-02	-y = -8.0000E-02	+z = 16.510	-z = -16.510		
2 Cuboid	3	1	+x = 3.3426	-x = -3.3426	+y = .22730	-y = -.42000	+z = 16.510	-z = -16.510		
3 Cuboid	2	1	+x = 3.8100	-x = -3.8100	+y = .22730	-y = -.42000	+z = 16.510	-z = -16.510		
----- Unit 4 External to Lattice 1 -----										
Reflector										
1 Core Boundary	0	1	+x = 6.1048	-x = -9.1352	+y = 6.4526	-y = -10.471	+z = -17.245	-z = -50.265		

**Table 6. Calculated Neutron Multiplication Factor For Arrays
Of Closely Packed Sectioned Fuel Elements When
Submerged**

Percent fresh fuel loading	Calculated* k_{eff} for close-packed array configuration, n_x, n_y, n_z		
	4x4x4	4x4x2	4x4x1
100	1.144	1.091	1.029
85	1.114	1.079	—
75	1.068	1.052	0.980
65	1.047	1.017	0.940
50	0.989	0.954	0.895

* Standard deviation does not exceed 0.005.

Loaded Cask

The major effect of the cask is that it is a more effective neutron reflector than water for the basket loaded with fresh NBSR sectioned fuel elements. The Monte Carlo code input geometry of the cask loaded with the fuel element sections centered in the basket compartments is given in Table 7. The material description input data is presented in Table 8. The calculated neutron multiplication factors of the cask loaded with three and four tiers of sectioned fuel elements in two configurations are given in Table 9.

The first entry of the table has the basket as described in the second entry of Table 3 which is used to evaluate the additional Δk_{eff} of the cask in place of water as 0.06. The second entry of Table 9 evidences an acceptable margin of subcriticality for the three-tier loading for a basket fabricated of 0.635-cm-thick stainless steel. The third entry has an additional tier of sectioned elements and the sections displaced toward the center of the cask. These two changes result in a positive Δk_{eff} of 0.04 to the configuration of the second entry. The k_{eff} of 0.95 represents a reduced but acceptable margin of subcriticality.

The fourth entry shows the effect of reducing the thickness of stainless steel in the quadrants of the basket to 0.32 cm as producing a Δk_{eff} of ~ 0.04 . The k_{eff} of 0.981 must be regarded as having a potential for criticality; hence, a minimum stainless steel thickness for the basket of 0.64 cm is suggested if B_4C is not used to separate quadrants. The final entry of Table 9 confirms the applicability of factors given in Fig. 1 to estimate the effect on k_{eff} due to reduced ^{235}U content. The factor from Fig. 1 for a 35 wt % reduction in ^{235}U is 0.9242. The k_{eff} of the third entry is 0.945 and the product of these two values is 0.87 in reasonable agreement with the calculated k_{eff} of 0.839.

Figure 2 displays the k_{eff} of the cask loaded to capacity (64 sectioned elements) with fresh fuel as a function of ^{235}U content. The two curves shown can be taken as upper bounds for the k_{eff} of the loaded cask. The solid curve, sectioned elements displayed toward center, is at most credible only if the cask were deliberately loaded in this configuration. The lower dashed curve is more likely to represent a random loading and it is inferred from the previous calculations with sectioned elements submerged. In either case these curves are over-estimates of expected k_{eff} 's if the reduced content is a result of ^{235}U fissioning.

Table 7. Geometry Description of MH-1A Shipping Cask And Loading

Region	Media For	Bias ID	Geometry Description For Those Units Utilized In This Problem					
----- Unit 1 -----								
1 Cuboid	1	1	+x = 3.1763	-x = -3.1763	+y = 3.8100E-02	-y = -3.8100E-02	+z = 13.937	-z = -14.280
2 Cuboid	2	1	+x = 3.3426	-x = -3.3426	+y = 6.3500E-02	-y = -6.3500E-02	+z = 16.510	-z = -16.510
3 Cuboid	3	1	+x = 3.3426	-x = -3.3426	+y = .21030	-y = -.21080	+z = 16.510	-z = -17.000
4 Cuboid	2	1	+x = 3.8100	-x = -3.8100	+y = .21080	-y = -.21080	+z = 16.510	-z = -17.000
5 Cuboid	3	1	+x = 4.4088	-x = -4.4088	+y = .21080	-y = -.21080	+z = 16.510	-z = -17.000
6 Cuboid	4	1	+x = 4.5676	-x = -4.5676	+y = .21080	-y = -.21080	+z = 16.510	-z = -17.000
----- Unit 2 -----								
1 Cuboid	2	1	+x = 3.3426	-x = -3.3426	+y = 8.0000E-02	-y = -8.0000E-02	+z = 16.510	-z = -17.000
2 Cuboid	3	1	+x = 3.3426	-x = -3.3426	+y = .42000	-y = -.22730	+z = 16.510	-z = -17.000
3 Cuboid	2	1	+x = 3.8100	-x = -3.8100	+y = .42000	-y = -.22730	+z = 16.510	-z = -17.000
4 Cuboid	3	1	+x = 4.4088	-x = -4.4088	+y = 1.2658	-y = -.22730	+z = 16.510	-z = -17.000
5 Cuboid	4	1	+x = 4.5676	-x = -4.5676	+y = 1.4246	-y = -.22730	+z = 16.510	-z = -17.000
----- Unit 3 -----								
1 Cuboid	2	1	+x = 3.3426	-x = -3.3426	+y = 8.0000E-02	-y = -8.0000E-02	+z = 16.510	-z = -17.000
2 Cuboid	3	1	+x = 3.3426	-x = -3.3426	+y = .22730	-y = -.42000	+z = 16.510	-z = -17.000
3 Cuboid	2	1	+x = 3.8100	-x = -3.8100	+y = .22730	-y = -.42000	+z = 16.510	-z = -17.000
4 Cuboid	3	1	+x = 4.4088	-x = -4.4088	+y = .22730	-y = -1.2658	+z = 16.510	-z = -17.000
5 Cuboid	4	1	+x = 4.5676	-x = -4.5676	+y = .22730	-y = -1.4246	+z = 16.510	-z = -17.000
----- Unit 4 External to Lattice 1 -----								
Reflector								
1 Core Boundary	0	1	+x = 9.1352	-x = -9.1352	+y = 10.471	-y = -10.471	+z = 50.265	-z = -50.265
2 Cuboid	5	1	+x = 9.3600	-x = -9.1352	+y = 10.471	-y = -10.696	+z = 50.265	-z = -50.265
3 Cuboid	3	1	+x = 9.3600	-x = -9.1352	+y = 10.471	-y = -10.696	+z = 66.040	-z = -66.040
4 Cuboid	4	1	+x = 9.3650	-x = -10.405	+y = 11.741	-y = -10.696	+z = 67.310	-z = -67.310
5 Cuboid	6	1	+x = 9.3600	-x = -29.772	+y = 31.108	-y = -10.696	+z = 86.678	-z = -86.678
6 Cuboid	4	1	+x = 9.3600	-x = -31.042	+y = 32.378	-y = -10.696	+z = 87.948	-z = -87.948

**Table 8. Materials And Number Densities Used In
MH-1A Shipping Cask Calculations**

**Mixing Table
Number of Scattering Angles = 1**

<u>Entry</u>	<u>Mixture</u>	<u>Nuclide</u>	<u>Density</u>
1	1	92503	1.40190E-03
2	1	92504	3.07730E-04
3	1	92842	9.15900E-05
4	1	92843	3.21800E-05
5	1	13100	5.31900E-02
6	1	8100	4.88910E-03
7	2	13100	6.02300E-02
8	3	502	1.00000E+00
9	4	200	1.00000E+00
10	5	5100	3.96300E-02
11	5	6100	9.98820E-03
12	5	26100	1.87960E-04
13	5	14100	1.06780E-04
14	5	13100	3.46810E-02
15	6	82100	3.29900E-02

Cross Sections Read From The AMPX Working Library On Unit 4

200	Type 304 Stainless Steel	7.9G/CC	Contains C,CR,MN,FE,NT,SI
502	DB/E Water	0.9982G/CC	H=.066742 O=.033371
5100	BORON		Hansen Roach
6100	CARBON		Hansen Roach
8100	OXYGEN		Hansen Roach
13100	ALUMINUM		Hansen Roach
14100	SILICON		XSDRN
26100	IRON		Hansen Roach
82100	LEAD		XSDRN
92503	U-235-3R	SIG P = 60	Hansen Roach
92504	U-235-4R	SIG P = 100	Hansen Roach
92842	U-238	SIG P = 900	Hansen Roach
92843	U-238	SIG P = 1000	Hansen Roach

..... 325 IO's Were Used Mixing Cross-Sections

..... 45 IO's Were Used Preparing The Cross-Sections

Table 9. Calculated Neutron Multiplication Factor Of The
MH-1A Shipping Cask For Various Loadings And
Cask Configurations

Cask	Cask Loading	Basket Description Stainless Steel Thickness, cm		Calculated	
	$n_x=n_y=4, n_z$	Between Elements A Quadrant	Between Quadrants	k_{eff}	$\pm \sigma$
1	3	0.318	$0.767(w/B_4C)^a$	0.781	0.004
2	3	0.635	0.635	0.902	0.005
3	4^b	0.635	0.635	0.945	0.005
4	4^b	0.318	0.635	0.981	0.005
5	$4^{b,c}$	0.635	0.635	0.839	0.005

^a The B_4C is 0.45-cm-thick and has a 0.159-cm-thick stainless steel cladding.

^b The sectioned elements in each compartment are displaced toward the center of the cask.

^c The ^{235}U content of sectioned elements is reduced to 65% of the fresh fuel loading.

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Fig. 1 System response to reduction in ^{235}U content of fuel elements

Fig. 2 Neutron multiplication factor of MH-1A shipping cask as a function of ^{235}U content of fresh fuel

DISCUSSION AND CONCLUSION

The results presented in Table A-2 demonstrate that the analytic method employed in this study is within the area of applicability established by the calculation of critical experiments using the KENO Monte-Carlo Criticality Program and the Hansen-Roach cross section sets. The calculated k_{eff} for the systems examined responds in an appropriate manner to the changes in parameters made and the data appear to be internally consistent. The worth of the B_4C in the cruciform of the basket shows some dependence on the loading configuration. Overall, the B_4C effectiveness in producing a negative Δk_{eff} is, in magnitude, more than sufficient to prevent criticality in the fully loaded cask. Furthermore, the k_{eff} 's produced by changes in loading configurations are greatly diminished from that possible when it is removed; as evidenced, for example, by the axial neutron coupling between tiers in the basket. It would appear, however, that the B_4C is not necessary as a primary control. If used in a basket, it would be reasonable to permit suspension of the requirement for periodic inspections and confirmation of its efficiency. Initial verification before putting the basket into service would be sufficient.

The calculated data show that criticality is not possible with a basket fabricated of 0.635-cm-thick stainless steel loaded to capacity with fresh fuel. This is observed with the basket submerged or in the cask. The cask is a better neutron reflector than water for arrays of this type of fuel element. The calculated Δk_{eff} of 0.06 for the change in reflector condition is not sufficient to pose a threat of criticality; i.e., the margin of subcriticality remains sufficient for normal and credible abnormal operations.

Since the metal-to-water ratio for the fabricated fuel elements is less than that capable of producing a maximum reactivity to a system, it follows that any reduction in water density, by temperature or voiding, will result in negative Δk_{eff} to the systems examined. The cask has sufficient integrity that it would seem that the condition of the cask, undamaged or damaged, would be of secondary concern to criticality.

The purpose of the cask is the transport of used fuel elements. Spent fuel elements are generally those that are no longer useful to sustain a nuclear chain reaction in the reactor. This is a result of the depleted ^{235}U content and the increased absorption of neutrons by the concomitant products of the fissioning process. The result of these accompanying effects and their impact on the margin of subcriticality are additions to the margin of safety in the use of the cask. The summary presented in Fig. 2 for the effect of reduced ^{235}U content alone is sufficient demonstration for the validity of expected lower k_{eff} 's than those calculated.

Ample evidence has been presented in this work to support the following conclusions.

- the presence of B_4C as a primary control for the prevention of criticality is not necessary,
- a basket fabricated of 0.535-cm-thick stainless steel provides a sufficient margin of subcriticality for shipment of fuel elements in the MH-1A cask, and
- NBSR fuel elements, or similar fuel elements, may be shipped in the MH-1A cask during any time in the element's life cycle.

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APPENDIX

VALIDATION OF CALCULATIONAL METHOD

Critical experiments with ORR and Bulk Shielding Reactor (BSR) fuel elements were performed at the Oak Ridge Critical Experiments Facility (ORCEF) and reported⁵ in 1953. A series of measurements established that a minimum of 15 elements containing 168 g ^{235}U each in a 4x4 matrix with a corner position vacant would be critical if the spacing between elements were 0.508 cm (0.5 in.). Other measurements used 12 of the 168 g elements with four other elements, having a 140 g ^{235}U loading, in two different arrangements of a 4x4 matrix with zero spacing between elements. Critical experiments with the SPERT-D fuel elements were also conducted at the ORCEF and reported⁶ in 1965. These elements contained 306.5 g ^{235}U . The SPERT-D plates have 57% more ^{235}U than the ORR plates and both were fabricated with a uranium-aluminum alloy* core clad with aluminum. There are 19 plates in the ORR element and 22 in the SPERT-D element. It is notable that the minimum critical mass is observed for the ORR 168 g ^{235}U elements, although fewer SPERT-D elements are required for criticality.

The ORR fuel elements are fabricated with curved plates. The two outer plates of an element are thicker (0.165 cm) than the 17 interior plates (0.127 cm). The element is described in the code as having flat plates. This is not a significant perturbation as the spacing between plates and between adjacent fuel elements is preserved. The dimensions of the fuel region in the plates and the atom number densities are given in Table 1. The experiments were calculated with the KENO Monte Carlo¹ code using the Hansen-Roach² 16-group neutron cross section sets. The arrangement of the fuel elements and the calculated k_{eff} 's of the selected experiments are presented in Table 2. The second and third entries of the table show the effect of the relocation of the lighter (L) ORR elements. Criticality was achieved when the lighter elements were located symmetrically positioned at the outer boundaries of the array. Subcriticality resulted when the lighter elements occupied the central region of the array. These experiments are a significant test of the geometry description of the fuel elements in the code and of the cross section set used.

* Current operations at ORR use an oxide of uranium with aluminum in place of the metal alloy.

The influence of cross section set selection on the calculated k_{eff} was explored by repeating the calculations of Table 2 using the Bonami option for cross section treatment in the AMPX system.⁷ The results of these tests suggest that the normal procedure for determining cross section sets to be used, i.e., on the basis of scattering potential, σ_p , could result in at most a negative bias of 0.02 in k_{eff} with an uncertainty of ± 0.1 . This implies that systems calculated to have a k_{eff} of 0.98 should be regarded as having a potential for criticality.

Table A-1. Description Of Fuel Plates And Atom Number Densities

<u>Element</u>	<u>ORR</u>	<u>ORR</u>	<u>SPERT-D</u>
^{235}U per element, g	168	140	306.5
No. of plates	19	19	22
<u>Fuel Region Dimensions, cm</u>			
width	6.2865	6.2332	
length	59.8348	60.9600	
thickness	0.0598	0.0508	
<u>Atom Densities($\times 10^{-24}$)</u>			
^{235}U	8.61079-4	7.18747-4	1.84954-3
^{235}U	6.22380-5	5.19507-5	1.33875-4
^{27}Al	4.14310-2	4.21440-2	5.53596-2
<u>Plate Dimensions, cm</u>			
width	7.11708	6.8682	
length	62.5475	63.8175	
thickness	0.127	0.1524	

Table A-2. Calculated k_{eff} For Critical Experiments
With OER and SPENT-D Fuel Elements

Number of Elements	Arrangement	Surface Separating, cm	Calculated k_{eff}	Experiment
<u>OER Elements</u>				
15		0.508	0.995 ± 0.005	Critical
16*		0.0	0.993 ± 0.005	Critical
16*		0.0	0.976 ± 0.005	Subcritical
<u>SPENT-D Elements</u>				
4 x 3.77 (17 plates in top row)		0.0	0.985 ± 0.005	Critical
4 x 3.09 (2 plates in top row)		1.27	0.992 ± 0.005	Critical

* Blank locations designate elements with 168 g ^{235}U ; "L" in location designates 140 g ^{235}U elements.

Calculations were also performed on arrangements typical of critical experiments with the ORR and HFBR fuel elements. These are presented in Table A-3.

Table A-3. Calculated Neutron Multiplication Factor For Submerged Arrangements of ORR and of HFBR Fuel Elements

Elements are in contact.

Fuel Number	Element Arrangement	k_{eff}		
		300 g ORR	350 g ORR	350 g HFBR
16	XXXX XXXX XXXX XXXX	1.138 ± 0.008	1.167 ± 0.008	1.132 ± 0.008^a
12	XXXX XXXX XXXX	1.040 ± 0.007	1.087 ± 0.007	1.054 ± 0.010
10	XX XXXX XXXX	1.012 ± 0.008^b	1.038 ± 0.006^c	1.007 ± 0.007
12	XXXX X X X X XXXX	0.922 ± 0.009	0.926 ± 0.008	0.908 ± 0.005

^a $k_{eff} = 0.844 \pm 0.012$ when surface separation of elements is 5.08 cm.

^b Replacing central two elements with 350 g ORR elements gave k_{eff} of 1.013 ± 0.007 .

^c Replacing central two elements with 300 g ORR elements gave k_{eff} of 1.031 ± 0.007 .