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Nuclear Criticality Assessment of Oak Ridge Research Fuel Element Storage

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NUCLEAR CRITICALITY ASSESSMENT OF OAK RIDGE
RESEARCH FUEL ELEMENT STORAGE

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ABSTRACT

Spent and partially spent Oak Ridge Research Reactor (ORR) fuel elements are retained in the storage section of the ORR pool facility. Determination of a maximum expected neutron multiplication factor for the storage area is accomplished by a validated calculational method. The KENO Monte Carlo code and the Hansen-Roach 16-group neutron cross section sets were validated by calculations of critical experiments performed with early ORR fuel elements and with SPERT-D fuel elements. Calculations of various fuel element arrangements are presented which confirm the subcriticality previously inferred from critical experiments and indicate the k_{eff} would not exceed 0.85, were the storage area to be filled to capacity with storage racks containing elements with the fissionable material loading increased to 350 g of ^{235}U .

INTRODUCTION

During the life cycle of a fuel element in typical operations of the ORR reactor, the element may spend several extended periods in storage. In addition, storage space is allocated to completely spent fuel elements which remain in storage to permit sufficient radioactive decay and to accumulate a fuel element shipment lot. These activities with elements outside the reactor core must be conducted in a manner that assures the subcriticality of all operations.

The criticality safety of present procedures was established on the basis of critical experiments performed with ORR fuel elements prior to 1958. Consideration is being given to increasing the fissionable material loading of the elements. It is an appropriate time to reconfirm the subcriticality of operations and to estimate the k_{eff} that may be expected from the proposed higher material loadings.

The variation in burnup and fuel element rotation implies the determination of subcriticality for any specific configuration would be singularly complex and not generally applicable. A conservative estimate of a maximum value of k_{eff} would result from the assumption of fresh elements in the analysis. The evaluation is conducted by a validated calculational method.

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 reported¹ in 1958. A series of measurements established that a minimum of 15 elements containing 168 g ^{235}U each in a 4×4 matrix with a corner position vacant would be critical if the spacing between elements were 0.508 cm (0.2 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 4×4 matrix with zero spacing between elements. Critical experiments with the SPERT-D fuel elements were also conducted at the ORCEF and reported² 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.

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

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 Carlo³ code using the Hansen-Roach⁴ 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.

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.⁵ 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 $+1\sigma$. This implies that systems calculated to have a k_{eff} of 0.98 should be regarded as having a potential for criticality.

Table 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	0.0698		0.0508
<u>Atom Densities ($\times 10^{-24}$)</u>			
^{235}U	8.61079-4	7.18747-4	1.84954-3
^{238}U	6.22380-5	5.19507-5	1.33875-4
^{27}Al	4.14310-2	4.21440-2	5.53536-2
<u>Plate Dimensions, cm</u>			
width	7.11708		6.8682
length	62.5475		63.8175
thickness	0.127		0.1524

CALCULATED ARRANGEMENTS OF FUEL ELEMENTS

A typical storage rack is shown in Fig. 1. There are three rows of 10 elements each, and these are separated by at least 15.2 cm of water. The region between rows within the rack is not accessible to elements. The guardrail and supporting gussets on the lateral surfaces maintain a 30 cm separation between elements in different storage racks. The dimensions of a fuel element storage position are 8.7 x 8.7 x 91.4 cm. The rack is fabricated of aluminum, and the partitions defining compartments are 0.32 cm thick. The surface separation of adjacent elements in a row may vary from 0.32 to about 1.2 cm.

Table 2. Calculated k-eff for critical experiments
with ORR and SPERT-D fuel elements

Number of Elements	Arrangement	Surface Separating, cm	Calculated k-eff	Experiment
ORR Elements				
15		0.508	0.995 ± 0.005	Critical
16*		0.0	0.993 ± 0.005	Critical
16*		0.0	0.976 ± 0.005	Subcritical
SPERT-D Elements				
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.

Fig. 1. ORR fuel storage rack.

A detailed description of a single rack having SPERT-D elements in the storage positions was calculated. The resulting k_{eff} was 0.68 ± 0.01 and is the first entry of Table 3. The rack is not present in the remaining entries of the table. The second SPERT-D entry indicates a more reactive configuration when the aluminum of the rack is removed, and the rows are separated 15.2 cm. The calculations of the ORR and the High Flux Beam Reactor (HFBR) elements, also shown in the second row of the table, imply

a more reactive configuration than is achievable in the storage pool since these results overestimate the possible coupling of several storage racks available at the facility. The remaining entries of the table confirm the experimentally inferred subcriticality² of two infinite rows of SPERT-D elements in contact and give comparative results for the ORR and HFBR elements in similar arrangements. Unlike the HFBR and SPERT-D fuel elements, the outer plates of the ORR fuel element are fuel bearing. This implies that additional reactivity is potentially available to the calculated ORR arrangements were the fuel elements to be slightly separated ($\sim 0.5 - 2$ cm). As the distance between fuel bearing plates in an array of HFBR elements when in contact is about 1.2 cm, comparison with ORR calculations allows an estimate of the expected Δk_{eff} .

Additional calculations of storage conditions were performed. These concerned the evaluation of the situation where an element is accidentally dropped between two storage racks. The expected increase in k_{eff} was evaluated from the calculations of two rows containing 10 each of 300 g ^{235}U elements separated by 24 cm. The elements in the rows were in contact. Calculations were performed with and without two 350 g ^{235}U elements in contact and centered in the space between rows. The k_{eff} 's were 0.840 ± 0.007 and 0.795 ± 0.009 , respectively, giving a Δk_{eff} of about 0.05. The calculations were repeated with the spacing between rows equal to 15.2 cm and resulted in a neutron multiplication factor of 0.953 ± 0.010 the two 350 g ^{235}U elements centered between the rows and 0.802 ± 0.009 without the extra elements. The Δk_{eff} for this closer spacing is about 0.15. These results suggest that a single fuel element

between two storage racks located no closer than 30 cm would be about equal to the uncertainty in the calculations of Table 3, i.e., about 0.01 in k_{eff} .

Table 3. Calculated neutron multiplication of various fuel elements in storage related configurations

Total Number of Elements	Arrangement Number and Surface Separation, (cm)		k_{eff}			
			SPERT-D	ORR		HFBR
			306.5 g	300 g	350 g	300 g
30 ^a	10,1.2	3,16.3	0.67 ± 0.01			
30	10,0	3,15.2	0.715 ± 0.008	0.73 ± 0.01	0.72 ± 0.01	0.80 ± 0.01
-	- ,0	- ,15.2	0.78 ± 0.01	0.86 ± 0.01	0.88 ± 0.01	0.85 ± 0.01
-	- ,0	2,0	0.974 ± 0.008	1.07 ± 0.01	1.08 ± 0.01	1.04 ± 0.01
-	- ,0	2,1.2	0.994 ± 0.008			
-	- ,0	2,7.6	0.882 ± 0.007			
-	- ,16.4	2,16.4	0.55 ± 0.01			
Element Description						
²³⁵ U per element, g			306.5	300	350	350
Number of Plates per element			22	19	19	18
Atom number densities of core loading:						
²³⁵ U			1.8495-3	2.1182-3	2.4713-3	2.6141-3
²³⁹ U			1.3388-4	1.5355-4	1.7916-4	1.8832-4
¹⁴⁰ U				6.0531-3	7.0678-3	7.4730-3
²⁷ Al			5.5359-2	5.1604-2	5.0159-2	5.2387-2
Plate Core Dimension, cm						
Width			6.233	6.289		5.697
Length			60.960	59.848		58.054
Thickness			0.0508	0.0508		0.0579
Outer Plate Dimensions, cm						
Width			6.609	6.670		6.213
Length			63.818	62.548		60.324
Thickness			0.112	0.127		0.128

^aAluminum rack included in this calculation only.

^b $k_{eff} = 0.772 \pm 0.011$ when surface separation of elements is 5.08 cm within and between the two rows.

Finally, calculations were performed on arrangements typical of critical experiments with the ORR and HFBR fuel elements. These are presented in Table 4.

These calculations are consistent with the results of Table 3 and provide further insight to the nuclear criticality safety assessment of higher ^{235}U loaded ORR elements.

Table 4. 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 $k_{\text{eff}} = 0.844 \pm 0.012$ when surface separation of elements is 5.08 cm.

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

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

CONCLUSIONS

A reasonable upper limit to an expected k_{eff} for storage operations at the ORR pool facility is 0.85. Under the present ORR element loading, a $k_{\text{eff}} \leq 0.75$ is a more probable value. These limits are also applicable to the incident where a fuel element is inadvertently placed or dropped between two storage racks. There is a sufficient margin of subcriticality in established procedures to adequately provide for the handling of fuel elements with up to 350 g ^{235}U loadings. No significant evidence appeared in the course of this study to suggest that elements of different loadings be segregated, although this may be dictated by other requirements.

RECOMMENDATIONS

Since the present operational procedures are adequate and there was no suggestion that the risk of criticality is changed, no specific recommendations are necessary.

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