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Nuclear Criticality Safety of the Fuel Element Fabrication Facility at Attleboro, Massachusetts

J. T. Thomas

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C-46

Printed in the United States of America. Available from
National Technical Information Service
5285 Port Royal Road
Springfield, Virginia 22161

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ORNL/CSD/TM-55
Distribution Category
UC-46

Contract No. W-7405 eng 26

COMPUTER SCIENCES DIVISION

NUCLEAR CRITICALITY SAFETY OF THE FUEL ELEMENT FABRICATION FACILITY AT ATTLEBORO, MASSACHUSETTS

J. T. Thomas

Date Published - June, 1978

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NUCLEAR CRITICALITY SAFETY OF THE FUEL ELEMENT FABRICATION FACILITY AT ATTLEBORO, MASSACHUSETTS

J. T. Thomas

ABSTRACT

The Attleboro Facility produces fuel elements for the ORR and the HFIR reactors at the Oak Ridge National Laboratory and for the HFBR reactor at the Brookhaven National Laboratory. It is proposed to utilize the criticality indicator system (CI) as a method for nuclear criticality control at the Attleboro fuel element fabrication facility. Application of the method requires an evaluation be made of the effect of hydrogenous moderation on the potential neutron multiplication factor of operations. Analyses are given which confirm the applicability of the CI system under credible normal and possible abnormal contingencies. It is also shown that no significant neutron multiplication occurs during normal operations and that a k_{eff} not exceeding 0.5 may be expected for abnormal conditions.

INTRODUCTION

Fuel elements are fabricated at the manufacturing facility in Attleboro, Massachusetts, operated by the Texas Instruments Corporation. Elements are produced for the Oak Ridge National Laboratory (ORNL) for use in the HFIR and the ORR reactors and for the Brookhaven National Laboratory (BNL) for use in the HFBR reactor. The Criticality Indicator system (CI) described in the Nuclear Safety Guide[1] provides the bases for control of nuclear criticality safety in the plant. The system controls the neutron interaction among subcritical quantities of fissionable materials in the absence of intervening hydrogenous moderation. The Nuclear Safety Guide recommends that, when hydrogenous moderation is a credible possibility, the effects of the moderation on the system be investigated by a validated calculational method. Since the fire protection capability of the plant incorporates a water sprinkler system, it is necessary to assess the effect on the degree of subcriticality of operations caused by possible moderation within areas and materials. The following analyses performed by a validated calculational method evaluate the effect of moderation on operations with materials in the form used in the plant.

Validation of Calculational Method

Critical experiments with ORR and BSR fuel elements were performed at the Oak Ridge Critical Experiments Facility (ORCEF) and reported[2] in 1958. A series of measurements established that a minimum of 15 elements containing 168 g of ^{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.). Another measurement used 12 of the 168 g elements with four elements having 140 g of ^{235}U in two different arrangements in a 4 × 4 pattern with zero spacing.

Critical experiments with the SPERT-D fuel elements were also conducted at the ORCEF and reported[3] in 1965. These elements contain 306.5 g of ^{235}U. The SPERT-D plates contain 57% more ^{235}U than the ORR plates and both were fabricated* with a uranium-aluminum alloy clad in aluminum.

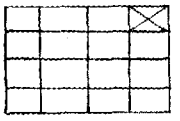
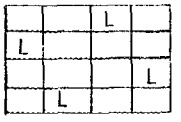
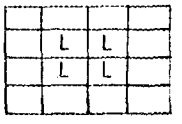
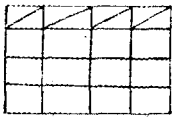
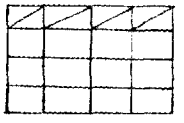
The dimensions of the fuel region in the plates and the atom number densities are given in Table 1. The experiments were calculated with the KENO Monte Carlo[4] code using the Hansen-Roach[5] 16-group neutron cross section sets. The arrangement of the fuel elements and the calculated k_{eff} are presented in Table 2. The influence of cross section set selection on the calculated k_{eff} was explored by repeating the calculations using the BONAMI option for cross section treatment in the AMPX system[6]. The results of these tests suggest that the normal procedure for determining cross section sets to be used, i.e., on the basis of σ_p, could result in at most a negative bias of 0.02 in k_{eff} with an uncertainty of $\pm 1\sigma$. This implies that systems calculated to have a k_{eff} of 0.98 should be regarded as having potential for criticality.

Table 1. Description of fuel plates and atom number densities

Element	ORR	ORR	SPERT-D
^{235}U per element, g	168	140	306.5
No. of plates	19	19	22
Fuel Region Dimensions, cm			
width	6.2865		6.2332
length	59.8348		60.9600
thickness	0.0698		0.0508
Atom Densities ($\times 10^{-24}$)			
^{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	5.53596-2
Plate Dimensions, cm			
width	7.11708		6.8682
length	62.5475		63.8175
thickness	0.127		0.1524

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

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 × 3.77 (17 plates in top row)		0.0	0.985 ± 0.005	Critical
4 × 3.09 (2 plates in top row)		1.27	0.992 ± 0.005	Critical

*L designates 140 g/element, remaining are 168 g/elements.

Application of Method

Fuel plates

The BNL fuel plates have a larger uranium loading than the elements produced for ORNL. The following analyses utilize the characteristics of the BNL element plates as described in Table 3. A waterproof cardboard box (35.6 × 17.8 × 61 cm, nominal) having a mass of 1.4 kg is used to transfer and store the fuel plates. The plates are arranged in a 3 × 8 matrix within the box and are separated by sheets of polyvinylchloride (CH_2CHCL at $\rho = 0.9016$ g/cm^3) for physical protection. There is approximately 800 grams of PVC per box as seven sheets, each about 0.06 cm in thickness. A box does prevent moderation between plates within the box; however, such internal moderation is examined. Storage of boxes is in separated linear arrays located along the outer boundaries of large operational areas (12 × 15 m, typically). The floors are of concrete and the building of light structure. A conservative representation is to coalesce all the storage arrays into a cuboidal

Table 3. BNL fuel plate description

	Fuel Region	
mass, g		Atom density ($\times 10^{-24}$)
U_3O_8	24.765	^{235}U = 2.61406-3
U(93.16)	20.962	^{238}U = 1.88321-4
Al	44.95	^{16}O = 7.47300-3
		^{27}Al = 5.23867-2
Dimensions, cm		
width	5.697	
length	58.054	
thickness	0.0579	
	Dimensions of Plate, cm	
width	6.632	
length	60.324	
thickness	0.128	

arrangement and to surround the resulting array with a closely fitting reflector of concrete 40.6 cm thick. This results in minimizing neutron leakage from the materials, enhancing neutron coupling among boxes and maximizing neutron reflection of the arrays. There are about two hundred box locations in the plant; however, the CI system specifies subcriticality for arrays of boxes two orders of magnitude greater than those in the plant. Analysis of larger arrays than anticipated represents a greater material inventory than is actually present, results in larger k_{eff} values than may be reasonably expected, and validates the generic bases of the CI system.

Calculations of the cuboidal arrays are presented in Table 4 as a function of the number of boxes, of the water density in and out of the boxes, and for the cardboard and a proposed aluminum box of the same dimensions but with 0.09-cm-thick walls. The code input used the aluminum box dimensions, and representation of the cardboard in this region was at a greater than normal density to maintain the cardboard mass. This perturbation has no significant effect on the calculated k_{eff}. The first four entries of the table compare the effect of the cardboard and aluminum boxes and their internal moderation by low density water. The $N = 12^3$ arrays of the first entry show the cardboard as an effective moderator. The $N = 8^3$ arrays with variable water density in the boxes explore the moderation effect on k_{eff} in the aluminum boxes. The fourth entry for $N = 12^3$ shows the reduced effectiveness of the cardboard as a moderator when the boxes contain low density water. This indicates the array of cardboard boxes is near optimum moderation when water at $\rho = 0.05$ is present. The remaining three entries of the table are with the boxes separated ~30 cm horizontally, ~12 cm vertically and in contact in the direction of plate length. This permits array moderation between boxes to be examined.

Table 4. Calculated k_{eff} of concrete reflected arrays of storage boxes having uranium-aluminum plates bearing ∿ 21 g U(93.2) per plate

Boxes contain 3 x 8 matrix of plates separated by polyvinylchloride.

Separation of Boxes in Array	Density of Water (g/cm^3) Between Plates	Density of Water (g/cm^3) Between Boxes	Number of Boxes in Concrete Reflected Array: Cardboard Boxes 12^3	Cardboard Boxes 16^3	Cardboard Boxes 20^3	Aluminum Boxes 8^3	Aluminum Boxes 10^3	Aluminum Boxes 12^3	Aluminum Boxes 16^3	Aluminum Boxes 20^3
0	0	0	0.731 ± 0.006	0.838 ± 0.009	0.905 ± 0.009	0.518 ± 0.011	--	0.627 ± 0.007	--	--
0	0.005	0	--	--	--	0.580 ± 0.011	--	--	--	--
0	0.010	0	--	--	--	0.627 ± 0.015	--	--	--	--
0	0.050	0	0.973 ± 0.007	--	--	0.832 ± 0.013	0.899 ± 0.010	0.957 ± 0.007	1.067 ± 0.006	1.133 ± 0.008
(a)	0	0	0.496 ± 0.007	--	--	--	--	0.443 ± 0.006	--	--
(a)	0	0.050	0.816 ± 0.006	0.899 ± 0.005	--	--	--	0.808 ± 0.006	--	--
(a)	0.050	0.050	0.834 ± 0.005	--	--	--	--	0.820 ± 0.006	--	--

(a) Centers of boxes spaced: $\pm x \approx 66$ cm, $\pm y \approx 42$ cm and $\pm z \approx 60$ cm, i.e., boxes in contact in z direction.

The fifth entry for $N = 12^3$ of the two box materials result in lower k_{eff}'s than the first entry because of increased neutron leakage from the array and a reduced effect of the cardboard boxes as moderation to the array. The sixth and seventh entries also evidence the reduced effect of the cardboard.

The boxes are sometimes open at work stations which would permit water to accumulate within the boxes. The neutron interaction between such units and storage units was explored by calculation of a concrete reflected array of 512 boxes ($N = 8^3$). The description of this array designated the central 64 boxes ($N = 4^3$) as representing those at work stations. The calculations are reported in Table 5 using the cardboard box. The k_{eff}'s would be less with aluminum boxes. The first two entries have low density water in the boxes at the work stations, and compare the compact array and the array of spaced boxes. The third entry represents the addition of low density water between all boxes of the array and results in the maximum k_{eff} observed. The fourth entry is the same as the third except the water density in the work station boxes has been increased to full density. The k_{eff} is not significantly different from the third entry and is indicative of overmoderation of the array.

While the arrays of Table 5 do show the effect of low density water between boxes, there remains a question of low density moderation occurring in larger void spaces. Calculation of arrays with large voids containing water at $\rho = 0.05$ g/cc would be wasteful, since a neutron traversing 2 to 4 m would have the same probability of survival as a neutron traversing 10 to 20 cm in water. In the interest of exploring a distance between work stations and between work stations and storage areas which may be significantly neutron-coupled, calculations were performed on an $N = 10^3$ array described in the following. The first, second, fifth, sixth, ninth and tenth tiers of the arrays were filled with storage boxes. The central 4×4 cells in the third and eighth tiers of the 10×10 locations were void spaces and the remaining positions designated storage boxes. The boxes representing work stations were contained in the fourth and seventh tiers of the array. The central 2×2 boxes of the tiers were designated work stations, and these were surrounded by a ring of void cells. The remaining locations were labeled storage boxes. The arrangement results in 912 positions designated as storage, 8 designated as work stations, and 88 voided cells.

Table 5. Computed k-eff of concrete reflected arrays of 8 x 8 x 8 cardboard boxes with variable moderation conditions

Box Spacing	Water Density, g/cc, at Storage Between Plates	Storage Between Boxes	Work Station Between Plates	Work Station Between Boxes	Array k-eff
Contact	0	0	0.05	0	0.670 ± 0.006
(a)	0	0	0.05	0	0.438 ± 0.006
(a)	0	.05	0.05	0.05	0.681 ± 0.005
(a)	0.05	.05	1.0	0.05	0.656 ± 0.006

(a) Boxes separated ~30 cm horizontally, ~12 cm vertically and in contact in the long dimension of boxes.

The results of the calculations are presented in Table 6. The first entry is consistent with the results of Table 5. The second entry represents open boxes at work stations having low density water within and between the clusters of four work locations and between the stations and the storage locations. The closely packed array prevents water between boxes at storage locations, and the boxes prevent internal moderation of the plates. The third and fourth entries show little change in reactivity with designated work station boxes filled with water at full density. The next five entries show similar results for spaced boxes. The last entry is a repeat of the ninth, but with double the water density in the void cells. This is equivalent to moderation at twice the void spacing but with a higher probability of neutron coupling between storage and work locations because the distances have remained constant. The negative effect on the array reactivity is slight and is indicative of the low reactivity of the units with moderation.

Table 6. Computed k-eff of concrete reflected arrays of 912 boxes of plates arranged[a] in a 10 x 10 x 10 cuboidal array with variable moderating conditions

Box Spacing	Water Density, g/cc, at 904 Storage Locations Between Plates	Between Boxes	8 Work Stations Between Plates	Between Boxes	Empty Cells (88)	Calculated Array k-eff
0	0	0	0.05	0	0	0.661 ± 0.006
0	0	0	0.05	0	0.5	0.698 ± 0.008
0	0	0	1.0	0	0	0.673 ± 0.007
0	0	0	1.0	0	0.5	0.692 ± 0.007
(b)	0	0.05	0	0.05	0	0.709 ± 0.006
(b)	0	0.05	0.05	0.05	0	0.725 ± 0.005
(b)	0	0	0.05	0.05	0.05	0.503 ± 0.005
(b)	0	0	1.0	0.05	0.05	0.496 ± 0.005
(b)	0	0.05	1.0	0	0.05	0.700 ± 0.006
(b)	0	0.05	1.0	0	0.10	0.681 ± 0.006

[a]See text for description of arrangement.

[b]Boxes separated in x direction by ∿30 cm, y direction by ∿12 cm, and are in contact in the z direction.

Compacts

The 24.765 g of U_3O_8 is mixed with 44.95 g of aluminum powder to form the core loading for one fuel plate. The mixture is pressed into compacts having dimensions and atom number densities given in Table 7.

Table 7. Description of typical HFBR compact

Composition		
Material	mass, g	Dimensions of Compact, cm
U_3O_8	24.765	5.5 × 6.7 × 0.68
Al	44.950	
Atom Number Densities:		
^{235}U = 1.99735-3		^{16}O = 5.712396-3
^{238}U = 1.44801-4		^{27}Al = 4.00442-2

After pressing, 24 compacts are handled as a lot and are placed in a stainless steel tray having a nominal wall thickness of 0.157 cm (0.062 in.) and inside dimensions 12.7 × 20.32 × 7.95 cm. The trays have a lip and nominal outside dimensions of 13.55 × 21.27 × 8.26 cm. The compacts are placed in the trays on edge in a 3 × 8 arrangement. The trays are normally covered; however, they are assumed in this analysis as uncovered when in sprinklered areas of the plant. The calculated k_{eff} of a single tray and of arrays of trays under various water conditions is reported in Table 8. The trays containing water at full density are filled. It is clear that, when trays are protected from accumulating water, as many as 64, reasonably close-packed, do not present a criticality threat. Sixty-four trays containing compacts and water and reflected by water could result in supercriticality. The initial effect of low density water introduced into a dry array may be regarded as not significant.

Table 8. Calculated k-eff of stainless steel trays each containing 24 fuel plate compacts arranged in cuboidal arrays reflected by 30.5-cm-thick water

Number of Trays and Arrangement[a]	Water Density, g/cc, in Trays	Between Trays	Array k-eff
1	0	--	0.406 ± 0.005
8 (2×2×2)	1.0	0	0.716 ± 0.005
	1.0	0.05	0.729 ± 0.005
16 (4×2×2)	1.0	0	0.803 ± 0.006
32 (4×4×2)	1.0	0	0.867 ± 0.005
	1.0	.05	0.876 ± 0.007
64 (4×4×4)	0	0	0.542 ± 0.004
	1.0	0	1.048 ± 0.008
	0.05	0.05	0.612 ± 0.006

[a]Trays are in contact in the two horizontal dimensions and separated 5.7 cm vertically.

Fuel elements

Critical experiments[7] with the HFIR fuel element components have demonstrated their subcriticality when submerged. A square annulus formed with 12 HFBR or with 12 SPERT-D fuel elements would also be subcritical submerged.

Elements in plant operations are transported and stored on carts which provide a minimum 30-cm surface separation between elements. The carts, however, can be adjacent to a work station allowing a box of plates, for example, to be 15-cm from the surface of the fuel element. Examination of the potential for criticality of this situation and to illustrate the k_{eff} of fuel elements with different degrees of water moderation, two arrays of SPERT-D elements separated by 15.2 cm were calculated. It is to be remarked that plant practice does provide a shield surrounding the fuel elements which prevents internal moderation, and there is no means by which water would be selectively retained between the fuel plates.

The use of the SPERT-D elements in place of the HFBR elements thus far calculated provides an experimentally measured assembly with a minimum critical mass comparable to the HFBR elements. The square annulus also results in greater neutron coupling between the plane surfaces of the two arrays than would occur with the cylindrical HFIR annuli. Sixteen complete SPERT-D elements (Table 2) are supercritical submerged. A square annulus with 12 elements is formed by removing the center four elements. Neutron interaction is with a second identical array located in a direction perpendicular to the surface of the fuel plates to enhance neutron coupling. The calculations also employed a 40.6-cm-thick concrete floor about 20 cm from the bottom of the elements. The water density is variable in the region between plates, between arrays, in the centers of the square annuli, and in the region 7.6 cm from the outer lateral surfaces of the arrays. The results of these calculations are given in Table 9. The first three entries have full density water between plates, a condition that is not credible, with increasing water density in the void regions of the arrays. A further increase in water density beyond 0.1 g/cc would result in decoupling the arrays and the k_{eff} would approach that of a subcritical submerged annulus.

Table 9. Calculated k-eff of two neutron interacting assemblies of SPERT-D fuel elements separated by 15 cm

Number of Elements and Arrangement[a]	Water Density, g/cm³ Between Plates	Center of Annulus	Outside Elements	k-eff
12 as Annulus	1.0	0.05	0.05	0.439 ± 0.006
	1.0	0.10	0.10	0.520 ± 0.007
"	1.0	0.25	0.25	0.699 ± 0.008
"	0.1	0.1	0.1	0.071 ± 0.002
16 as 4×4 Array	0	0[b]	0.1	0.037 ± 0.001
"	0.1	0.1[b]	0.1	0.073 ± 0.002
"	1.0	1.0[b]	1.0	0.984 ± 0.010

[a]Fuel elements in contact.

[b]Occupied by fuel elements.

The fifth through seventh entries would represent a slightly supercritical configuration* submerged and with a thicker reflector than described in the calculation. Two HFIR outer elements submerged at a 15 cm separation or in contact are known to be subcritical by experiment.[8] The arrangements calculated demonstrate sufficient subcriticality to obviate concern with location of any single element adjacent to work stations or storage array; and because of the low k_{eff} of elements protected from water, any number may be permitted.

Additional calculations reported in Table 10 were performed with HFBR fuel elements. The low density water in the reflected array of the 4 × 4 × 1 arrangement produces greater k_{eff}'s than observed in Table 9 because of the closely fitting thick water reflector. Sixteen elements, submerged and spaced at 5.1 cm surface separation, are subcritical. An infinite planar 2 × ∞ × 1 array with elements separated 5.1 cm is also subcritical. These data are useful to support a more efficient operation in the rinsing of HFBR and ORR elements since they would allow more than a single element in the rinse tank. For example, six elements with at least 5.0 cm between element surfaces in any arrangement would be subcritical.

Table 10. Calculated k-eff of water reflected arrangements of HFBR fuel elements

Arrangement Array	Surface Separation, cm	Water Density g/cc, in Array	k-eff
2×∞×1	5.1	1.0	0.772 ± 0.01
4×4×1	5.1	1.0	0.844 ± 0.01
4×4×1	0.0	0.025	0.547 ± 0.01
4×4×1	0.0	0.050	0.570 ± 0.01
4×4×1	0.0	0.075	0.584 ± 0.01
4×4×1	0.0	0.10	0.597 ± 0.01
12 as Square Annulus	0.0	1.0	0.908 ± 0.005

*The reactivity coupling of two critical cores at this separation in water can be expected to be less than a few tens of cents.[8]

Discussion

The analyses performed with compact cubic arrays are an overly conservative approximation of the plant operations. Consider the largest array of Table 4 having 8000 units and a k_{eff} ~0.9. The dimensions of the array would be 7.1 × 12.2 × 3.6 m whereas the plant dimensions are of the order of 15.2 × 80 × 9 m. If the concrete assumed as a reflector surrounding the cubic array were to be moved from the array to the boundaries of the operations area, the k_{eff} of the array would decrease to about 80% of its value. Further, the light building structure and the concrete floor are less effective as a reflector than the 40.6 cm concrete assumed or thick water. If the concrete reflector at the boundaries of the operations area were conservatively replaced by a thick water reflector, the k_{eff} would be further reduced to less than 85% of its value. Thus, the 20^3 array centered in the area would be expected to have a k_{eff} not exceeding 0.9 × 0.85 × 0.8 or ~0.6. The number of units in storage, in operations and as fuel elements is less than 500. Reducing the number from 8000 to 500 would cause the k_{eff} to decrease to about 73% of its value, resulting a k_{eff} less than 0.4.

The dispersion of the units throughout the operations area would result in at least an additional 50% reduction in k_{eff}. The maximum k_{eff} for the entire plant can be estimated to be about 0.2 without optimum moderation. The Δk_{eff} from moderation would be some small fraction of the maximum observed in the analysis of the cubic arrays (~0.4, internal and external to the units). The dispersion of fissionable materials and the presence of water at optimum density would result in some decoupling of storage arrays and of work locations. It is evident that the likelihood of k_{eff} exceeding 0.5 is very low.

Operations are conducted in a manner providing protection from internal moderation of fuel elements, of fuel plates in storage, and of compacts in storage. Internal moderation that may occur at individual work stations is of little consequence as the data of Tables 5 and 6 show. It follows that the CI system can effectively control the nuclear criticality safety under credible normal and abnormal contingencies.

Conclusions

The calculational results demonstrate that the CI system does provide criticality control in all operations at the facility. The following may be said of the points addressed in the study.

- Storage arrays of boxes with 24 plates each have a larger margin of subcriticality when close-packed than when spaced. The use of aluminum boxes would provide an additional margin of subcriticality.
- A minimum surface separation of 15 cm between assembled fuel elements and work stations or between elements and storage arrays provides an ample margin of subcriticality for the variable conditions of moderation and neutron reflection that may occur in operations.
- No additional administrative controls are necessary for the movement of materials, location of storage areas or proximity of several work stations provided the criteria of the CI system are met.
- There is no danger of criticality from the sprinkler system nor from hoses with fog nozzles. Immediate action in fighting fires is permissible and would be prudent.

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