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Criticality Safety Evaluation for the Advanced Test Reactor Enhanced Low Enriched Uranium Fuel Elements

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Revision 1/ July 19, 2016. Revision 1 compares the reactivity of the ATR HEU Mark IV elements with the Mark VII elements.	L. M. Montierth	Charles Stuart

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1. Introduction

The Global Threat Reduction Initiative (GTRI) convert program is developing a high uranium density fuel based on a low enriched uranium (LEU) uranium-molybdenum alloy. Testing of prototypic GTRI fuel elements is necessary to demonstrate integrated fuel performance behavior and scale-up of fabrication techniques. GTRI Enhanced LEU Fuel (ELF) elements based on the ATR-Standard Size elements (all plates fueled) are to be fabricated for testing in the Advanced Test Reactor (ATR). While a specific ELF element design will eventually be provided for detailed analyses and in-core testing, this criticality safety evaluation (CSE) is intended to evaluate a hypothetical ELF element design for criticality safety purposes. Existing criticality analyses have analyzed Standard (HEU) ATR elements from which controls have been derived. This CSE documents analysis that determines the reactivity of the hypothetical ELF fuel elements relative to HEU ATR elements and whether the existing HEU ATR element controls bound the ELF element. The initial calculations presented in this CSE analyzed the original ELF design, now referred to as Mod 0.1. In addition as part of a fuel meat thickness optimization effort for reactor performance other designs have been evaluated. As of early 2014 the most current conceptual designs are Mk1A and Mk1B that were previously referred to as conceptual designs Mod 0.10 and Mod 0.11, respectively.

Revision 1 evaluates the reactivity of the ATR HEU Mark IV elements for a comparison with the Mark VII elements.

2. Description

A brief listing of the various facilities where ATR fuel is present is given in Section 2.1. A description of the HEU ATR elements is given in Section 2.2.2. Descriptions of the ELF elements are given in Section 2.2.3.

2.1 Facilities Containing ATR Fuel

ATR fuel is handled and stored at several facilities at INL. Facilities at the ATR Complex are the ATR, the Advanced Test Reactor Critical (ATRC) Facility and the Nuclear Materials Inspection and Storage (NMIS) Facility. The ATR provides high neutron flux for testing reactor fuels and other materials. ATR fuel is handled and stored at the ATR Facility within the reactor vessel, the working canal, the storage canal and up on the reactor main floor. The working canal is directly adjacent to the reactor and is used to transfer fuel, experiments and reactor components between the storage canal and the reactor. The storage canal is used for the storage of fuel, experiments and reactor components. The ATRC Facility is a low power pool version of the high-power ATR core that is used for experimental needs. The NMIS facility is used to store unirradiated and slightly irradiated (< 200mR/hr on contact) fuel. The ATR racks in NMIS are approved for the storage of ATR fuel as intact elements and as fuel plates. ATR fuel is transferred between the three facilities within the ATR Complex using ATR fresh fuel shipping containers. CSEs have been performed and have derived controls for the handling, storage and transfer of ATR fuel at and between these facilities. Transfer of spent ATR fuel to the Fluorinel Dissolution Process and Fuel Storage (FAST) facility is done in the ATR spent fuel element transfer cask.

2.2 Description of the ATR Fuel

In the history of the ATR, there have been numerous variations of HEU ATR fuel elements, i.e., Marks IV, V, VI and VII. Currently, the ATR reactor HEU elements are the Mark VII Standard Size non-borated (7FNB), Standard Size borated where all plates except plates 5 through 15 are borated (7F), and the reduced YA element where all plates except plates 5 through 15 are borated and plate 19 is a "dummy" fuel plate, i.e., it is made entirely of type T-6061 aluminum and contains no fuel. For criticality safety purposes the boron content is conservatively neglected and the Standard elements are thus treated identical. This element is referred to here as a "typical" ATR element and bounds the other HEU fuel element variants, including the Mark IV and V elements currently used at ATRC. The hypothetical ELF element design is based on the ATR Standard Size elements and does not contain any burnable absorbers.

2.2.1 Mark IV, V and VI HEU Fuel Elements

The Mark IV[1], V[2], and VI[3] type fuel elements are older designs of ATR fuel elements that are no longer manufactured or used in the ATR reactor. The normal fuel loading for the ATRC core is 40 fuel elements that consists of any combination of Mark IV, V, VI and VII elements. The geometry of these fuel elements of interest to Criticality Safety has not changed significantly over the years. The radial features for each plate are shown in Table 1 and apply for all HEU Fuel Elements. In the axial direction the fueled portion of each plate averages to 48 in. and the total length is 49.5 in.

The U-235 and B-10 loadings and the fuel compositions have changed with the evolving fuel element types. The Mark IV fuel element has a U_3O_8-aluminum fuel matrix, and the Mark V, VI and VII fuel elements have an UAL_X-aluminum fuel matrix. More details concerning fuel composition and loading are given in Sections 2.2.1.1, 2.2.1.2, 2.2.1.3 and 2.2.2

Table 1. Individual Plate Dimensions for All ATR HEU Fuel Element Types

Plate Number	Plate Inner Radius (in.)	Plate Thickness, (in.)	Fuel Thickness, (in.)
1	3.015	0.08	0.020
2	3.173	0.05	0.020
3	3.301	0.05	0.020
4	3.429	0.05	0.020
5	3.557	0.05	0.020
6	3.685	0.05	0.020
7	3.813	0.05	0.020
8	3.941	0.05	0.020
9	4.069	0.05	0.020
10	4.197	0.05	0.020
11	4.325	0.05	0.020
12	4.453	0.05	0.020
13	4.581	0.05	0.020
14	4.709	0.05	0.020
15	4.837	0.05	0.020
16	4.965	0.05	0.020
17	5.093	0.05	0.020
18	5.221	0.05	0.020
19	5.349	0.10	0.020

2.2.1.1 HEU ATR Mark-IV Fuel Elements

The U_3O_8-Al-B_4C fuel core of each fuel plate is a blended mix of powdered U_3O_8, aluminum powder and boron carbide powder. The specified U-235 enrichment is 93%.[1] The element fuel loading uses the same composition in each plate unlike the zone loaded Mark VII elements. The ranges of U-235 and B_4C loading for each plate are given in Table 2. The nominal element U-235 loading is listed in Reference 4 as 975 g and a maximum loading of 980 g in Reference 5, which includes an added tolerance. The U-s35 loading for the element should be within 0.5% of the sum of the specified loading of all 19 element plates. If this total is 975 g then the U-235 mass uncertainty is ~±5 g. (Interestingly, the sum of the maximum U-235 values for each plate listed in Table 2 is 961 g. which is less than either of these two values.)

Specified drawings for the ATR Mark IV fuel element are: 120393, 120394 and 120395.

Table 2. Fuel Loadings by Plate for Mark IV Fuel Elements

Plate Number	Range of U-235 Content, (g) [a]	Range of B_4C, (g)
1	23 - 30	0.15 - 0.30
2	28 - 36	0.15 - 0.30
3	29 - 38	0.15 - 0.30
4	31 - 40	0.15 - 0.30
5	32 - 42	0.20 - 0.40
6	34 - 44	0.20 - 0.40
7	35 - 45	0.20 - 0.40
8	37 - 47	0.20 - 0.40
9	38 - 49	0.20 - 0.40
10	39 - 51	0.20 - 0.40
11	41 - 53	0.25 - 0.50
12	42 - 55	0.25 - 0.50
13	44 - 57	0.25 - 0.50
14	45 - 58	0.25 - 0.50
15	47 - 60	0.25 - 0.50
16	48 - 62	0.25 - 0.50
17	50 - 64	0.30 - 0.60
18	51 - 66	0.30 - 0.60
19	50 - 64	0.30 - 0.60
a Information is taken from Reference 1		

2.2.1.2 HEU ATR Mark-V Fuel Elements

The Mark V element fuel cores consist of compacted powdered UAl_x alloy blended with aluminum powder and boron carbide. The core is enveloped by an aluminum cladding. The uranium is specified as having a U-235 enrichment of 93%. The specified U-235 loading for the Mark V fuel element is 975 g, and the individual plate U-235 and B_4C loadings are given in Table 3. The U-235 loading for the element should be within 0.5% of the sum of the specified loading of all 19 element plates. Using the plate values in Table 3 gives an uncertainty of ±5 g of U-235.

Specified drawings for the ATR Mark V fuel element are: 120393, 120394, 120395 (same as for the Mark IV element), and 036021.

Table 3. Plate Fuel Loadings for Mark V and VI Fuel Elements

Plate Number	Mark V U-235 Content, (g) [a]	Mark V B_4C, (g)	Mark VI U-235 Content, (g) [a]	Mark VI B-10, (mg)
1	30.3	0.16	30.3	23
2	36.3	0.2	36.3	29
3	38.2	0.21	38.2	30
4	40.1	0.22	40.1	32
5	42.0	0.23	42.0	33
6	44.0	0.24	44.0	34
7	46.0	0.25	46.0	36
8	47.8	0.26	47.8	37
9	49.8	0.27	49.8	39
10	51.7	0.28	51.7	40
11	53.6	0.29	53.6	42
12	55.6	0.3	55.6	43
13	57.5	0.31	57.5	44
14	59.4	0.32	59.4	46
15	61.4	0.33	61.4	47
16	63.3	0.34	63.3	49
17	65.2	0.35	65.2	50
18	67.2	0.36	67.2	52
19	65.6	0.36	65.6	52
total	975	5.28	975	758

a Information is taken from References 2 and 3.

2.2.1.3 HEU ATR Mark-VI Fuel Elements

The Mark VI element fuel cores are the same as those of the Mark V elements, i.e., they consist of compacted powdered UAl_x alloy blended with aluminum powder and boron carbide. The specified Mark VI element U-235 loading is given as 975 ±10 g, and the B-10 loading is 0.758 ±0.02 g. The uranium isotopic composition is specified to be: U-235 content 93% ± 1.0%; U-238 content 6.0% ± 1.0%; U-236 content 0.3% ± 0.2%; and U-234 content 0.6% ± 0.2%. The individual plate U-235 and B-10 loadings are also given in Table 3. The Mark V and VI U-235 plate loadings are the same. From a criticality safety point of view the Mark V and VI elements are the same.

Drawings specified for the ATR Mark VI fuel element are: 035658, 035659 and 035660.

2.2.2 HEU ATR Mark VII Fuel Elements

The Standard Size ATR Mark VII zone loaded fuel element consists of 19 curved aluminum clad uranium aluminide (UAl_x) plates containing highly enriched uranium. The isotopic composition of the uranium is: U-235 content 93±1 wt%; U-238 content 6.05% ± 1.0%; U-236 content maximum of 0.7%; and U-234 content maximum of 1.2%..[1] The highest fissile loading (U-235) of the fresh fuel element is 1075 g.[7] The allowable fuel loading (U-235) uncertainty for each fuel plate is ±1 percent.[1] The allowed fuel element U-235 loading and uncertainty are 1075 ± 10 g, giving a maximum loading of 1085 g for a Standard Sized ATR fuel element. The allowed U-235 loading for the ATR Reduced YA element is 1022.4 ± 10 g as plate 19 is a dummy plate containing no fuel.

Figure 1 presents a simplified view of a typical ATR fuel element. The fuel plates are 49.5 in. long with a fuel zone that is 48 in. long.

The thickness of each plate is 0.05 in. except plates 1 and 19, which are 0.08 in. and 0.1 in., respectively. The fuel matrix section in each plate is 0.02 in. thick. The cladding is made of type T-6061 aluminum. The plates are held in place by aluminum side plates that are 2.549 in. wide, 0.187 in. thick and 49.5 in. long. The water gap between plates is 0.078 in. thick. When assembled, the angle of curvature of the fuel elements is 45° with inner and outer radii of 2.964 in. and 5.513 in, respectively[8]. The detailed dimensions of each fuel plate and maximum U-235 content for the Mark VII, V and VI plates are presented in Table 4. The U-235 masses for the two innermost and two outermost Mark V &VI element plates are greater than the corresponding Mark VII plates, even though the Mark VII total U-235 mass is ~1086 g and the Mark V&VI total mass is ~985 g. This is a consequence of the Mark VII zone loading, which decreases U-235 loading for the innermost and outermost element plates.

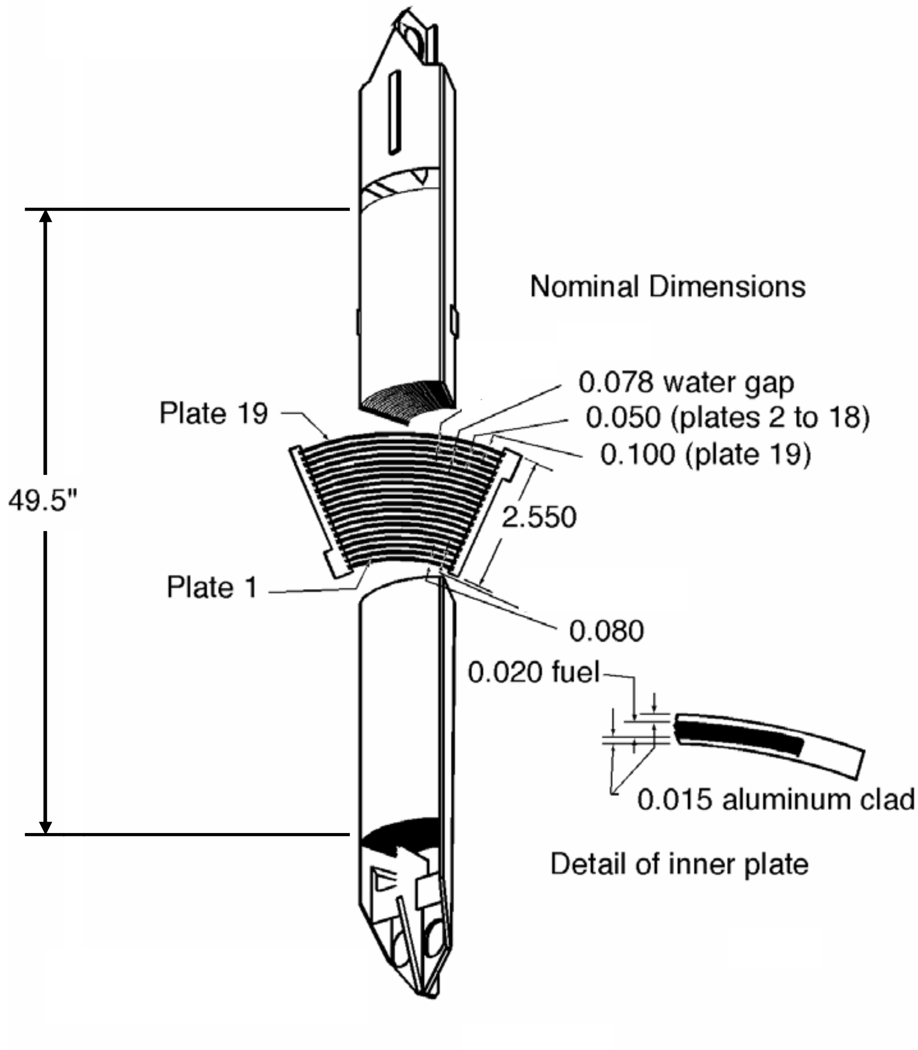


Figure 1. Simplified View of the HEU ATR Fuel Element (dimensions are in inches)

Table 4. Individual Plate Dimensions and U-235 Content for Mark V, VI and VII Fuel Elements [a]

Plate Number	Plate Inner Radius [b] (cm)	Outer Radius [b] (cm)	Mark VII U-235 content (max) (g) [c]	Mark V & VI U-235 content (max) (g)[c]
1	7.65810	7.86130	24.543	30.603
2	8.05942	8.18642	29.391	36.663
3	8.38454	8.51154	39.087	38.582
4	8.70966	8.83666	40.804	40.501
5	9.03478	9.16178	52.621	42.420
6	9.35990	9.48690	55.146	44.440
7	9.68502	9.81202	57.570	46.460
8	10.01014	10.13714	59.994	48.278
9	10.33526	10.46226	62.418	50.298
10	10.66038	10.78738	64.842	52.217
11	10.98550	11.11250	67.266	54.136
12	11.31062	11.43762	69.690	56.156
13	11.63574	11.76274	72.114	58.075
14	11.96086	12.08786	74.538	59.994
15	12.28598	12.41298	77.063	62.014
16	12.61110	12.73810	64.640	63.933
17	12.93622	13.06322	66.559	65.852
18	13.26134	13.38834	54.338	67.872
19	13.58646	13.84046	53.126	66.256

a The number of digits in the values cited in this and subsequent tables may be the result of a calculation, e. g., the conversion from English to metric units, or may reflect the input from another source; consequently, the number of digits should not be interpreted as an indication of enhanced accuracy.

b Dimensions are taken from Reference 8. Slightly different inner radius dimensions are given for plates 11 through 19 in Reference 9.

c Maximum mass is the specified plate mass plus 1%.

2.2.3 ATR U-10Mo ELF Element

The ELF element geometry is similar to the Standard Size elements except the fuel meat utilizes an U-10Mo alloy to replace the standard UAl_x that is currently used in HEU ATR fuel.[10] The ELF elements contain 19 plates with a U-10Mo monolithic fuel. The fuel alloy consists of 10 wt% molybdenum and no burnable absorber, and the remainder of the alloy is uranium metal at 19.75% + 0.20% - 0.30 % U-235 enrichment. (This gives a U-235 enrichment ranging from 19.45% to 19.95%.)

The nominal density of the U-10Mo [11] is given as 16.902 g/cm^3, which gives a U-235 density of 3.0043 g/cm^3 for the given enrichment and 90% uranium. The U-235 mass loading for each plate is determined from the plate dimensions, fuel meat thickness and U-235 density. The three ELF designs described here, the Mod 0.1, Mk1A and Mk1B, vary in fuel meat thicknesses and thus total U-235 loading per element. The fuel meat thicknesses vary from 0.007 in. (7 mils) to 0.018 in. (18 mils) with the centermost plates having the larger thicknesses. The numbers of unique fuel meat thicknesses are 9, 3 and 5 for Mod 0.1, Mk1A and Mk1B, respectively, i.e., this is the number of plate thicknesses that are used for each fuel design. The specified fuel meat thicknesses for the element plates are given in

Table 5, and elements with plates having these fuel meat thicknesses are referred to in this CSE as “nominal fuel meat thickness” plates. The fuel meat is surrounded on both sides by a thin zirconium layer, 0.001 in. thick, to mitigate interactions between the fuel meat and aluminum cladding. A fuel meat thickness uncertainty of 1 mil due to manufacturing tolerances[12] is also accounted for in this CSE. ELF elements with fuel meat thicknesses increased by 1 mil are referred to as “thicker fuel meat” plates. A cross-sectional plot and other details for a 13 mil fuel meat thickness U-10Mo plate are shown in Figure 2.

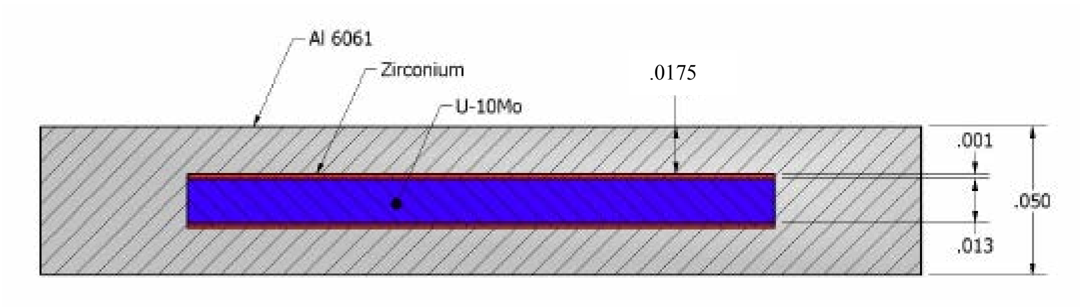


Figure 2. U-10Mo Fuel Plate Cross-sectional View for a 13 mil Thick Fuel Meat (dimensions are in inches)

Table 5. Individual Plate Nominal Thicknesses for U-10Mo ELF Elements

Plate Number	Mod 0.1 Fuel Meat thickness, [a] cm (mils)	Mk1A Fuel Meat thickness [b], cm (mils)	Mk1B Fuel Meat thickness, [b] cm (mils)
1	0.02032 (8)	0.02032 (8)	0.02540 (10)
2	0.02286 (9)	0.03302 (13)	0.02540 (10)
3	0.02540 (10)	0.03302 (13)	0.03302 (13)
4	0.03048 (12)	0.04064 (16)	0.03302 (13)
5	0.03302 (13)	0.04064 (16)	0.03810 (15)
6	0.03556 (14)	0.04064 (16)	0.03810 (15)
7	0.03810 (15)	0.04064 (16)	0.04572 (18)
8	0.03810 (15)	0.04064 (16)	0.04572 (18)
9	0.03810 (15)	0.04064 (16)	0.04572 (18)
10	0.03810 (15)	0.04064 (16)	0.04572 (18)
11	0.03810 (15)	0.04064 (16)	0.04572 (18)
12	0.03810 (15)	0.04064 (16)	0.04572 (18)
13	0.03810 (15)	0.04064 (16)	0.03810 (15)
14	0.03556 (14)	0.04064 (16)	0.03302 (13)
15	0.03048 (12)	0.04064 (16)	0.03302 (13)
16	0.02794 (11)	0.03302 (13)	0.03302 (13)
17	0.02286 (9)	0.02032 (8)	0.02540 (10)
18	0.02032 (8)	0.02032 (8)	0.02032 (8)
19	0.01778 (7)	0.02032 (8)	0.02032 (8)

a Dimensions are taken from Reference 10.
b Dimensions are taken from Reference 13.

3. Unique or Special Requirements

The purpose of this CSE is to compare the k_{eff}s of the ELF elements and the Standard Size HEU element rather than determine if a specified acceptance criteria is satisfied.

4. Methodology and Validation

All calculations listed in this report are performed using MCNP5, version 1.51 with the ENDF/B-V continuous energy cross section library on Sun and HP workstations running the Red Hat Enterprise LINUX Release 4 operating system. MCNP5 and its libraries are installed and maintained in accordance with an approved quality assurance plan.[14]

4.1 Methodology

Calculational models to determine reactivity are developed for this evaluation. These calculations used the Monte Carlo N-Particle Transport Code (MCNP) computer program[15] and ENDF/B-V cross sections to determine the criticality potential of ATR fuel types. ENDF/B-V cross sections are used to derive the current ATR handling and storage controls. Validation of the MCNP code is described in this section.

Benchmark experiments containing the same or similar attributes as the evaluated cases analyzed in this CSE are identified and evaluated here.

4.2 Validation

4.2.1 Validation of HEU ATR Elements

Validation results for the HEU ATR fuel elements are not repeated here as these results have previously been presented elsewhere.[16, 17, 18, 19, 20, 21, 22, 23, 24] These HEU benchmarks include cases with cadmium absorption,[18, 19] boron absorption[22] and with beryllium[18] and lead[22] reflection. In all cases it is not necessary to apply any bias to the results.

4.2.2 Validation of U-10Mo ELF Elements

The enrichment used in the ELF elements is about 20%, and the choice of applicable benchmark experiments is complicated due to there being no known moderated benchmark experiments available for validation containing uranium alloyed with Mo. The International Criticality Safety Benchmark Evaluation Project (ICSBEP) considers 20% to be intermediate enrichment (IEU). Two moderated benchmark experiments with enrichments that bracket 20% are used to validate the U-10Mo ELF elements. One of these benchmark experiments consists of stainless steel clad $U(17)O_2$ fuel rods moderated and reflected by water. Though not integral with the fuel, the clads main constituent is iron (~70%), whose thermal absorption cross section is similar to that of Mo (2.6 barns). The other experiment consists of uranium-polytetrafluoroethylene ($U(30)F_4(CF_2)_n$) and polyethylene (CH_2) cubes reflected by paraffin. Brief descriptions of these benchmark experiments are given in this section. The MCNP5 results for these experiments using ENDF/B-V cross sections are given in Table 6. The last column of this table is the MCNP energy of average neutron lethargy causing fission (EALF).

Stainless steel clad $U(17)O_2$ fuel rods were water moderated and reflected in benchmark experiment IEU-COMP-THERM-002.[25] Experiments were performed in 1970-1973 in the MATR facility at the Institute of Physics and Power Engineering, Obninsk, Russia. The fuel rods were arranged in hexagonal lattices with a pitch of 6.8 cm. Each lattice was comprised of fuel rods containing either no absorber, gadolinium absorber, or cadmium absorber. The lattices were fully reflected on all sides by water. The critical mass was determined for "cold" (~20° C) and "hot" (~200° C) assemblies. Results are presented in the first set of Table 6 for the cold, no absorber fuel rods and cold, cadmium absorber element cases.

Benchmark experiment IEU-COMP-THERM-001 consisted of one-inch cubes of uranium-polytetrafluoroethylene ($U(30)F_4(CF_2)_{n)}$ and polyethylene (CH_2) reflected by paraffin.[26, 27] The arrays were assembled with different numbers of the two cube types to vary H/U-235 ratios from 32 to 220. Additional details are given in Table 6. Results are only presented for those benchmark experiments that had EALF values comparable to that of a near-critical array of U-10Mo ELF elements, 1.2×10^{-4} kev.

Table 6. Results for Moderated Intermediate Enrichment U-235 Benchmark Experiments

Experiment / MCNP Input File Name	Description	$k_{eff} \pm \sigma$	EALF [a] (kev)
IEU-COMP-THERM-002; U(17)O_2 fuel rods			
CASE_1	34 fuel rods at temperature of 22.7° C; no absorber elements; benchmark k_{eff} = 1.0014 ± 0.0039	0.9975 ± 0.0005	9.2×10^{-5}
CASE_5	68 fuel rods at temperature of 14.5° C; cadmium absorber elements present; benchmark k_{eff} = 1.0014 ± 0.0043	0.9965 ± 0.0005	1.0×10^{-4}
IEU-COMP-THERM-001; U-poly cube array results; benchmark k_{eff} = 1.000 ± 0.004			
exp04	10×10×8 array size;298 U cubes with 596 CH_2 cubes	0.9988 ± 0.0006	2.6×10^{-4}
exp05	16×14×14 array size; 400U cubes with 2800 CH_2 cubes	1.0064 ± 0.0006	1.1×10^{-4}
exp13	9×9×11 array size; 302 U cubes with 604 CH_2 cubes	0.9979 ± 0.0006	2.6×10^{-4}
exp14	8×8×16 array size; 356 U cubes with 712 CH_2 cubes	0.9987 ± 0.0006	2.6×10^{-4}
exp15	8×7×26 array size; 488 U cubes with 976 CH_2 cubes	0.9998 ± 0.0006	2.6×10^{-4}
Average values of k and EALF [b]		1.0003 ± 0.0031	2.3×10^{-4}

a EALF is the energy of average neutron lethargy causing fission
b The average values of k_{avg} and its corresponding variance, u, are determined from the following formulas: $k_{avg} = \Sigma k_i/N$ and $u^2 = \Sigma(k_{avg} - k_i)^2/N$

4.2.3 Summary of Validation Results

The range of applicability of the benchmark cases presented in this section is determined by primary physical parameters that characterize a particular fissionable configuration. These physical parameters include material properties, geometry properties and trending parameters such as the EALF or H/X ratio for moderated systems. An area or range of applicability for the benchmark experiments is defined and used to determine the bias for configurations evaluated here. The choice of the benchmark experiments is typically based on the fissionable element, enrichment, chemical form, configuration geometry and if applicable neutron absorber, moderator material, reflector material, and any other important consideration.

Benchmark applicability to this analysis is demonstrated as the benchmark and evaluated fissionable material is U-235, the evaluated enrichment of 20% is bracketed by the benchmark enrichments of 17% and 30%, and the evaluated energies of average neutron lethargy causing fission fall in the range of that for the benchmark experiments. These comparable energies are an indication that the degree of moderation and the geometries are sufficiently similar that the benchmarks are correlated with the evaluated cases. The critical benchmark experiments used here are applicable to the systems evaluated in this analysis, and the calculated results for the experiments show good correlation with the measured critical results. It is not necessary, therefore, to apply any bias to the results calculated in this report.

5. Process Analysis

This section is not applicable. This CSE does not analyze critical scenarios or develop unique controls for the storage or handling of ATR fuel elements. This report analyzes the reactivity of the U-10Mo ELF elements relative to the Standard Size HEU ATR element to show that the ELF elements are bound by existing HEU ATR controls.

6. Evaluation & Results

The information provided in Section 2 is used to develop the ATR models. The Mark IV, V and VI elements have similar U-235 loadings and zone loading is not incorporated. As such the Mark IV element is chosen as the comparison to the Mark VII element as it has a different fuel matrix than the other HEU types. In Section 2.2.1.1 the Mark IV nominal U-235 loading is 975 g and the maximum loading is given as 980 g. For the analysis given here the maximum loading is conservatively chosen to be 990 g. as it bounds the 985 g, i.e., 975 g + 10 g, given for the Mark V and VI elements. The Mark IV loadings per plate are determined by proportioning the total U_3O_8-aluminum volume between the fuel plate volumes. Table 7 lists this U-235 loading plate used in this analysis. These plate loadings are within ~1.1% (all plates except one are within less than 0.3%) of the Mark V and VI U-235 loadings scaled from 975 g to 990 g in Table 3. The U-235 enrichment for Mark IV fuel is 93%.

Table 7. Modeled Fuel Loadings by Plate for Mark IV Fuel Elements

Plate Number	U-235 Content, (g)
1	30.680
2	36.817
3	38.785
4	40.752

Enrichments of 93% and 19.75% are used for the Mark VII ATR HEU and U-10Mo elements, respectively. The Mark VII HEU ATR plate loadings are given in Table 4 which includes an additional 1% U-235 for each plate giving a total U-235 loading of 1085.75 g, i.e., 1075 g +1%, which is slightly larger than that given in Section 2.2.2. Any boron content of the elements is neglected. The number densities for the materials and uranium isotopic mass abundances are given in Appendix A. Sample input decks are given in Appendix B.

The model U-235 loadings for the U-10Mo plates and the thicker fuel meats, i.e., nominal thickness + 1 mil, are calculated by electronic spreadsheet and given below in Table 8. In addition to the uncertainty in the fuel meat thickness, a 1% U-235 mass uncertainty is assumed when determining the U-235 mass (actual calculated loading plus 1%). This is done by increasing the U content in the U-10Mo alloy and is done in order to match the U-235 uncertainty used in most of the HEU models and accounts for uncertainties in density, enrichment and composition. The model U-235 loadings used in this section are determined from the fuel meat volumes and U-235 density, which is 1% larger than the value given in Section 2.2.3. The total model U-235 loadings for the Mod 0.1 elements are 1479.8 g and 1601.6 g for the nominal and thicker fuel meat plates, respectively.

Table 8. Plate Fuel Volumes and Model U-10Mo ELF Plate U-235 Mass Loadings

Plate Number	Fuel Meat Volume,[a] cm^3	Mod 0.1 Model Fuel Meat Volume[b], cm^3	Mod 0.1 Model U-235 Mass[c], g	Mod 0.1 (thicker fuel meat) Model U-235 Mass[d], g	Mk1A (thicker fuel meat) Model U-235 Mass[d], g	Mk1B (thicker fuel meat) Model U-235 Mass[d], g
1	11.14	11.140	33.802	38.027	38.027	46.478
2	13.32	13.328	40.442	44.936	62.910	49.429
3	15.59	15.600	47.337	52.071	66.272	66.272
4	19.66	19.670	59.686	64.659	84.555	69.633
5	22.34	22.338	67.781	72.994	88.636	83.422
6	25.16	25.164	76.355	81.809	92.717	87.263
7	28.15	28.148	85.410	91.104	96.798	108.186
8	29.31	29.334	89.011	94.945	100.879	112.747
9	30.54	30.521	92.612	98.786	104.960	117.308
10	31.72	31.707	96.212	102.626	109.041	121.869
11	32.91	32.894	99.813	106.467	113.121	126.429
12	34.07	34.080	103.413	110.307	117.201	130.990
13	35.28	35.267	107.013	114.147	121.282	114.147
14	34.03	34.023	103.239	110.613	125.362	103.239
15	30.12	30.112	91.371	98.985	129.442	106.599
16	28.46	28.473	86.396	94.251	109.959	109.959
17	24.01	24.008	72.848	80.942	72.848	89.036
18	21.96	21.973	66.674	75.008	75.008	75.008
19	19.89	19.888	60.347	68.968	77.590	77.590
sum	487.66	487.666	1479.762	1601.647	1786.606	1795.605

a The individual plate volumes are taken from Reference 5, where it states "These volumes were calculated by (Monte Carlo Code) Serpent and are not exact, but are tightly converged."

b The model volumes are calculated by spreadsheet whose input is the MCNP model surfaces that describe the fuel volumes.

c The model mass is determined from the model volume and a U-235 density of 3.0344 g/cm^3, which is 1% larger than the density given in Section 2.2.2.

d The thicker plate model masses are determined from the increased U-235 density and the fuel volume for a 1 mil increase in the fuel meat thickness of each plate. Total U-235 masses for the nominal thickness Mk1A and Mk1B elements are 1664.72 g and 1673.72 g, respectively.

The ATR fuel elements are explicitly modeled with 19 curved, aluminum clad fuel plates and aluminum side plates. The non-fueled ends of the ATR elements are ignored, and the element length is 49.5 in.

Results for the HEU ATR Mark VII elements are given in Section 6.1.1, the Mark IV elements are given in Section 6.1.2, the U-10Mo ELF results are given in Section 6.1.3, a comparison of HEU and U-10Mo ELF results are given in Section 6.1.4, and ELF results for previous CSE cases that derive and/or support current HEU ATR controls are given in Section 6.1.6.

For convenience in referring to cases in a given table, groups of cases may be referred to as a "set," where the set of cases examines variations to a single or limited number of parameters. A preceding header (in bold type) within each table denotes the set.

6.1 ATR Reactivity Results

As was done for the U-10Mo Full Size Demonstration elements[28], the reactivity of the two fuel types is compared by determining the reactivity of a single element and a near-critical element array for each fuel type. Since the elements are more reactive when moderated, they are modeled with water moderation and reflection. While there are other materials that are better reflectors than water, the use of these materials would not change the results of the comparison presented here. The moderated element configurations are evaluated to be as reactive as reasonably possible. This is done by varying the spacing between elements to find the most reactive configurations.

6.1.1 Mark VII HEU ATR Elements

A previous CSE[17] has evaluated near-critical water moderated and reflected configurations of HEU ATR elements using a previous version of MCNP (probably version MCNP4a, circa 1994, but simply referred to as MCNP) that are seen in Figure 3. The element fuel loading was 1075 g of U-235 with an enrichment of 93% and no boron. The reported values for k_{eff} were 0.984 ± 0.002 and 0.985 ± 0.003 for the hexagonal-like array (Configuration A) and circular-like configuration (Configuration B), respectively. A k_{eff} of 0.444 ± 0.002 was reported for a single water moderated and reflected element.

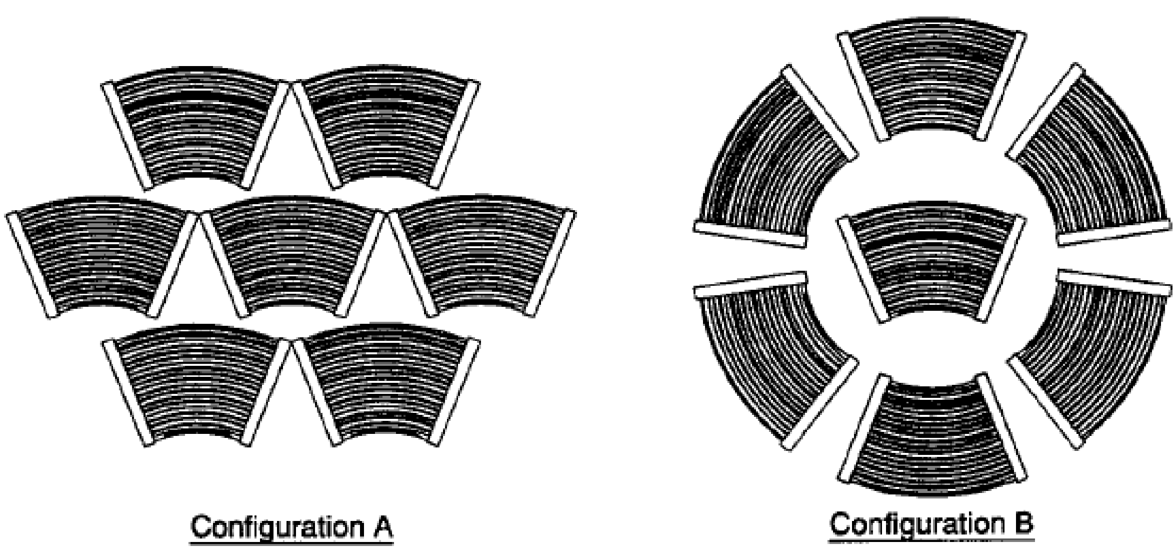
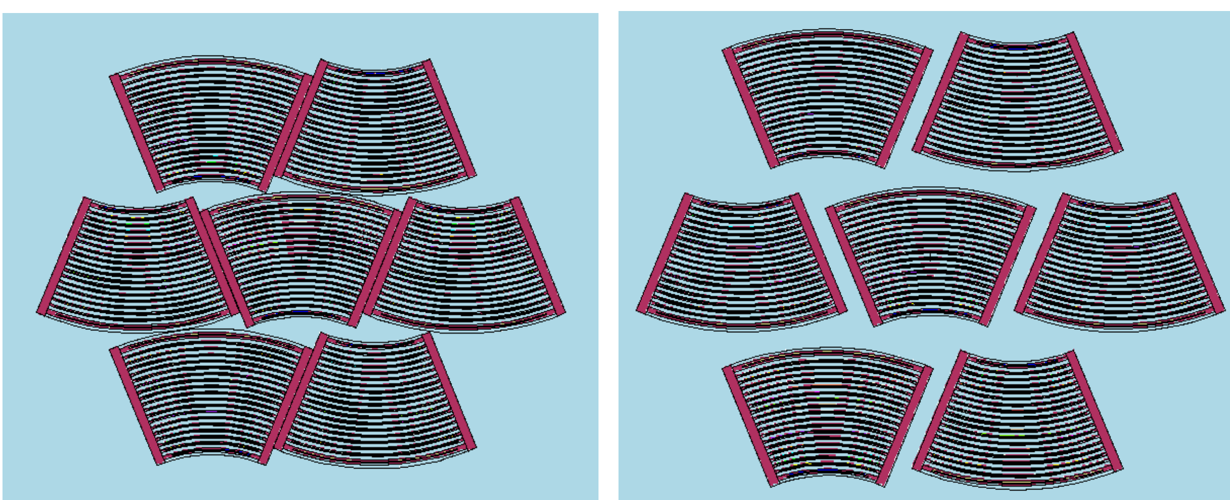


Figure 3. Near-Critical Configurations of (HEU) ATR Elements
(from Figure 3 of Reference 17)

Similar configurations are evaluated with the HEU ATR model used in this section to verify that the results are consistent. These results are presented in Appendix D, and are summarized in this section. The single element result for k_{eff} is 0.4481 ± 0.0006, which agrees with the previous value of k_{eff} from Reference 17 to ~2σ (σ from the previous calculation is used). The k_{eff} for a configuration similar to Configuration A in Figure 3 is 0.9904 ± 0.0007. This is just larger than the previous result by ~3σ, though it is reasonable considering the slightly higher loading (1085.75 g U-235 compared to 1075 g) and the uncertainty due to not knowing the exact positioning of the ATR elements.

A configuration with a more uniform spacing between adjacent side-by-side elements than Configuration A in Figure 3 is used to investigate reactivity changes with increasing space between elements. This configuration is shown in Figure 4. The elements are essentially touching in the first frame of the figure, and the elements are moved in the "conventional" x and y directions as the spacing increases. The most reactive configuration is shown in the second frame, Figure 4(b), where k_{eff} is 0.9960 ± 0.0007. This value is 0.012 Δk more reactive than the value for Configuration A (Figure 3) from Reference 17. Results for different spacings are given in the third set of Appendix D, Table D-1.

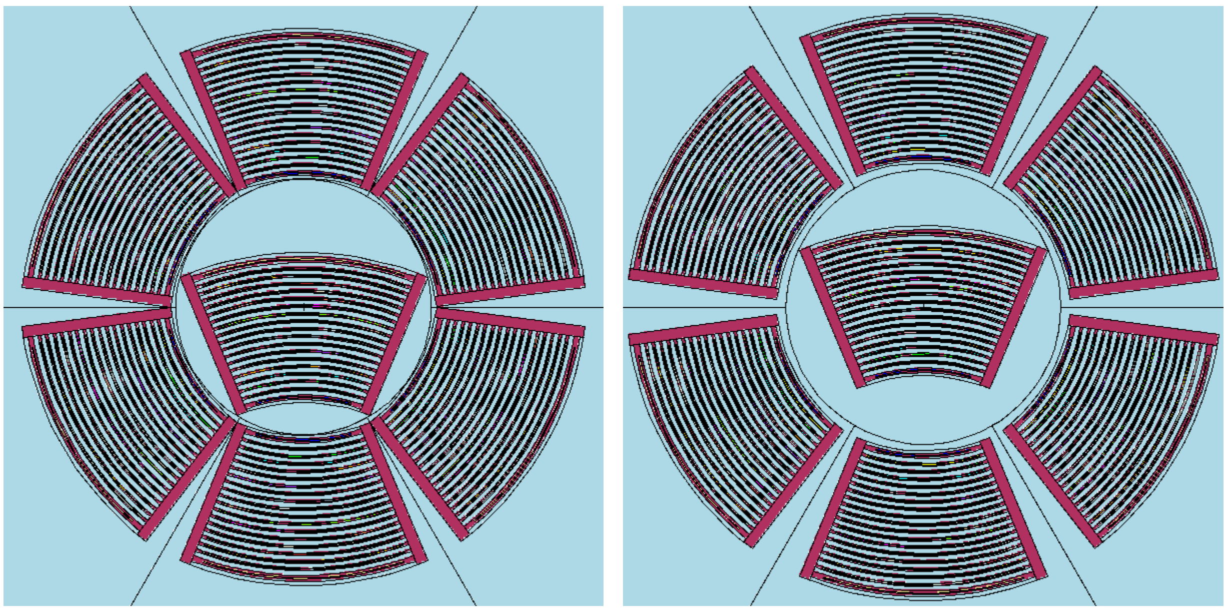


a) This is case heu_7b of Table D-1where adjacent elements are essentially touching

b) This is case heu_7b_1.1 of Table D-1 where adjacent elements are separated by 1.1 cm

Figure 4. Configurations Similar to Configuration A of Figure 3 to Investigate Increased Spacing between Elements

Configurations similar to Figure 3, Configuration B but with different radial spacing between the center element and the outer ring of elements are shown in Figure 5. The spacing between elements is increased by increasing the radius of the outer ring of elements (azimuthal spacing remains unchanged) while the center element remains fixed. Results for these configurations are given in Appendix D, Table D-2, and the most reactive case has a k_{eff} of 0.9977 ± 0.0007 which is essentially the same as the most reactive array case of Table D-1. This value is larger than Configuration B, see Figure 3, result of Reference 17 (mentioned above) by 0.013 Δk indicating that the configuration used in this CSE is more reactive than that used in Reference 17 and/or the ATR model used here is more reactive.



a) This is case heu_7c_ma of Table D-2 where elements are at closest approach

b) This is case heu_7c_0.2 of Table D-2 where elements are in most reactive configuration

Figure 5. Configurations Similar to Configuration B of Figure 3 to Investigate Increased Spacing between Elements

6.1.2 Mark IV HEU ATR Elements

The same configurations as shown in Figure 4 and Figure 5 are evaluated for the Mark IV elements. These results are presented in Appendix D, Table D-3 and Table D-4, and are summarized in this section. The single element result for k_{eff} is 0.4469 ± 0.0006, which agrees within statistics with the Mark VII value. The k_{eff} for a configuration similar to Configuration A in Figure 3 is 0.9880 ± 0.0007. This is ~3.4σ less reactive than the Mark VII result. The most reactive case for configurations shown in Figure 4 corresponds to the exact spacing as shown in Figure 4(b) and k_{eff} is 0.9949 ± 0.0006 and agrees within statistics with the Mark VII value. The most reactive result for configurations shown in Figure 5 is a k_{eff} of 0.9959 ± 0.0007, which is ~2.6σ less reactive than that for the Mark VII element. Comparison of the Mark IV and VII results for the configurations of Figure 4 and Figure 5, Table D-1 through Table D-4, for all values of configuration spacing shows that the majority of cases agree within statistics. In all but a couple of cases the Mark VII results are larger than those of the Mark IV though the difference is less than ~2σ. For the cases where the Mark VII results are larger than the Mark IV results the largest differences (four cases) are ~5σ.

6.1.3 U-10Mo ELF Elements

The U-10Mo ELF elements are evaluated in this section. The configurations evaluated are identical to those used for the HEU fuel (Table D-1 and Table D-2 of Appendix D) and are the same as shown in Figure 4 and Figure 5, though the most reactive cases occur for slightly different spacings. The results for the nominal fuel meat thickness and the thicker fuel meat ELF elements with different spacings between elements are presented in Appendix D, Table D-5 and Table D-6 respectively. The single ELF element results for k_{eff} for each Mod are given in Table 9 for the nominal and thicker fuel meat elements. The most reactive values of k_{eff} for each Mod are also given in this table for the nominal and thicker fuel meat element configurations similar to Configurations A and B of Table 6. Results for Mk1A and Mk1B are statistically equivalent (σ ~ 0.0006), which is consistent with their very comparable element masses, see Table 8.

Table 9. Summary of Most Reactive ELF Results

Configuration	Description	k_{eff} + 2σ, most reactive case(s)		
		Mod 0.1	Mk1A	Mk1B
Single ELF Element	Nominal fuel meat thickness	0.4572	0.4653	0.4656
	Thicker fuel meats	0.4635	0.4705	0.4719
ELF Array Configurations, see Figure 4	Nominal fuel meat thickness	0.9737	0.9845	0.9852
	Thicker fuel meats	0.9822	0.9898	0.9920
ELF Array Configurations, see Figure 5	Nominal fuel meat thickness	0.9753	0.9867	0.9863
	Thicker fuel meats	0.9832	0.9937	0.9926

6.1.4 Comparison of the Mark IV and VII HEU Elements

Mark IV and VII results for the hexagonal-like configurations shown in Figure 4 and the circular-like configuration of Figure 5 are plotted as a function of increasing spacing between fuel elements in Figure 6. The peak reactivity occurs at spacings of 0.1 cm and 1.1 cm for the circular-like and hexagonal-like configurations, respectively. The peak reactivity value is essentially the same having a k + 2σ value of ~0.997 for both configurations. The Mark IV and VII results are essentially indistinguishable over the entire range of spacings indicating that the Mark IV elements are no more reactive than the Mark VII elements. This also applies to the Mark V and VI elements as their U-235 loading is slightly less than what is modeled for the Mark IV elements.

As the Mark IV element results agree within statistics to those of the Mark VII, no other comparisons are made except in Section 6.1.6.6 where Mark IV results are given for cases with differing moderation. Unless noted otherwise, all HEU results given in Section 6.1.6 are obtained with the Mark VII model.

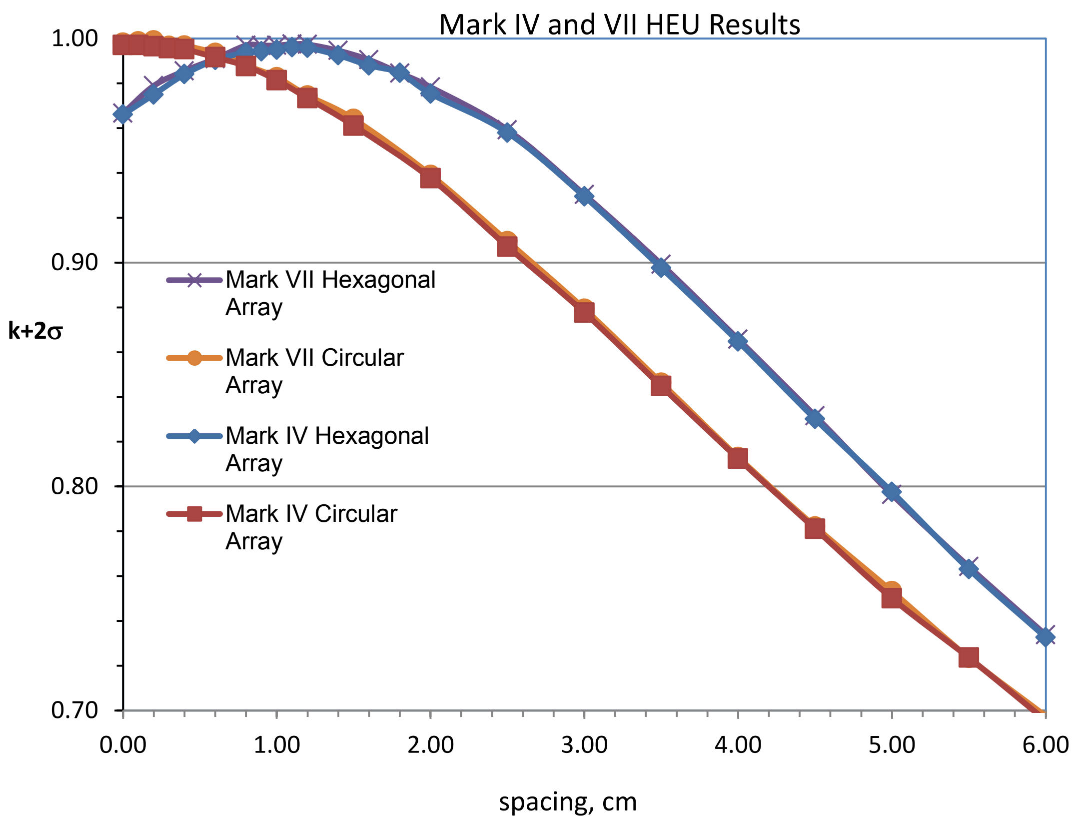
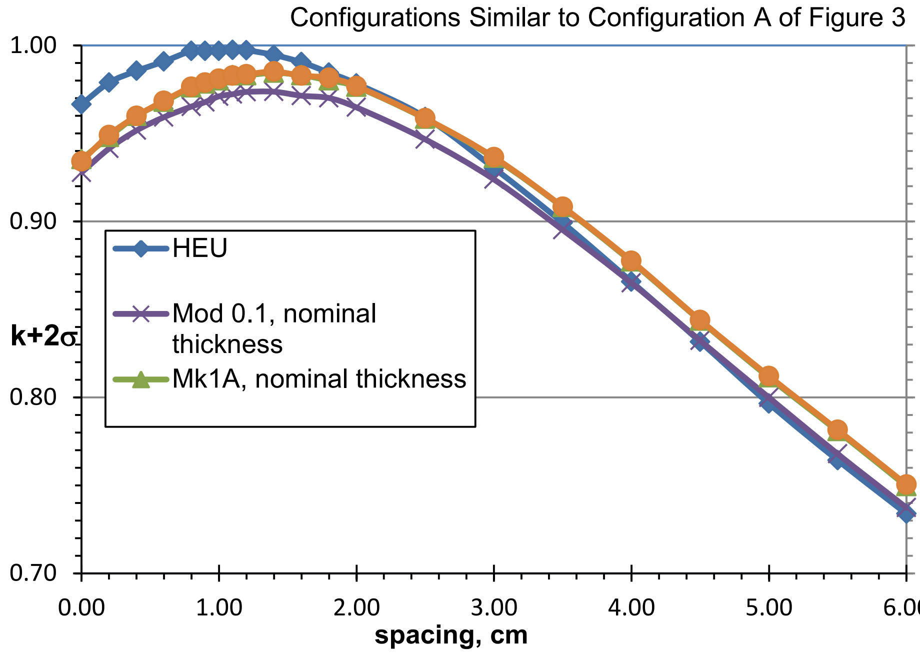


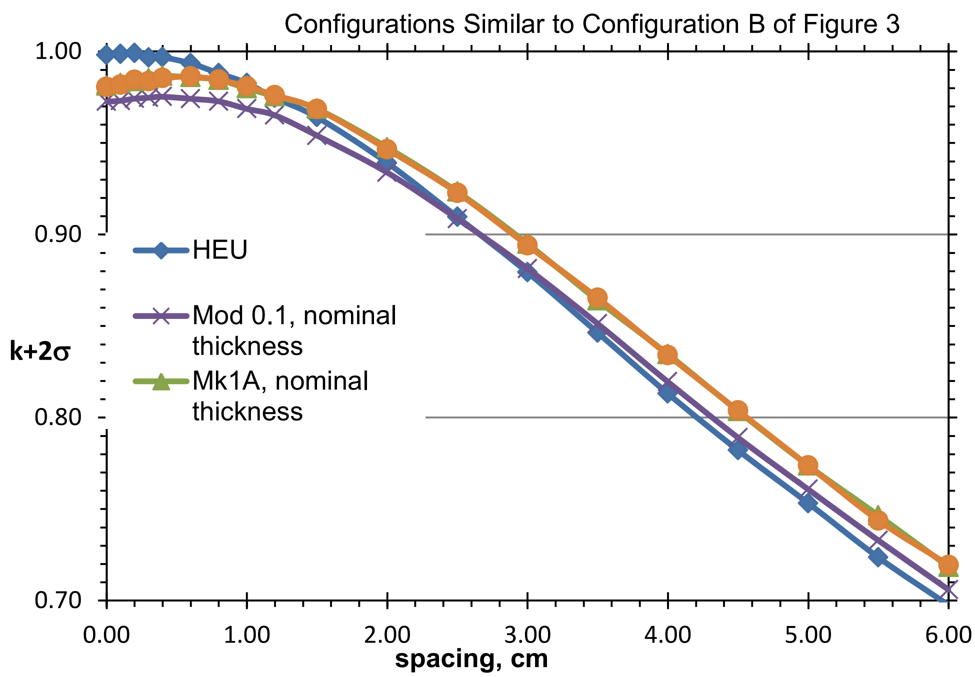
Figure 6. Mark IV and VII Element Comparison

6.1.5 Comparison of the HEU and U-10Mo ELF Elements

The reactivity of HEU and ELF configurations is plotted as a function of increased spacing between fuel elements in Figure 7. The behavior of the reactivity for the two array configurations at smaller values of spacing is quite different. This is a consequence of the spacing between elements when they are at closest approach, i.e., at closest approach there is very little spacing between elements in the configuration shown in Figure 4(a), whereas there is more spacing between elements in the other type of configuration shown in Figure 5(a). The maximum values of reactivity for each fuel type and thickness are essentially the same for the two configurations, though the HEU maximum values are larger than those for the ELF elements in all cases. The ELF maximum values of reactivity occur at slightly larger values of spacing than those for the HEU fuel elements. For increased values of spacing, the reactivity of the ELF elements becomes greater than that of the HEU elements though the increase is quite small for the Mod 0.1 nominal thickness elements. Even though the values of k_{eff} at larger values of spacing are sufficiently small to not require changing existing HEU controls, increasing the number of elements from seven to larger numbers of elements as would be present in a storage pool or storage rack (with the same or similar element-to-element spacing) requires evaluation.

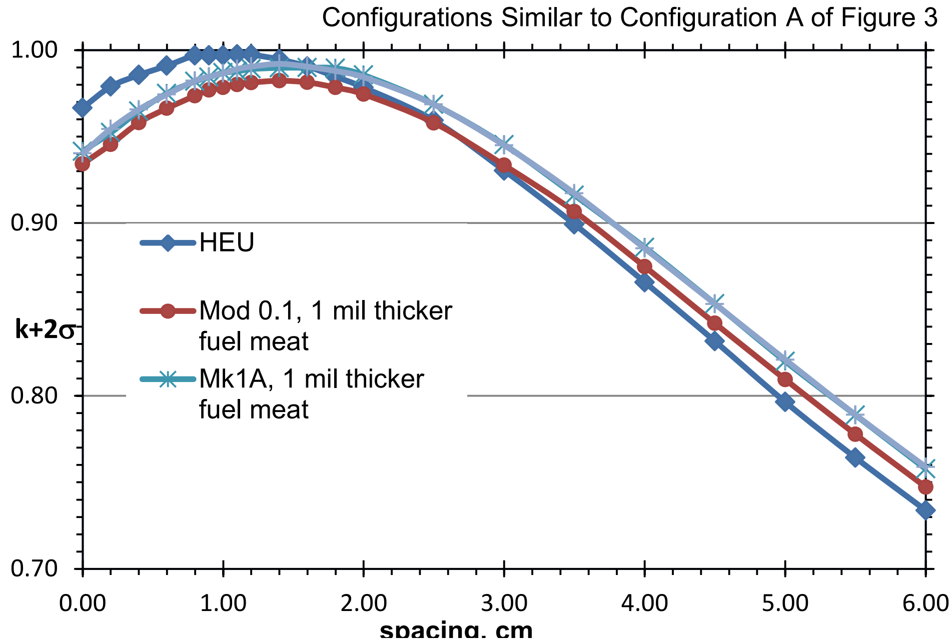


a) Comparison of Configurations Similar to Configuration A in Figure 3, nominal thickness fuel meats

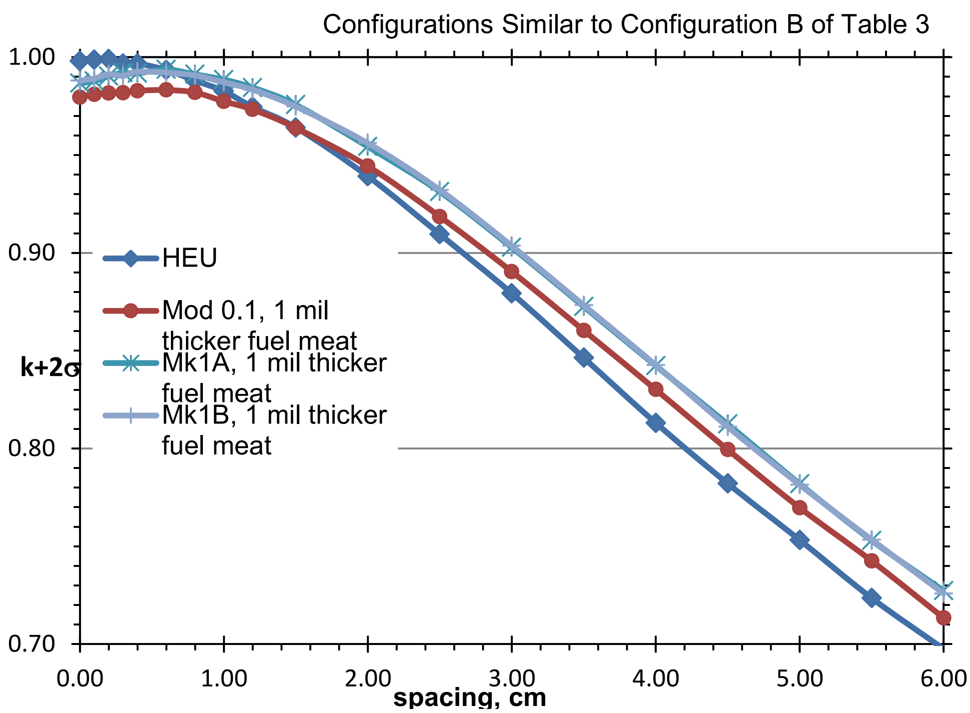


b) Comparison of Configurations Similar to Configuration B in Figure 3, nominal thickness fuel meats

Figure 7. Array Reactivity Plotted as a Function of Increased Spacing between Elements



c) Comparison of Configurations, thicker fuel meats



d) Comparison of Configurations, thicker fuel meats

Figure 7. Array Reactivity Plotted as a Function of Increased Spacing between Elements (continued)

A summary of the most reactive HEU and Mk1B element cases is given in Table 10. The Mk1B is chosen because its reactivity is essentially the same as that of the Mk1A, both being larger than that of the Mod 0.1. The most reactive values of k_{eff} (same fuel type) for the configurations similar to Configurations A and B of Figure 3 are quite similar even though the element arrangement is considerably different. The difference between HEU and ELF largest reactivities, Δk, is also tabulated for each configuration. The HEU fuel elements arrays are more reactive than the ELF arrays, though a single ELF element is more reactive than an HEU element, which is consistent with the results in Figure 7. As the spacing between elements increases sufficiently, the elements begin to decouple and the system reactivity asymptotes to the single element (unit) reactivity. This would occur at values of the spacing several times larger than that shown in Figure 7.

Table 10. Comparison of Most Reactive HEU and ELF Mk1B Results

Configuration (and Number of Elements)	k_{eff} + 2σ (most reactive case)			Difference Δk, (HEU – ELF) nominal / thicker plates	Difference Δk/k, (HEU – ELF)/HEU nominal / thicker plates, %
	HEU ATR Elements	U-10Mo ELF Elements (nominal thickness)	U-10Mo ELF Elements (thicker)		
Single ATR element	0.4492	0.4656	0.4719	-0.0165 / -0.0227	-3.7 / -5.1
Configurations Shown in Figure 4	0.9975	0.9852	0.9920	0.0123 / 0.0054	1.2 / 0.5
Configurations Shown in Figure 5	0.9991	0.9863	0.9926	0.0128 / 0.0065	1.3 / 0.6

6.1.6 Evaluation of Previous CSE Results with U-10Mo ELF Elements

Current ATR handling, storage and transportation controls are derived and/or verified in previous CSEs. [16, 18, 19, 20, 22, 23] Since the controls are derived for HEU fuel, the results shown in Figure 7 and summarized in Table 10 would indicate that ELF elements of either fuel meat thickness would most likely be enveloped by HEU fuel provided the spacing between elements are optimal (most reactive) or near optimal. On the other hand, greater than optimal spacing of ELF fuel elements would most likely exceed the reactivity of equivalently spaced HEU fuel, though the increase in reactivity may be small provided the magnitudes of the single element Δk/ks are a reasonable indicator of this increase. For Mk1B fuel, the largest magnitude values of Δk/k for greater spacing cases from Figure 7 are -3.1% and -4.1% for nominal and thicker fuel meats, respectively, which are bound by the single element values in Table 10. This relationship can be seen in Figure 8 where Δk/k values from Figure 7(a) and from the single element results are plotted as a function of the reciprocal spacing between elements. This suggests that the largest increase in k_{eff} would be no larger than 5% for the thicker fuel meat Mk1B fuel. Typically, this or smaller increases as shown in Figure 8 would not invalidate existing controls though ultimately this depends on how conservative the results are, the exact value of $k_{eff} + 2\sigma$, and other considerations. This and other issues are investigated in this section using cases from previous ATR CSEs. These cases are chosen on the basis of being used to derive controls, most reactive, or other unique features, e.g., they may contain neutron absorbers or special reflectors.

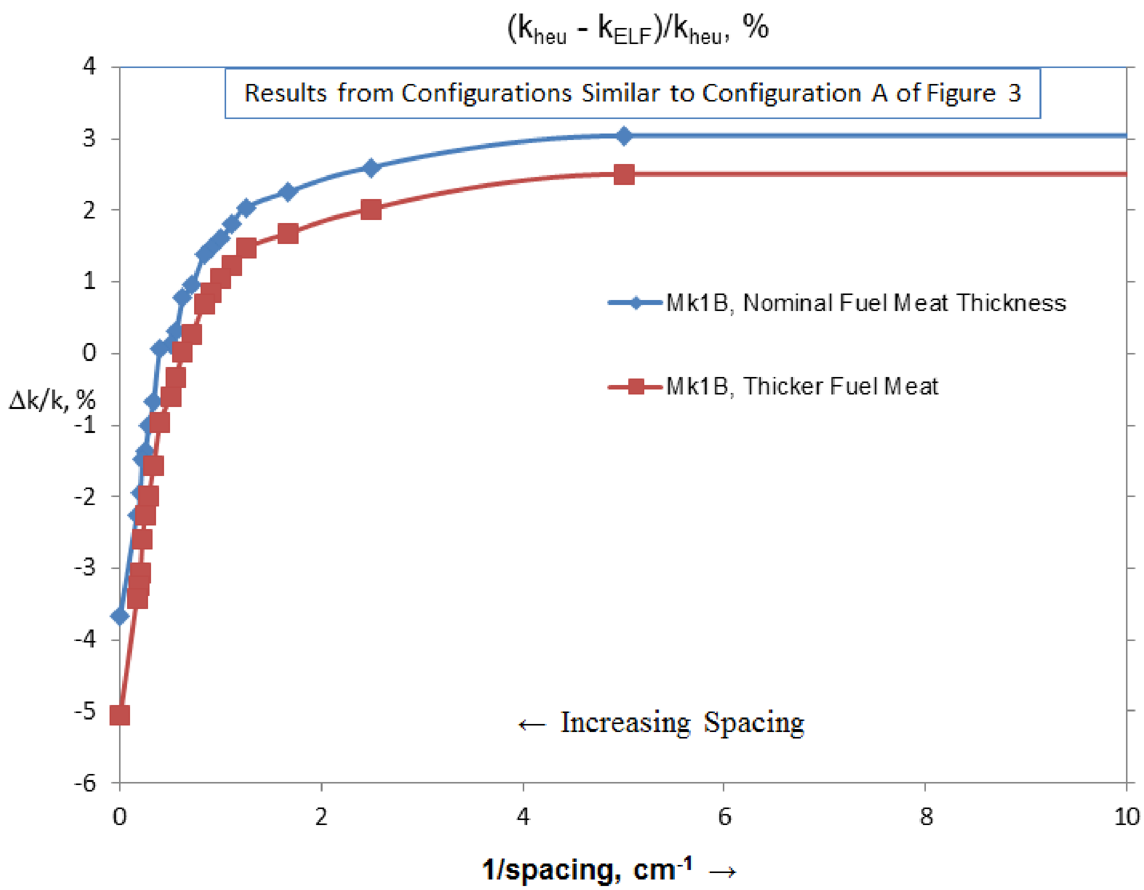


Figure 8. Relative Reactivity Change Plotted as a Function of Reciprocal Element Spacing

The indentified cases from these previous CSEs [16, 18, 19, 20, 22, 23] are investigated in Sections 6.1.6.1 - 6.1.6.6, and evaluated for ELF elements. These sections give a description, the detailed references for each case, and the values of $k_{eff} + 2\sigma$ and σ of each case. The majority of results are for the original ELF design, Mod 0.1, and some of the more reactive cases are evaluated for the Mk1B thicker fuel meat fuel. Results for this latter fuel are essentially the same as those for the thicker fuel meat Mk1A and bound the nominal fuel meat thickness Mk1A and Mk1B fuels. Additional information, additional detailed descriptions and other related cases are given in the cited references.

6.1.6.1 Analysis for Evaluated ATR Racks in ATRC and NMIS[19]

Dry, cadmium poisoned storage racks are used in both the ATRC Facility and the Nuclear Materials Inspection and Storage (NMIS) Facility for the storage of ATR fuel elements and miscellaneous odd lot fuel. In ATRC, these racks are referred to as the ATRC fuel storage cabinets and in NMIS as the ATR fuel racks. The rack positions in the two facilities are of identical construction, although overall the size of the racks varies. The storage racks contain 4 positions across a shelf. The racks are 8 and 11 shelves high within ATRC and NMIS, respectively. The ATRC cabinets are comprised of two racks situated side by side, creating an 8 × 8 array of storage positions. The NMIS racks are comprised of 18 racks, creating a 72 × 11 array of storage positions.

The racks are constructed predominately of plywood with a thin (minimum 0.01 in.) sheet of cadmium on the top and bottom of each shelf. Storage positions are separated by plywood spacers. In some of the racks, the plywood has been replaced by polyethylene of the same thickness. Figure 9 shows the rack construction.

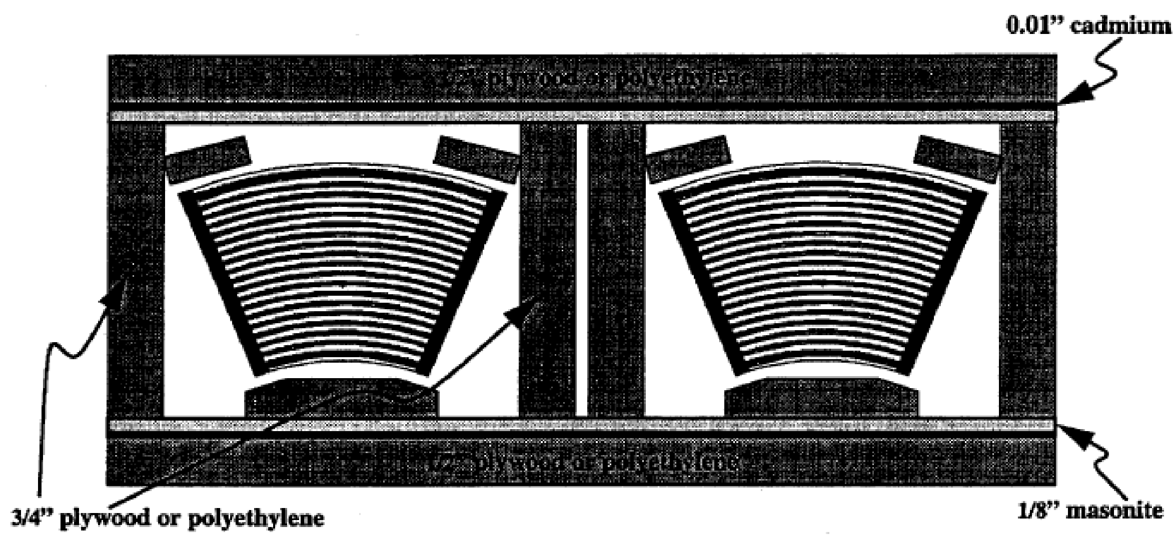


Figure 9. ATR Fuel Rack Storage Positions

Each storage position is 4 in. high by 4.5 in. wide with a length of 60 in. Positions are spaced 1.625 in. apart (edge-to-edge) within a shelf, and shelves have a center-to-center spacing of 6.5625 in. Position dimensions and spacings are shown in Figure 10.

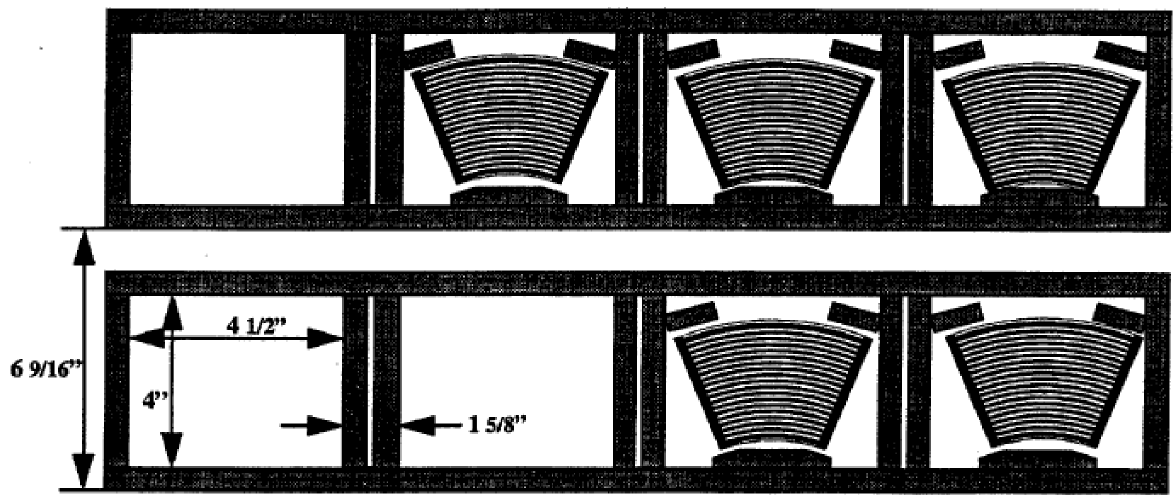


Figure 10. ATR Fuel Storage Racks – Dimensions and Spacings

The following cases are taken from Reference19 and are used to evaluate the ATR storage racks and cabinets for ELF elements. These cases are listed as Cases 1, 2 and 3 in Table 11.

- Case 1: This is case atr04 of Table1, Reference 19. An infinite array of ATRC fuel storage cabinets/NMIS ATR fuel racks contains one infinitely long ATR element per position. Racks are fully flooded and contain cadmium lining on top and bottom of each shelf.

- Case 2: Last case of Table 2 "partial flooding", i.e., flooded elements with reduced water density between elements, Reference 19. An infinite array with infinite rack length of ATRC fuel storage cabinets/NMIS ATR fuel racks contains one ATR element per position. Racks are partially flooded and contain cadmium lining on top and bottom of each shelf.

- Case 3: Case atr05 of Table 3, Reference 19. Infinite array with infinite rack length of ATRC fuel storage cabinets/NMIS ATR fuel racks. Racks are fully flooded and cadmium lining in the racks is neglected.

Results for Cases 1-3 are given in Table 11. The original HEU k_{eff} values are repeated, and values from MCNP5, version 1.51 are listed for HEU and nominal and larger fuel meat thickness Mod 0.1 and thicker Mk1B elements. The rack containing ELF fuel increases in k_{eff} relative to the HEU fuel. Values of Δk/k are also given where Δk is defined to be $k_{eff, HEU} - k_{eff, ELF}$. The Δk/k values for Case 1 show the Mod 0.1 to be slightly more reactive than the HEU elements. It is unnecessary to evaluate the Mk1B for this case as the k_{eff} values are significantly below 0.95. The Mk1B thicker fuel meat fuel is evaluated for Case 2 and increases k_{eff} by 5.22% though this does not require changing existing HEU controls. The largest $k_{eff} + 2\sigma$ value occurs for the thicker fuel meat Mk1B Case 3 but is less than the 0.95 limit. Likewise, this slight increase does not require any changes to existing HEU controls as the model for this case is extremely conservative, i.e., the infinite array of racks holds infinitely long ATR elements, and the cadmium in the racks is neglected.

Table 11. HEU and ELF Results for ATRC and NMIS Storage Racks

Case (MCNP Input File)	Description	$k_{eff} \pm \sigma$	$k_{eff} + 2\sigma$	$\Delta k/k$, (HEU – ELF) / HEU, %
Case 1, HEU and Mod 0.1 ELF elements; HEU $k_{eff} + 2\sigma$ = 0.584				
atr04	HEU results[a] from Reference 19	0.582 ± 0.001	0.584	–
atr04	Previous case but MCNP5, version 1.51	0.5842 ± 0.0006	0.5854	–
atr5L04	ELF elements, nominal thickness fuel meats	0.5918 ± 0.0006	0.5931	-1.32%
atr5Lt04	ELF elements, thicker fuel meats	0.6003 ± 0.0006	0.6016	-2.77%
Case 2 HEU and ELF elements; HEU $k_{eff} + 2\sigma$ = 0.820				
atrPartial	HEU results from Reference 19	0.818 ± 0.001	0.820	–
atrPrt	Previous case but MCNP5, version 1.51	0.8163 ± 0.0007	0.8177	–
atr5LPrt	Mod 0.1 elements, nominal thickness fuel meats	0.8225 ± 0.0007	0.8238	-0.75%
atr5LtPrt	Mod 0.1 elements, thicker fuel meats	0.8391 ± 0.0007	0.8404	-2.78%
atr_11_5LtPrt	Mk1B elements, thicker fuel meats	0.8591 ± 0.0007	0.8604	-5.22%
Case 3, HEU and ELF elements; HEU $k_{eff} + 2\sigma$ = 0.923				
atr05	HEU results from Reference 19	0.921 ± 0.001	0.923	–
atr05	Previous case but MCNP5, version 1.51	0.9203 ± 0.0006	0.9214	–
atr5L05	Mod 0.1 elements, nominal thickness fuel meats	0.9207 ± 0.0006	0.9219	-0.05%
atr5Lt05	Mod 0.1 elements, thicker fuel meats	0.9327 ± 0.0006	0.9338	-1.35%
atr_11_5Lt05	Mk1B elements, thicker fuel meats	0.9453 ± 0.0006	0.9464	-2.66%

a HEU values of k_{eff} and σ were obtained with MCNP version older than MCNP5, version 1.51.

6.1.6.2 Analysis for ATR Racks in ATR Canal[16, 18]

The ATR storage canal is a deep, water filled channel connected to the ATR. The canal is used to store fuel and experiments waiting to be placed in the reactor, and spent fuel and irradiated experiments waiting for radiation levels to decrease so they can be moved elsewhere. Storage of irradiated ATR fuel elements takes place in fixed position, cadmium lined storage racks (or grids) in this canal. Three different types of storage racks are used for storage of ATR fuel elements in the canal: 1) New Type ATR racks, [Fuel storage grids 9 through 23 (Drawing 035713)] 2) Old Type ATR racks [Canal fuel storage grid 6 (Drawing 120787)], and 3) CPP racks [Fuel storage grids 29, 35, and 36 (Drawing 117015)].

The three sections of the ATR Canal are: the working canal, the storage canal and the Advanced Test Reactor Critical (ATRC) Facility canal, see Figure 11. The working canal is directly adjacent to the reactor and is used to transfer fuel, experiments and reactor components between the storage canal and the reactor. The storage canal is used for the storage of fuel, experiments and reactor components.

The storage canal is 8 ft wide, 156 ft long and 21 ft deep, except for a section in the east end that is 40 ft deep. The canal is constructed of 5.5 to 7 ft thick reinforced concrete.

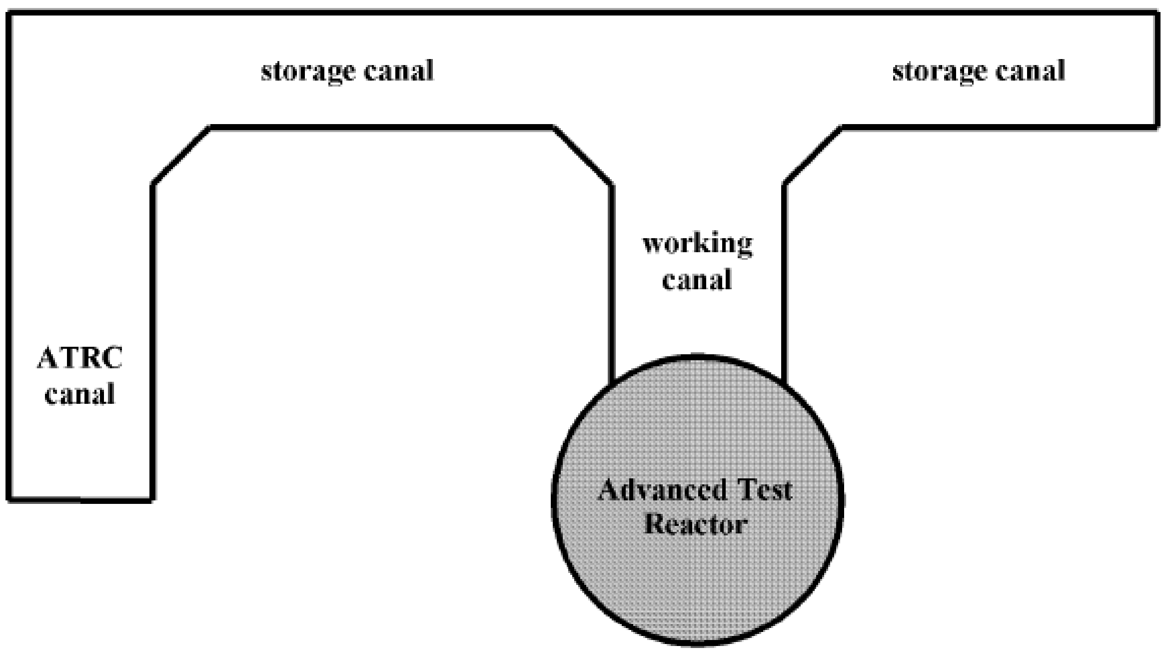


Figure 11. Layout of the ATR and the ATR Canal

The New Type ATR rack is comprised of 40 circular storage tubes arranged in rows of four and five tubes as shown in Figure 12. The storage positions are arranged in a triangular pitch with 6.5 in. spacing between centers within a row and 6.1875 in. between row centers. The overall height of these racks is 61.75 in., while the total length of the cadmium absorber in each position is 58 in. (centered along the height of the storage rack). The dimensional tolerances of the New Type ATR rack are ± 1/32 in.

Each storage position is a 5.0 in. inner diameter tube consisting of an inner and outer aluminum tube with a 0.02 in. thick sheet of cadmium sandwiched between them. The inner aluminum tube has a wall thickness of 0.125 in. and the outer aluminum tube has a wall thickness of 0.049 in. The storage position lengths are 59.25 in., and the cadmium sheet lengths are 58 in. centered along the height of the position. The New Type ATR rack storage position is shown in Figure 13.

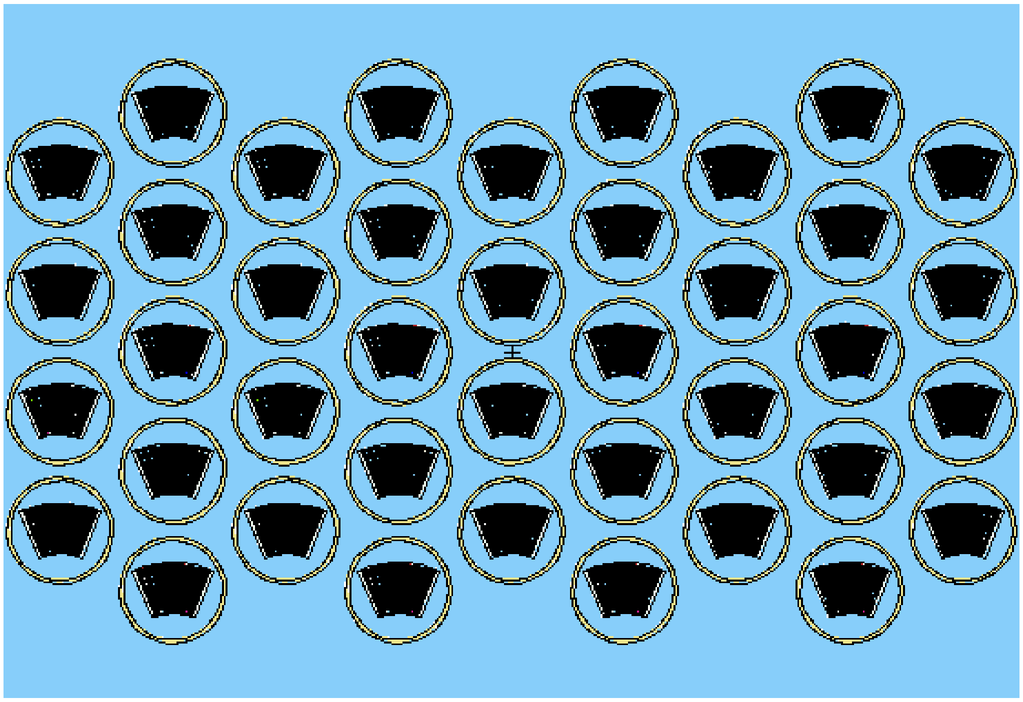


Figure 12. Cross-sectional View of New Type Storage Rack

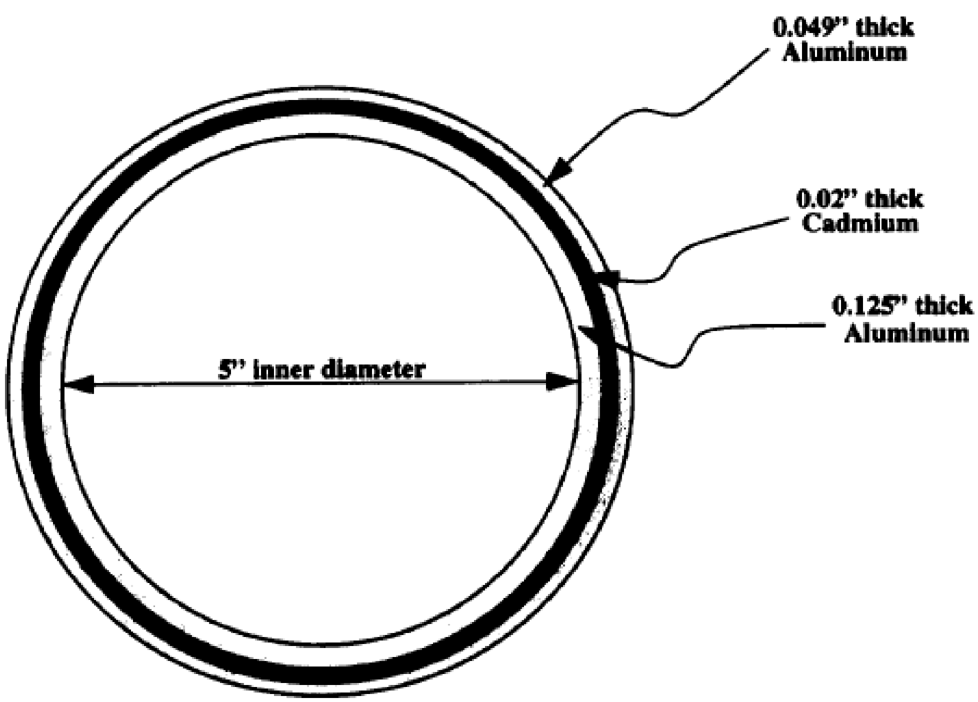


Figure 13. New Type ATR Rack Storage Position

One of the New Type ATR racks is positioned directly under one of the recycle discharge pumps where the outlet water flow has apparently caused movement of a few of the rack's storage tubes. This has caused a spacing change larger than anticipated between some of the storage positions within the rack. Observation of the suspected rack determined that there was some rack movement greater than what was originally evaluated in the supporting CSE.[18] The largest movement was observed to be about 0.5 in. The case chosen for the ELF evaluation is taken from the last case of Table 4 of Reference 16, which evaluates a center-to-center spacing tolerance between storage racks of 0.5 in., a center-to-center spacing within a row of 6 in., which represents a ½ in. tolerance and is the most reactive case of Reference 16. The MCNP models neglect cadmium and place reflective boundary conditions around the storage rack and 30 cm of water above and below the elements. This section analyzes this spacing change for ELF fuel and combinations of ATR and ELF fuel.

Results for the rack containing HEU and ELF elements are given in Table 12. The first set of results is for the rack containing only HEU elements, and the second set of results is for nominal and thicker fuel meat Mod 0.1 and Mk1B thicker fuel meat elements. The ELF elements are seen to be more reactive than the HEU elements by 0.70% and 2.0% for the Mod 0.1 nominal and thicker fuel meat elements, respectively, and 3.4% for the thicker fuel meat Mk1B elements.

In the third set of Table 12, results are given for varying numbers of Mod 0.1 thicker fuel meat ELF elements with HEU elements filling the remainder of the rack. A given number of ELF elements are positioned in the inner portion of the rack and the remainder of the rack is populated with HEU elements. The process continues by varying the number of ELF elements. Likewise, the same process continues but HEU elements are modeled in the inner portion of the rack surrounded by sufficient ELF elements to fill the rack. Results of these two positioning models are shown in Figure 14 for nominal and thicker fuel meat elements. The results for the nominal thickness elements show slight variations whether the ELF or HEU elements are in the inner portion of the rack, whereas the variations between the thicker fuel meat ELF elements in the inner or outer portion of the rack are considerably larger. These variations are most likely due to the fact that no attempt is made to optimize the positioning of the elements. Barring these variations, the results show that as the number of ELF elements in the array increases so does the reactivity, indicating that an array of both ELF and HEU elements is less reactive than an array of ELF elements. Though optimization is well beyond the scope (or need) of this CSE, optimization would slightly alter this relationship of reactivity with increasing number of ELF elements as it is noted in Table 12 that the reactivity of 34 ELF elements (and 4 HEU elements) is the same as that of 40 ELF elements. Unless noted otherwise, no additional cases with both HEU and ELF elements will be evaluated in this CSE. Though the Mod 0.1 ELF elements are more reactive than the HEU elements, this increase (2.0% for thicker fuel meat fuel) is insufficient to cause any changes to existing rack storage HEU controls.

The last set of the table presents results similar to the previous set but for the Mk1B thicker fuel meat fuel. These results are also plotted in Figure 14 .

Table 12. Results for HEU and ELF Elements in New Type Storage Rack

Case (MCNP Input File)	Description	$k_{eff} \pm \sigma$	$k_{eff} + 2\sigma$
Rack filled with HEU elements			
tolerance0p50	HEU results[a] from Reference 16	0.8261 ± 0.0010	0.8281
toler_new	Previous case but MCNP5, version 1.51	0.8255 ± 0.0006	0.8266
Rack filled with ELF elements			
tol0p50Lt	Mod 0.1 ELF nominal thickness fuel	0.8312 ± 0.0006	0.8324
tol0pT50Lt	Mod 0.1 ELF thicker fuel meat	0.8421 ± 0.0006	0.8433
tol0pT50L11t	Mk1B ELF thicker fuel meat	0.8534 ± 0.0005	0.8545
Rack filled with varying number of Mod 0.1 ELF (thicker fuel meat) and HEU elements;[b] ELF elements are positioned in the inner portion of the rack			
tolHha	40 HEU elements	0.8277 ± 0.0006	0.8289
tolHhaT4	4 Mod 0.1 ELF elements and 36 HEU elements	0.8303 ± 0.0006	0.8314
tolHhaT7	7 Mod 0.1 ELF elements and 33 HEU elements	0.8311 ± 0.0006	0.8322
tolHhaT19	19 Mod 0.1 ELF elements and 21 HEU elements	0.8357 ± 0.0006	0.8369
tolHhaT21	21 Mod 0.1 ELF elements and 19 HEU elements	0.8349 ± 0.0006	0.8362
tolHhaT24	24 Mod 0.1 ELF elements and 16 HEU elements	0.8389 ± 0.0006	0.8401
tolHhaT25	25 Mod 0.1 ELF elements and 15 HEU elements	0.8378 ± 0.0006	0.8390
tolHhaT30	30 Mod 0.1 ELF elements and 10 HEU elements	0.8380 ± 0.0006	0.8391
tolHhaT34	34 Mod 0.1 ELF elements and 6 HEU elements	0.8419 ± 0.0006	0.8431
tolHhaT36	36 Mod 0.1 ELF elements and 4 HEU elements	0.8399 ± 0.0006	0.8411
tol0pT50Lt	40 Mod 0.1 ELF elements and no HEU elements	0.8421 ± 0.0006	0.8433
Rack filled with varying number of Mk1B ELF (thicker fuel meat) and HEU elements;[b] ELF elements are positioned in the inner portion of the rack			
tolHha	40 HEU elements (result repeated from previous set)	0.8277 ± 0.0006	0.8289
tolHhaT11_4	4 Mk1B ELF elements and 36 HEU elements	0.8316 ± 0.0006	0.8328
tolHhaT11_7	7 Mk1B ELF elements and 33 HEU elements	0.8355 ± 0.0006	0.8366
tolHhaT11_19	19 Mk1B ELF elements and 21 HEU elements	0.8438 ± 0.0006	0.8449
tolHhaT11_21	21 Mk1B ELF elements and 19 HEU elements	0.8410 ± 0.0006	0.8421
tolHhaT11_24	24 Mk1B ELF elements and 16 HEU elements	0.8478 ± 0.0005	0.8489
tolHhaT11_25	25 Mk1B ELF elements and 15 HEU elements	0.8468 ± 0.0006	0.8480
tolHhaT11_30	30 Mk1B ELF elements and 10 HEU elements	0.8500 ± 0.0006	0.8512
tolHhaT11_34	34 Mk1B ELF elements and 6 HEU elements	0.8511 ± 0.0006	0.8523
tolHhaT11_36	36 Mk1B ELF elements and 4 HEU elements	0.8505 ± 0.0006	0.8516
tol0pT50L11t	40 Mk1B ELF elements, no HEU elements (result repeated from second set)	0.8534 ± 0.0005	0.8545

a HEU values of k_{eff} and σ were obtained with a MCNP version older than MCNP5, version 1.51.

b HEU model used in third and fourth sets of result is slightly more reactive than that used in Reference 16 and for results in the first set of this table, e.g., for more reactive model with all HEU elements, $k + 2\sigma$ = 0.8289.

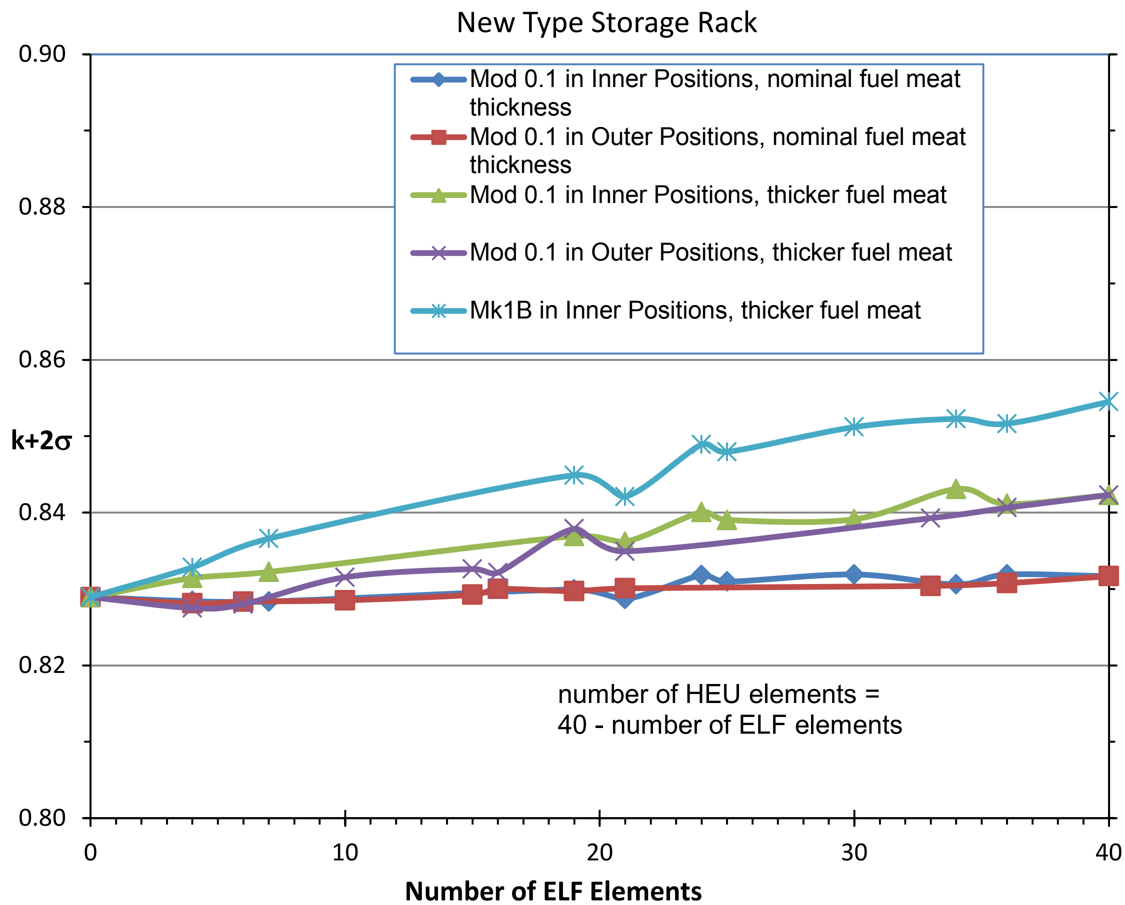


Figure 14. Reactivity of New Type Storage Rack for Varying Numbers of HEU and ELF Elements

The Old Type ATR racks consist of 40 storage positions per rack. Storage positions are 'D' shaped tubes arranged in pairs. Each rack contains 4 rows with 5 pairs per row, see Figure 15. Positions have a 6 in. center-to-center spacing within rows and a 9.25 in. center-to-center spacing between rows. The overall rack height is 53.9375 in. (including base). The cadmium absorber within each storage position has a length of 48.75 in. There is an additional extension grid that can be attached onto the top of these racks. The extension grid brings the overall rack height to 63.9375 in. (including base) and adds an additional 9.5 in. of cadmium, bringing the total cadmium length to 58.25 in. Tolerances on the Old Type ATR rack dimensions are ±1/32 in. Note that an Old Type ATR rack is also in the ATRC canal, which is also bound by the analysis in Reference 18.

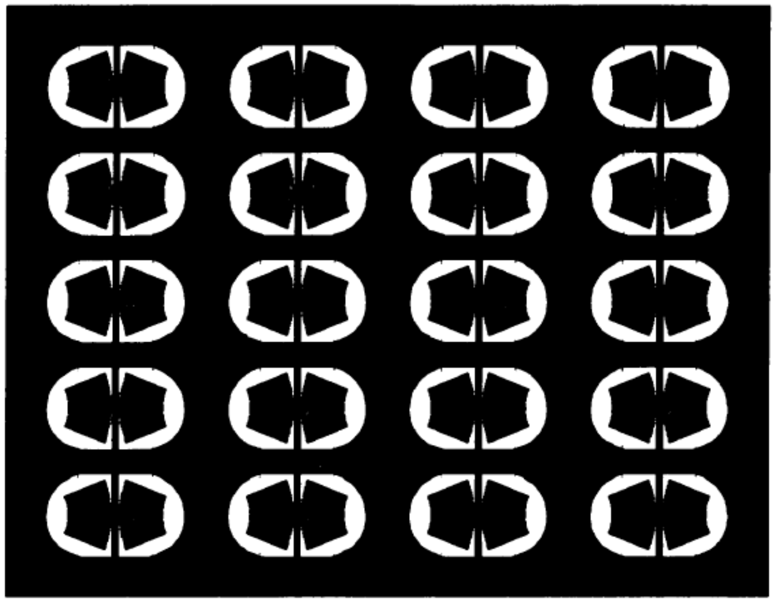


Figure 15. Old Type ATR Rack

Each individual 'D' shaped storage position in the Old Type ATR racks has inside dimensions of 4.625 in. by 3.5 in., see Figure 16. The storage position walls are constructed of 0.02 in. thick cadmium sandwiched between two 0.04 in. thick sheets of aluminum.

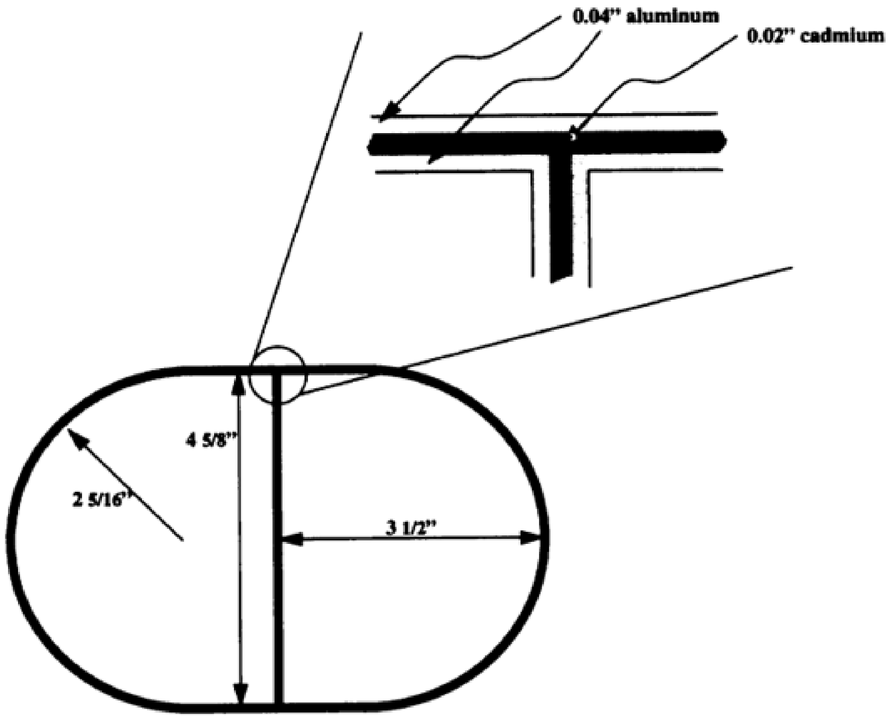


Figure 16. Storage Position for Old Type ATR Rack

Like the New Type ATR racks, the CPP racks are composed of circular, cadmium lined storage tubes. Each rack contains 92 storage positions. Storage positions are arranged on a triangular pitch except for the two middle rows which are arranged on a square pitch, see Figure 17. Positions within the same row have an 8 in. center-to-center spacing. Between rows, positions have a 7 in. center-to-center spacing within the triangular pitch and an 8.0 in. center-to-center spacing within the square pitch. The length of the circular storage tubes is 51 in., while the total rack height is 55 in. Tolerances on the CPP rack dimensions are ± 1/32 in.

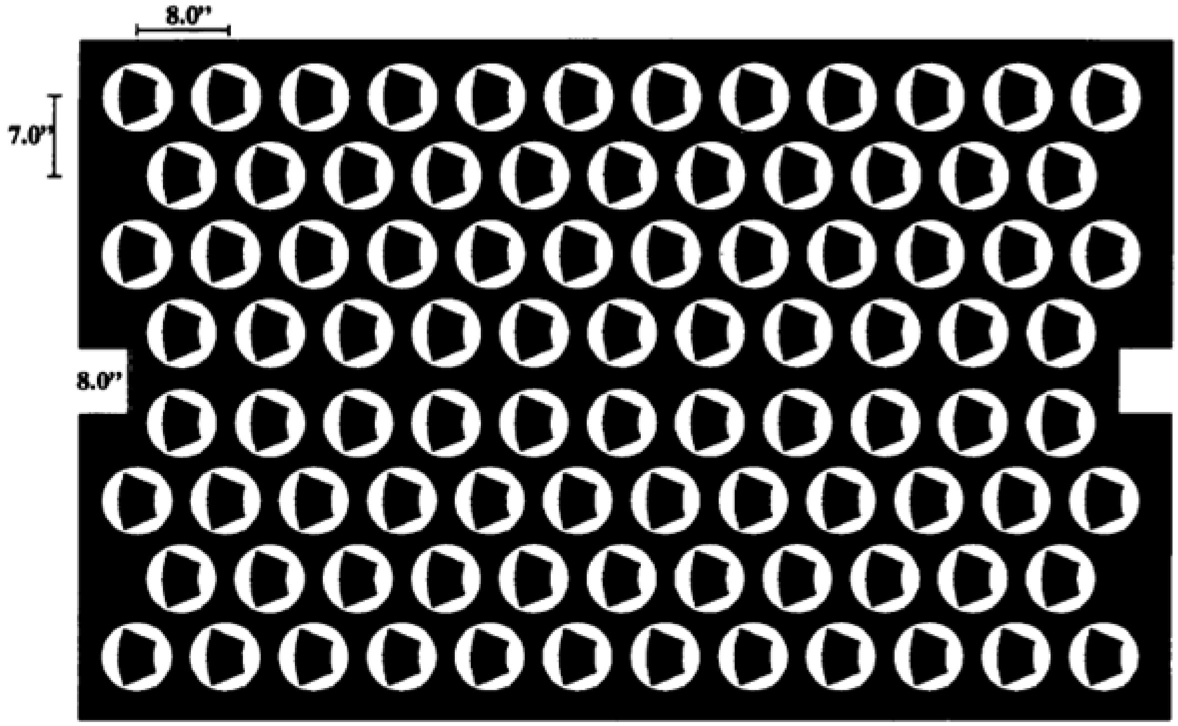


Figure 17. CPP Rack

Each storage position is constructed of a 5.75 in. ID aluminum tube of 0.125 in. thickness. A 0.02 in. thick sheet of cadmium is sandwiched between the inner aluminum tube and the 0.049 in. thick outer aluminum tube, see Figure 18.

No results are presented for the CPP racks as these racks are conservatively bound by the New Type ATR racks.

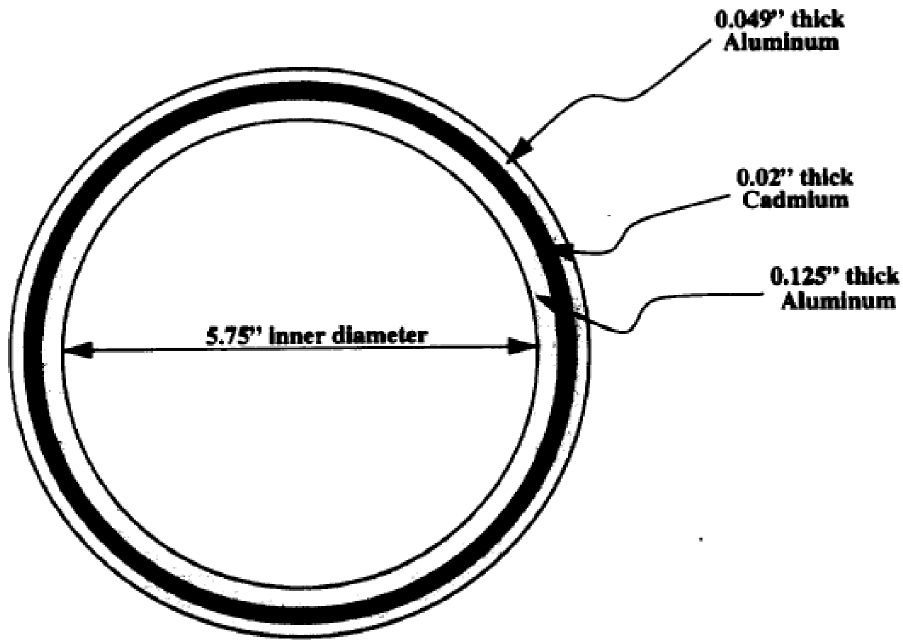


Figure 18. Storage Position CPP Rack

The following cases are taken from Reference 18 and are used to evaluate the ATR storage racks in the ATR Storage canal for ELF elements. These cases are listed as Cases 1 and 2 in Table 13.

- Case 1: Case O7 of Table 5, Reference 18. This evaluates an infinite array of Old Type ATR racks. Racks are fully flooded and cadmium in the racks is neglected. This is the most reactive case of Reference 18.

- Case 2: Case O9 of Table 6, Reference 18. A 2×2 water flooded array of Old Type ATR racks is evaluated with 30 cm of beryllium reflection. Cadmium in the racks is neglected.

Results for these cases are given in Table 13. For Case 1, the largest reactivity occurs for the thicker fuel meat Mk1B fuel but this case does not require changing existing HEU controls. The only case to exceed the 0.95 limit is the thicker fuel meat Mk1B case of Case 2. The Case 2 model is very conservative because it neglects the cadmium poison in the racks and is surrounded by a 5-sided, thick beryllium reflector. The ELF elements are slightly more reactive for these cases but do not require changing existing HEU controls. This conclusion also applies should positions in the rack contain other non-fissionable items, e.g., miscellaneous specimens, as this analysis would bound these situations.

Table 13. HEU and ELF Results for Old Type Storage Racks in the ATR Storage Canal

Case (MCNP Input File)	Description	$k_{eff} \pm \sigma$	$k_{eff} + 2\sigma$	Δk/k, (HEU – ELF) / HEU, %
Case 1, HEU and ELF elements; HEU $k_{eff} + 2\sigma = 0.939$				
O7	HEU results from Reference 18	0.935 ± 0.002	0.9390	–
Orack07	Previous case but MCNP5, version 1.51	0.9320 ± 0.0006	0.9331	–
Orack5L07	Mod 0.1 ELF elements, nominal thickness fuel.	0.9271 ± 0.0006	0.9282	0.525%
Orack5Lt07	Mod 0.1 ELF elements, thicker fuel meat	0.9358 ± 0.0006	0.9370	-0.418%
Orck5L11t07	Mk1B ELF elements, thicker fuel meat	0.9473 ± 0.0006	0.9485	-1.65%
Case 2, HEU and ELF elements; HEU $k_{eff} + 2\sigma = 0.941$				
O9	HEU results from Reference 18	0.937 ± 0.002	0.941	–
Orack09	Previous case but MCNP5, version 1.51	0.9356 ± 0.0006	0.9368	–
Orack5L09	Mod 0.1 ELF elements, nominal thickness fuel meat	0.9306 ± 0.0006	0.9318	0.53%
Orack5Lt09	Mod 0.1 ELF elements, thicker fuel meat	0.9385 ± 0.0006	0.9397	-0.31%
Orck5L11t09	Mk1B ELF elements, thicker fuel meat	0.9513 ± 0.0006	0.9525	-1.68%
Orack5Lt09+cd	Case Orack5Lt09 but cadmium included in rack	0.5082 ± 0.0007	0.5095	–
Orck5L11t09+cd	Case Orck5L11t09 bit cadmium included in rack	0.5174 ± 0.0006	0.5187	–

a HEU values of k_{eff} and σ were obtained with MCNP version older than MCNP5, version 1.51.

6.1.6.3 Analysis of non-ATR Fuel in the ATR Storage Canal[21] and Reactor Vessel[29]

The ATR storage canal is a deep, water filled channel connected to the reactor, see Figure 11. The canal is used to store fuel and experiments waiting to be placed in the reactor, and spent fuel and irradiated experiments waiting for radiation levels to decrease sufficiently so that the items can be moved elsewhere for long term storage. Experiments and miscellaneous items are stored in a number of storage locations, which include the 4-position experiment storage racks, the 6-position experiment storage rack, the transfer station, the I-piece grids, and canal hooks. In this section the interaction of non-ATR experimental materials with ATR elements, which are the most common fuel item found in the canal, is investigated. The evaluation of the storage and handling of non-ATR fuel in the ATR and ATRC storage canals is given in Reference 21.

The loop experiments are limited to a maximum 4 in. diameter and are stored in stainless steel experiment cans. Two types of experiment cans are used. The outer diameters of the experiment cans are 5.0 in. and 3.25 in. These diameters correspond to the section of can that contains the fueled experiments. Above this section, the top part of the can has a larger outer diameter of 6.62 in., which keeps the cans centered within the 4- and 6-position racks. Wall thicknesses for both cans are 0.25 in.

The 4-position experiment racks contain four fixed storage positions per rack and are used to store loop experiments. Two 4-position racks are in the ATR working canal and provide 8 experiment storage positions. The storage positions have 6.75 in. diameters and are spaced on 9 in. centers in a linear array. The racks are wall mounted and are designed to space the center of the storage position 7.5 in. from the canal wall i.e., 4.118 in. between the wall and the edge of the storage position. The 4-position racks are constructed of stainless steel.

The two 4-position experiment racks are modeled as a single 8 storage position linear array spaced on 9 in. centers. This is conservative because the spacing between the two positions in adjacent racks would be larger.

The back of the rack is reflected by concrete while the top and bottom are reflected by water. Depending on the scenario, non-ATR materials, reflectors or water flooded ATR elements can be positioned on the front and sides of the racks to determine the effects of these materials on material in rack storage. Rack structural material is conservatively modeled as water due to stainless steels neutron absorbing properties.

While transferring ATR elements within the canal it is possible that the elements can be moved up against the racks where they can neutronically interact with material in the rack. The placement of such ATR elements adjacent to the 4-Position Racks is shown in Figure 19 and the results are summarized in Table 14.

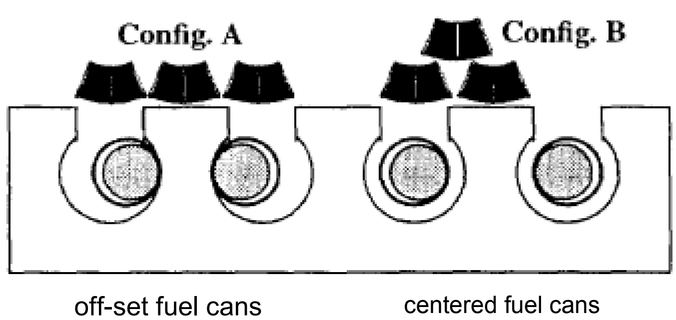


Figure 19. Interaction Configurations for 4-Position Racks

The 6-position experiment racks are modeled with overall dimensions of 25.63 in. × 50.00 in. This is conservative as the width is that of the rack middle-section and not the wider lower-section. The smaller width allows and out-of-rack materials and ATR elements to be brought closer to the loaded storage positions. The reflection and modeling of the racks and positioning of different items next to the rack is done the same as is done for the 4-position racks.

Two different configurations of three ATR elements positioned next to the 6-position rack containing fissionable material are shown in Figure 20. The effect of the interaction of the elements with the rack material is evaluated and the results are summarized in Table 14.

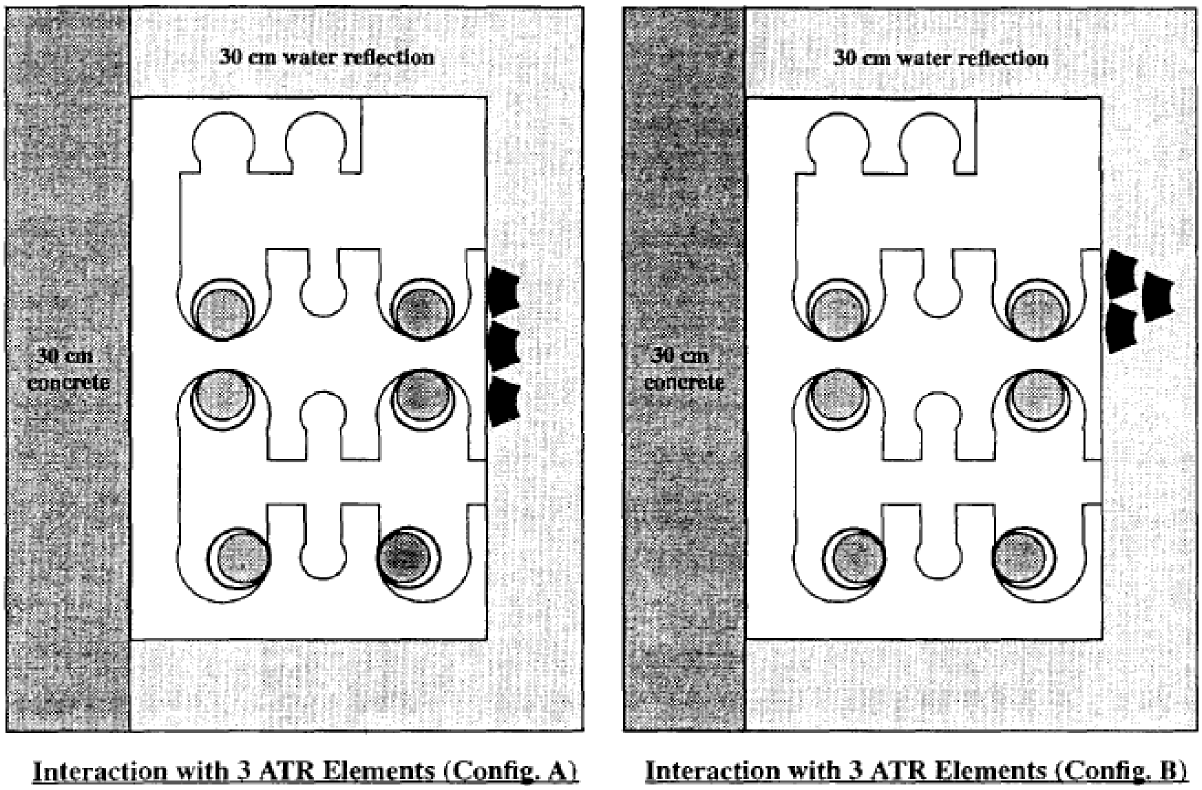


Figure 20. Interaction Configurations for 6-Position Racks

A final scenario of this section analyzes the interaction of out-of-rack materials with the ATR canal storage structures. These storage structures include miscellaneous grids, racks and hooks, e.g., I-piece grids and canal storage hooks. For this case a 13 cm radius uranium-water sphere containing 365 g U-235 is positioned next to three ATR fuel elements. The sphere and elements are positioned adjacent to a concrete reflector as shown in Figure 21. The sphere radius is optimally chosen to maximize reactivity. When considering the interaction of the elements and sphere, it may be possible to produce a slightly more reactive system by adjusting the radius, but a significantly higher reactivity is very unlikely. Additionally, modeling the system as uranium-water solution incorporates excessive conservatism. Results for the interaction cases are summarized in Table 14.

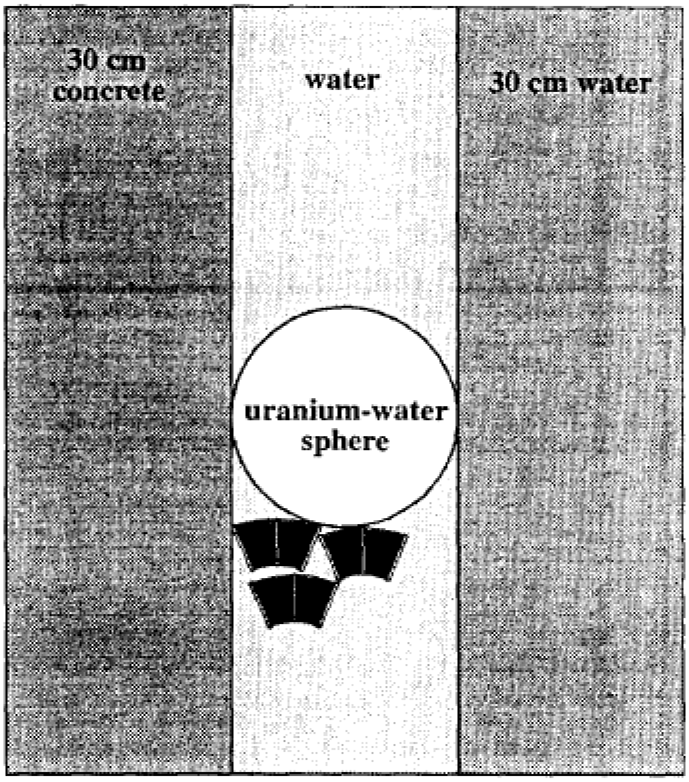


Figure 21. Interaction with Out-of-Rack Material

The following cases are taken from Reference 21 and are used to evaluate the ATR storage racks and the out-of-rack material for ELF elements. ATR fuel elements are included in the analysis as they are the most common fuel item found in the canal. These cases are listed as Cases 1-5 in Table 14 and are described here.

- Case 1: Next to the last case of Table 4, Reference 21. Three ATR elements are adjacent to a 4-Position Rack that contains 3.0 kg of U-235 and water in each position. The uranium containing cans are offset as shown in Figure 19, Configuration A.

- Case 2: Last case of Table 4, Reference 21. Same as Case 1 except the three ATR elements are positioned as shown in Figure 19, Configuration B.

- Case 3: Next to the last case of Table 8, Reference 21. Three ATR elements are positioned next to a 6-Position Rack that contains 3.0 kg of U-235 and water in each position. This is shown in Figure 20, Configuration A.

- Case 4: Last case of Table 8, Reference 21. Same as Case 3 except the three ATR elements are positioned as shown in Figure 20, Configuration B.

- Case 5: Last case of Table 10, Reference 21. Three ATR elements are positioned next to a uranium-water sphere that contains 365 g of optimally moderated U-235. This configuration is shown in Figure 21. The 365 g of U-235 is the total storage structure mass limit, i.e., miscellaneous grids, racks and hooks.

Results for these cases are given in Table 14. The reactivity of the Mod 0.1 and Mk1B ELF fuels is comparable to that of the HEU fuel with the largest increase being less than 0.5% (thicker fuel meat Mk1B). This slight increase in reactivity does not require changing existing HEU controls.

Table 14. HEU and ELF Results for ATR Interaction in Experimental Racks with non-ATR Material

Case (MCNP Input File)	**Description**	**$k_{eff} \pm \sigma$**	**$k_{eff} + 2\sigma$**	**Δk/k, (HEU – ELF) / HEU, %**
Case 1, HEU and ELF elements; HEU $k_{eff} + 2\sigma = 0.902$				
atr03A	HEU results[a] from Reference 21	0.900 ± 0.001	0.902	–
atr03A	Previous case but MCNP5, version 1.51	0.9014 ± 0.0008	0.9030	–
atr03A_4	Mod 0.1 ELF elements, nominal thickness fuel	0.9000 ± 0.0007	0.9014	0.18%
atr03TA_4	Mod 0.1 ELF elements, thicker meat	0.9024 ± 0.0007	0.9038	-0.09%
atr_11_03TA_4	Mk1B ELF elements, thicker meat	0.9064 ± 0.0007	0.9078	-0.53%
Case 2, HEU and Mod 0.1 ELF elements; HEU $k_{eff} + 2\sigma = 0.895$				
atr03B	HEU results[a] from Reference 21	0.893 ± 0.001	0.895	–
atr03B	Previous case but MCNP5, version 1.51	0.8946 ± 0.0007	0.8961	–
atr03B_4	Mod 0.1 ELF elements, nominal thickness meat	0.8915 ± 0.0007	0.8928	0.37%
atr03TB_4	Mod 0.1 ELF elements, thicker fuel meat	0.8942 ± 0.0007	0.8956	0.06%
Case 3, HEU and Mod 0.1 ELF elements; HEU $k_{eff} + 2\sigma = 0.879$				
atr03A	HEU results[a] from Reference 21	0.877 ± 0.001	0.879	–
atr03A	Previous case but MCNP5, version 1.51	0.8796 ± 0.0006	0.8808	–
atr03A_8	Mod 0.1 ELF elements, nominal thickness meat	0.8782 ± 0.0008	0.8798	0.11%
atr03TA_8	Mod 0.1 ELF elements, thicker fuel meat	0.8807 ± 0.0007	0.8821	-0.15%
Case 4, HEU and Mod 0.1 ELF elements; HEU $k_{eff} + 2\sigma = 0.872$				
atr03B	HEU results[a] from Reference 21	0.870 ± 0.001	0.872	–
atr03B	Previous case but MCNP5, version 1.51	0.8692 ± 0.0008	0.8707	–
atr03B_8	Mod 0.1 ELF elements, nominal thickness meat	0.8681 ± 0.0007	0.8694	0.15%
atr03TB_8	Mod 0.1 ELF elements, thicker fuel meat	0.8662 ± 0.0007	0.8677	0.34%
Case 5, HEU and ELF elements; HEU $k_{eff} + 2\sigma = 0.897$				
atr03c	HEU results[a] from Reference 21	0.895 ± 0.001	0.897	–
atr03c	Previous case but MCNP5, version 1.51	0.8972 ± 0.0006	0.8984	–
atr03c_10	Mod 0.1 ELF elements, nominal thickness meat	0.8963 ± 0.0006	0.8975	0.10%
atr03Tc_10	Mod 0.1 ELF elements, thicker fuel meat	0.8963 ± 0.0007	0.8977	0.08%
atr_11_03Tc_10	Mk1B ELF elements, thicker fuel meat	0.9005 ± 0.0006	0.9018	-0.38%

a HEU values of k_{eff} and σ were obtained with MCNP version older than MCNP5, version 1.51.

The ATR reactor vessel contains two storage racks that are used for the storage of ATR fuel.[29] Currently, these vessel storage racks are limited to a maximum of two (HEU) ATR elements between both racks, but are not approved for use during reactor operation. Reference 17 determines the minimum critical number of optimally spaced in water ATR elements to be seven. The two elements in the vessel storage rack are subcritical, and an overbatch greater than three times the allowed storage limit would be necessary to create the potential for a criticality safety concern. Controls also limit handling operations within the reactor vessel to a maximum of two ATR elements out of approved storage at one time. Handling fuel elements next to the vessel storage racks could result in an array containing a maximum of four elements under normal conditions, which is safely subcritical.

Section 6.1.2 shows that the minimum critical number of ELF elements (all fuel designs) is seven elements optimally spaced in water, indicating that no changes to these existing HEU controls are required.

6.1.6.4 Analysis for ATR Fuel Element Transport Racks[20]

Moveable racks known as ATR Transport Racks are used to move and store intact ATR fuel elements at the NMIS facility, the ATR facility, and the ATRC facility. The ATR Transport Racks are designed to hold 8 ATR elements in a linear arrangement, and they allow fuel elements to be moved more efficiently and safely within these facilities.

The ATR Transport Racks are mobile racks that securely hold up to 8 ATR fuel elements in a linear arrangement (single row) in fixed positions. The racks are nominally evaluated with 8 elements, though more recently the racks have been modified to hold only four elements. Rack positions hold the elements at 15° off vertical with the elements spaced on 6.5 in. centers. The racks are 72 in. wide, 34 in. deep and 71 in. high. The elements are held in place by two spring loaded bars. Figure 22 shows the front and side views of the ATR Transport Rack.

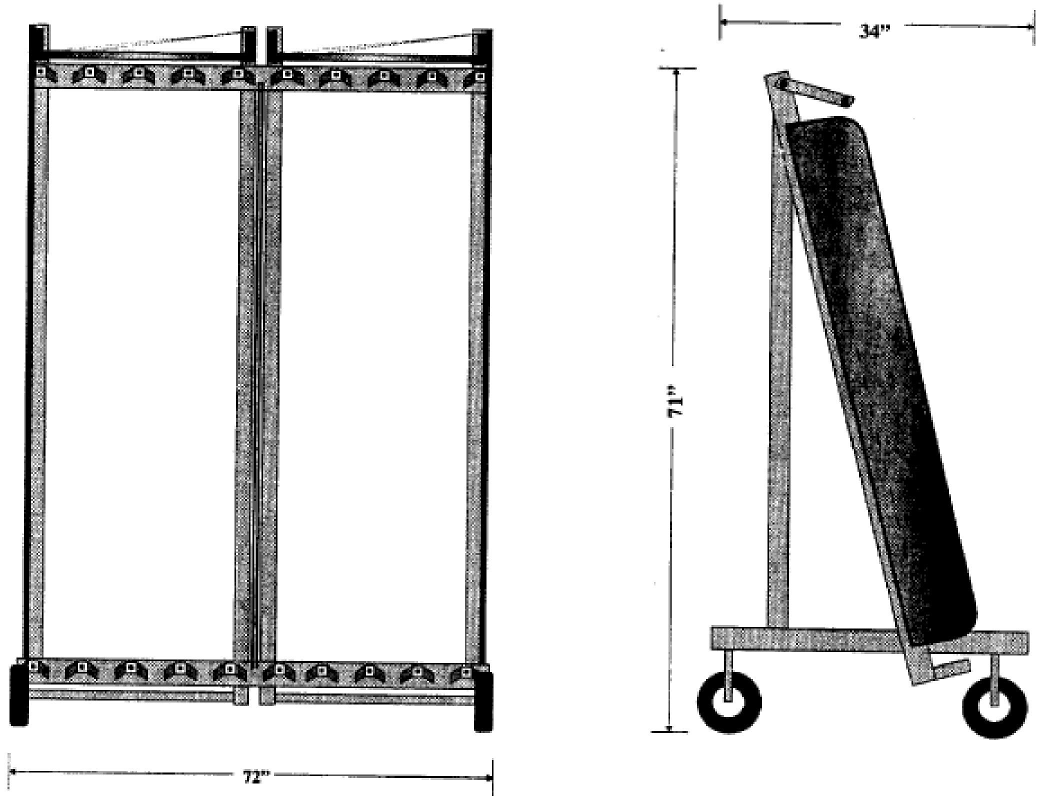


Figure 22. Front View and Side View of ATR Transport Racks

Three cadmium-plywood assemblies are installed on each transport rack. An assembly is situated along each outer edge with the remaining assembly in the center of the rack. These assemblies are composed of a 0.02 in. thick cadmium sheet laminated between two 0.25 in. sheets of plywood. These Cd/plywood assemblies are approximately 0.5 in. wide, 53 in. long and 6 in. deep.

The following cases are taken from Reference 20 and are used to evaluate the ATR Transport Racks for ELF elements. These cases are listed as Cases 1, 2, 3, 4 and 5 in Table 15.

- Case 1: Most reactive case "flood010" of Table 1, Reference 20. Infinite 2-d array of transport racks each holding a linear array of 8 ATR elements is evaluated. Arrays are reflected from above and below by 30 cm of water and 30 cm of concrete, respectively. Water density fraction inside the array is 10% and cadmium is neglected.

- Case 2: Most reactive case "flood010" of Table 2, 3rd column, Reference 20. Similar to previous case except racks are in Configuration A of Figure 23 and each rack is overloaded with three additional ATR elements.

- Case 3: Most reactive case “flood013” of Table 4, 3rd column, Reference 20. A 6×6 array overloaded with 7 additional elements is evaluated. The water density is 13% of normal density, and cadmium is neglected.

- Case 4: Case “configA8” in last row, 2nd column, Table B1, Reference 20. Infinite 2-d array of transport racks and arrays are fully flooded. The ATR elements are positioned as shown in Configuration A of Figure 23. Each rack holds 8 additional ATR elements.

- Case 5: Case “configD8” in last row, 5th column, Table B1, Reference 20. Previous case except ATR elements are positioned as shown in Configuration D of Figure 23.

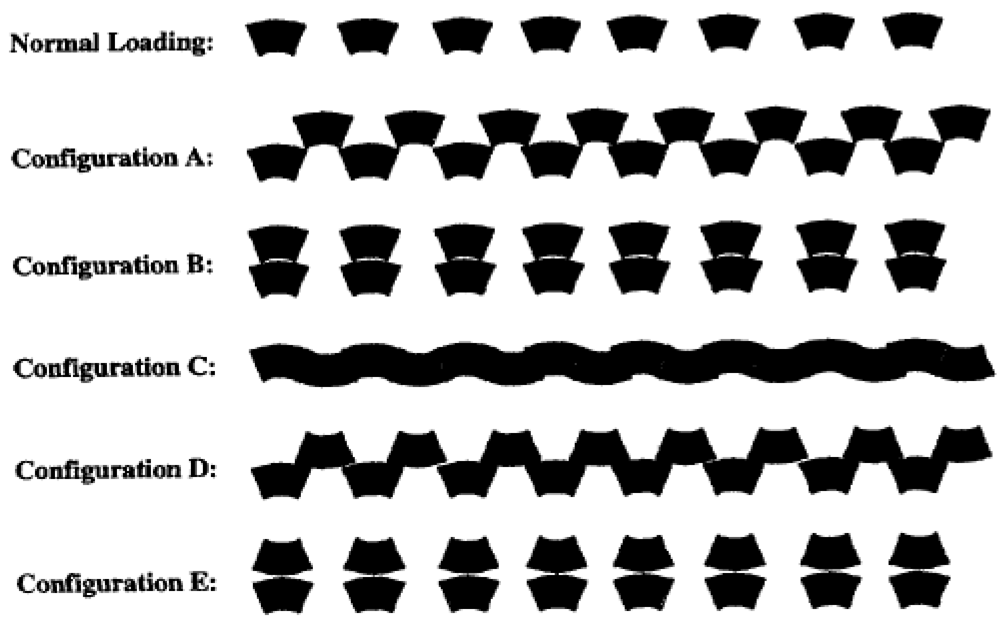


Figure 23. Overloading Configurations

Results for these cases are given in Table 15. Cases 2 and Mk1B3 do not pose any safety concern as the models are extremely conservative. Cases 4 and 5 confirm that Configuration A is more reactive than Configuration D[20] for the ELF elements verifying that the appropriate (most reactive) cases are evaluated. For most cases in this section, the ELF elements have slightly higher reactives but this does not require changing existing HEU controls.

Table 15. HEU and ELF Results for ATR Fuel Element Transport Racks

Case (MCNP Input File)	Description	$k_{eff} \pm \sigma$	$k_{eff} + 2\sigma$	Δk/k, (HEU – ELF) / HEU, %
Case 1, HEU and ELF elements; HEU $k_{eff} + 2\sigma = 0.886$				
flood010	HEU results from Reference 20	0.884 ± 0.001	0.886	–
flood1_010	Previous case but MCNP5, version 1.51	0.8844 ± 0.0006	0.8856	–
flood5L1_010	Mod 0.1 ELF elements, nominal thickness fuel	0.8963 ± 0.0006	0.8976	-1.36%
flood5Lt1_010	Mod 0.1 ELF elements, thicker fuel meat	0.9061 ± 0.0006	0.9073	-2.45%
flood5L11t1_010	Mk1B ELF elements, thicker fuel meat	0.9163 ± 0.0006	0.9175	-3.60%
Case 2, HEU and ELF elements; HEU $k_{eff} + 2\sigma = 0.954$				
flood010	HEU results from Reference 20	0.952 ± 0.001	0.954	–
flood2_010	Previous case but MCNP5, version 1.51	0.9521 ± 0.0007	0.9534	–
flood5L2_010	Mod 0.1 ELF elements, nominal thickness fuel meat	0.9543 ± 0.0006	0.9555	-0.22%
flood5Lt2_010	Mod 0.1 ELF elements, thicker fuel meat	0.9632 ± 0.0006	0.9644	-1.15%
flood5L11t2_010	Mk1B ELF elements, thicker fuel meat	0.9733 ± 0.0006	0.9745	-2.21%
Case 3, HEU and ELF elements; HEU $k_{eff} + 2\sigma = 0.939$				
flood013	HEU results from Reference 20	0.937 ± 0.001	0.939	–
flood4_013	Previous case but MCNP5, version 1.51	0.9367 ± 0.0007	0.9380	–
flood5L4_013	Mod 0.1 ELF elements, nominal thickness fuel meat	0.9318 ± 0.0006	0.9331	0.52%
flood5Lt4_013	Mod 0.1 ELF elements, thicker fuel meat	0.9394 ± 0.0006	0.9406	-0.28%
flood5L11t4_013	Mk1B ELF elements, thicker fuel meat	0.9505 ± 0.0006	0.9518	-1.47%
Case 4, HEU and ELF elements; HEU $k_{eff} + 2\sigma = 0.833$				
configA8	HEU results from Reference 20	0.831 ± 0.001	0.833	–
configB_A8	Previous case but MCNP5, version 1.51	0.8293 ± 0.0006	0.8306	–
config5LB_A8	Mod 0.1 ELF elements, nominal thickness fuel meat	0.8240 ± 0.0006	0.8253	0.64%
config5LtB_A8	Mod 0.1 ELF elements, thicker fuel meat	0.8306 ± 0.0006	0.8318	-0.14%
config5L11tB_A8	Mk1B ELF elements, thicker fuel meat	0.8422 ± 0.0007	0.8435	-1.55%
Case 5, HEU and Mod 0.1 ELF elements; HEU $k_{eff} + 2\sigma = 0.821$				
configD8	HEU results from Reference 20	0.819 ± 0.001	0.821	–
configB_D8	Previous case but MCNP5, version 1.51	0.8196 ± 0.0006	0.8208	–
config5LB_D8	Mod 0.1 ELF elements, nominal thickness fuel meat	0.8100 ± 0.0006	0.8112	1.17%
config5LtB_D8	Mod 0.1 ELF elements, thicker fuel meat	0.8173 ± 0.0006	0.8185	0.28%

a HEU values of k_{eff} and σ were obtained with MCNP version older than MCNP5, version 1.51.

6.1.6.5 Analysis for ATR Shipping Cask with ATR Fuel Elements[22]

The CSE evaluated in this section is concerned with the effect of possible cask deformation due to a shipping accident. Structural analysis has addressed possible shipping cask deformation due to a drop or an impact accident indicating that some deformation of the ATR cask can be expected under certain scenarios.

The ATR shipping cask is designed to hold eight ATR elements. The center of the cask is taken up by a central spacer of 6.5 in. outer diameter composed of 0.25 in. thick aluminum. Another tube (5.5 in. OD, 0.25 in. thick aluminum) sits within this for added structural support. The inner diameter of the cask is 12.75 in., followed by 0.25 in. of stainless steel and 10.5 in. of lead as shielding. Dividers radiate from the central aluminum tube, radially, to divide the cask into eight storage positions. The dividers are made of aluminum and boron that act as a neutron poison. The cask cavity length is just less than 53 in. with additional lead on the top and bottom. Prior to the start of cask transport, the water level in the cask must be sufficiently high so as to be visible in the sight glass. This indicates that there is sufficient water to cover the fuel though it may not completely fill the cask. Figure 24 shows a top view of the shipping cask.

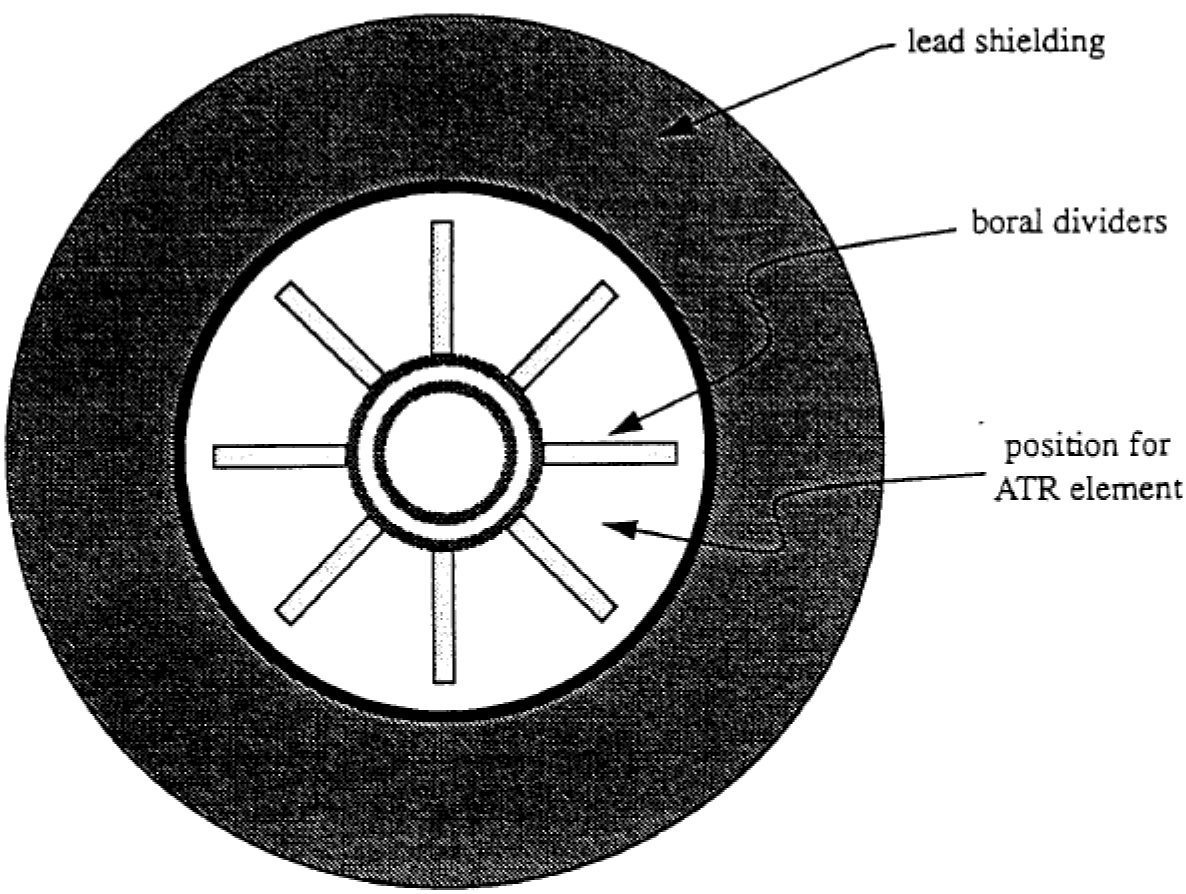


Figure 24. Top View of ATR Shipping Cask

The following cases are taken from Reference 22 and are used to evaluate the ATR Shipping Cask for ELF elements. These cases are listed as Cases 1, 2, 3 and 4 in Table 16.

- Case 1: Case 1, Table 1, Reference 22. Shipping cask with boral spacer that divides 8 nominally positioned ATR elements is evaluated. A cross-sectional view of the cask is shown in Figure 24.
- Case 2: Case 3, Table 1, Reference 22. Previous case except all ATR elements are withdrawn 11 in. above the boral spacer.
- Case 3: Case 4, Table 1, Reference 22. Same as Case 1 above except boral spacer is replaced with water.
- Case 4: Case 16, Table 4, Reference 22. Same as Case 2 above except boral spacer plate is missing 6 of the 8 dividers, and fuel elements are 6 in. above divider.

Results for these cases are given in Table 16. The ELF reactivities for all cases in the table are comparable or in most cases smaller than that of the HEU fuel. Cases 2-4 have smaller reactivities even for the thicker fuel meat Mk1B fuel than the equivalent HEU cases. Less reactive LEU than HEU fuel is consistent with the more closely spaced array results of Section 6.1.4 and would be expected as the elements are closely spaced in the cask and the boral spacer is either mostly or completely neglected. The ELF elements do not require changing existing HEU controls for these cases and are less reactive than the HEU elements, except the thicker fuel meat element case of Case 1 is slightly more reactive.

Table 16. HEU and ELF Results for Evaluated ATR Cask with ATR Elements

Case (MCNP Input File)	Description	$k_{eff} \pm \sigma$	$k_{eff} + 2\sigma$	$\Delta k/k$, (HEU – ELF) / HEU, %
Case 1, HEU and Mod 0.1 ELF elements; HEU $k_{eff} + 2\sigma = 0.705$				
cask01	HEU results from Reference 22	0.701 ± 0.002	0.705	–
cask01L	Previous case but MCNP5, version 1.51	0.7034 ± 0.0006	0.7046	–
caskl01L	Mod 0.1 ELF elements, nominal thickness fuel meat	0.6912 ± 0.0007	0.6926	1.70%
casklt01L	Mod 0.1 ELF elements, thicker fuel meat	0.7048 ± 0.0006	0.7061	-0.21%
Case 2, HEU and ELF elements; HEU $k_{eff} + 2\sigma = 0.853$				
cask03	HEU results from Reference 22	0.849 ± 0.002	0.853	–
cask03L	Previous case but MCNP5, version 1.51	0.8480 ± 0.0007	0.8493	–
caskl03L	Mod 0.1 ELF elements, nominal thickness fuel meat	0.8161 ± 0.0007	0.8174	3.76%
casklt03L	Mod 0.1 ELF elements, thicker fuel meat	0.8255 ± 0.0007	0.8268	2.65%
casklt11_03L	Mk1B ELF elements, thicker fuel meat	0.8361 ± 0.0006	0.8374	1.40%
Case 3, HEU and ELF elements; HEU $k_{eff} + 2\sigma = 1.018$				
cask04	HEU results from Reference 22	1.014 ± 0.002	1.018	–
cask04L	Previous case but MCNP5, version 1.51	1.0134 ± 0.0006	1.0146	–
caskl04L	Mod 0.1 ELF elements, nominal thickness fuel meat	0.9612 ± 0.0006	0.9624	5.14%
casklt04L	Mod 0.1 ELF elements, thicker fuel meat	0.9695 ± 0.0006	0.9707	4.33%
casklt11_04L	Mk1B ELF elements, thicker fuel meat	0.9777 ± 0.0006	0.9789	3.52%
Case 4, HEU and ELF elements; HEU $k_{eff} + 2\sigma = 0.947$				
cask16	HEU results from Reference 22	0.943 ± 0.002	0.947	–
cask16L	Previous case but MCNP5, version 1.51	0.9431 ± 0.0007	0.9446	–
caskl16L	Mod 0.1 ELF elements, nominal thickness fuel meat	0.9002 ± 0.0007	0.9016	4.55%
casklt16L	Mod 0.1 ELF elements, thicker fuel meat	0.9102 ± 0.0007	0.9115	3.50%
casklt11_16L	Mk1B ELF elements, thicker fuel meat	0.9198 ± 0.0007	0.9212	2.48%

a HEU values of k_{eff} and σ were obtained with MCNP version older than MCNP5, version 1.51.

6.1.6.6 Analysis for the Single Element ATR FFSCs[23]

Fresh ATR fuel elements are shipped from the manufacturer to the ATR facility in Fresh Fuel Shipping Containers (FFSCs). The single element FFSC is a stainless steel box designed to hold a single ATR fuel element or a set of loose ATR fuel plates.

For storage and shipping operations, the accumulation of fissile packages into arrays is typically controlled by the Criticality Safety Index (CSI). The CSI for an individual package is calculated based on the loading of the package and the number of damaged and undamaged packages required to create a critical array. The number of packages in the array is controlled by limiting the cumulative CSI total of the array.

The existing CSI from the Certificate of Compliance for the single element ATR FFSC is calculated based on transportation accident scenarios. While the transport CSI analysis is bounding, it is overly conservative for handling and storage operations at ATR Complex since potential transportation accidents yield far greater damage to packages. Using the transportation CSI for storage operations, therefore, is conservative, but unduly restricts the number of single element FFSCs that can be stored together in an array.

The single element ATR FFSC is a stainless steel box 8 in. square by 73 in. long consisting of two nested shells. The outer shell is 8 in. square stainless steel tube (8 in. outer dimension) with 0.1875 in. wall thickness, while the inner shell is 6 in. outer diameter round stainless steel tube with 0.12 in. wall thickness. The 6 in. OD inner tube has an internal length of 67.88 in. Both shells are constructed of type 304 stainless steel. The inner shell is wrapped in 1 in. thick thermal insulation with a 0.015 in. thick (28 GA) type 304 stainless steel liner outside the insulation. The thermal insulation is 26.5 wt% aluminum, 23.4 wt% silicon, and 50.2 wt% oxygen with a density of 0.096 g/cm^3.

Figure 25 shows the single element FFSC body and the fuel handling enclosure used for transport of an intact ATR fuel element. The stainless steel outer body shell has been removed from this figure to show the insulation wrap around the inner 6 in. OD shell.

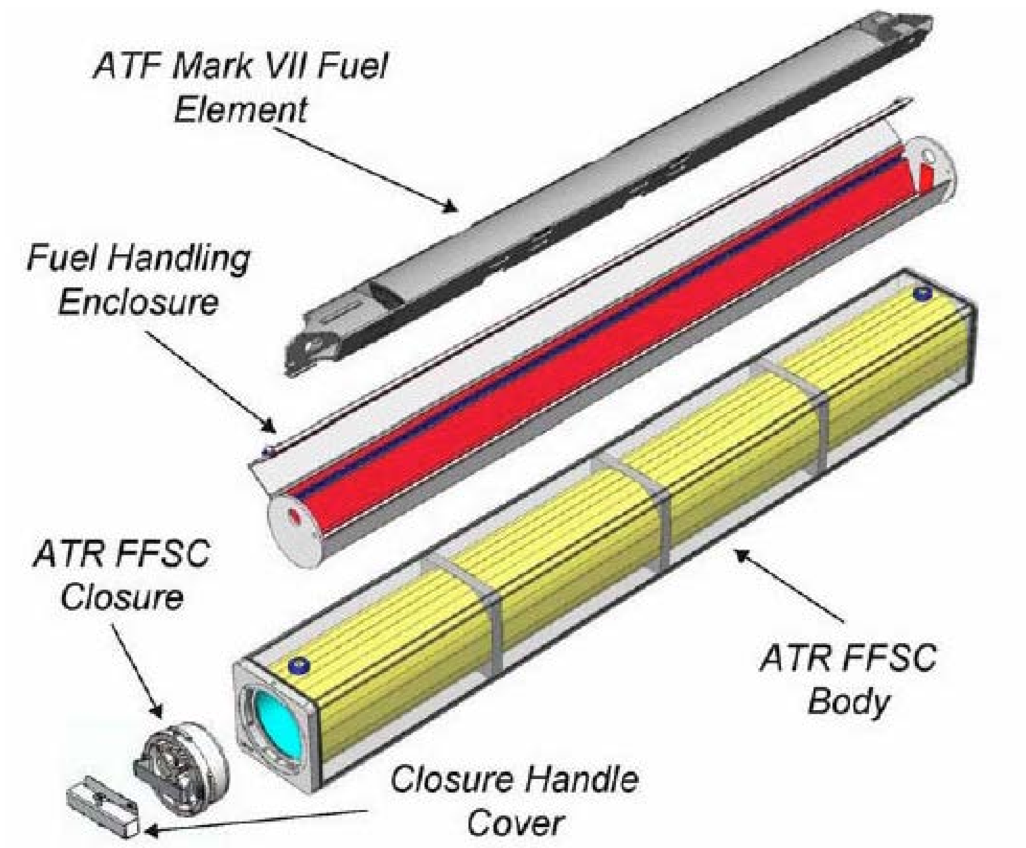


Figure 25. Single Element ATR Fresh Fuel Shipping Container

The bottom end of the 6 in. OD inner shell is a 0.375 in. stainless steel plate with 1 in. thick thermal insulation. The end of the FFSC is 0.875 in. thick, 8 in. square stainless steel plate. The bottom end of the FFSC is shown in Figure 26.

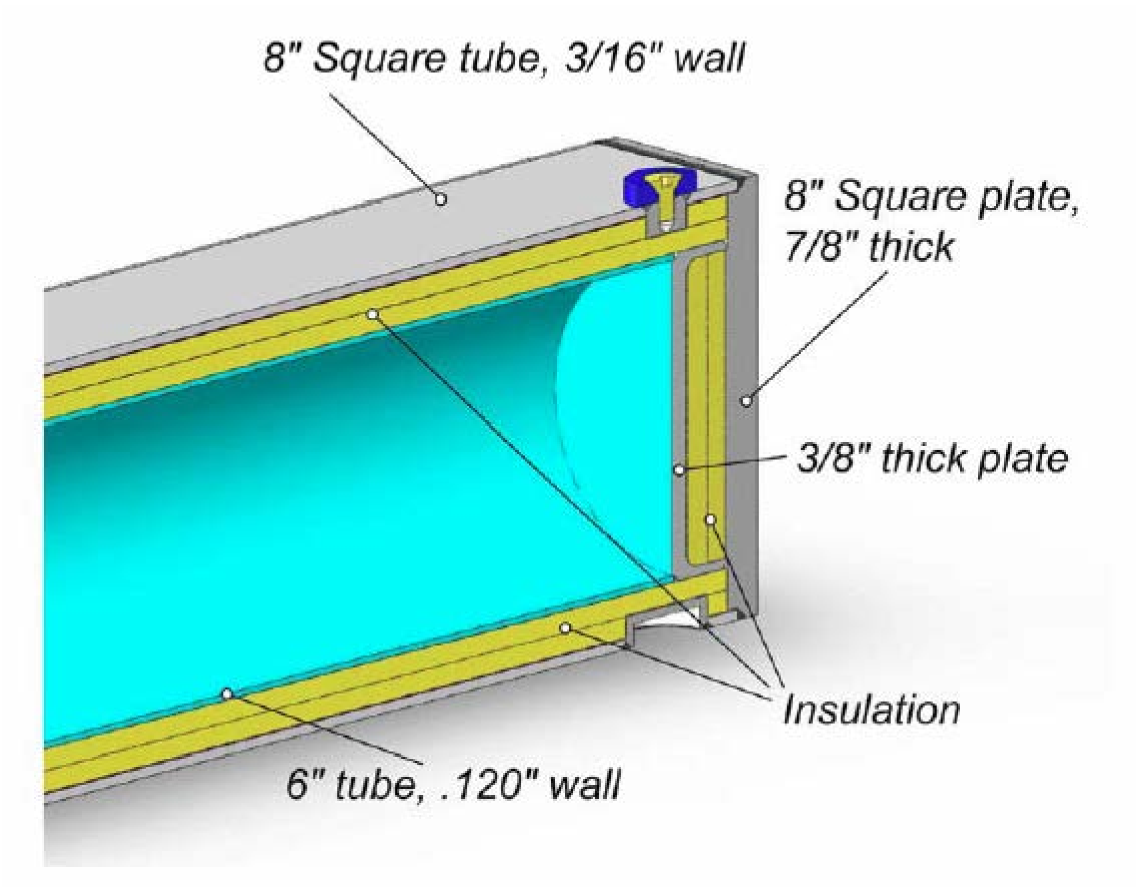


Figure 26. Bottom End of Single Element ATR Fresh Fuel Shipping Container

The closure for the FFSC is comprised of 1 in. thick thermal insulation sandwiched between a 0.375 in. thick stainless steel plate and a 0.25 in. thick stainless steel plate. Additional stainless steel parts make up the locking and handling devices of the closure. The top end of the FFSC is shown in Figure 27 and the FFSC closure is shown in Figure 28.

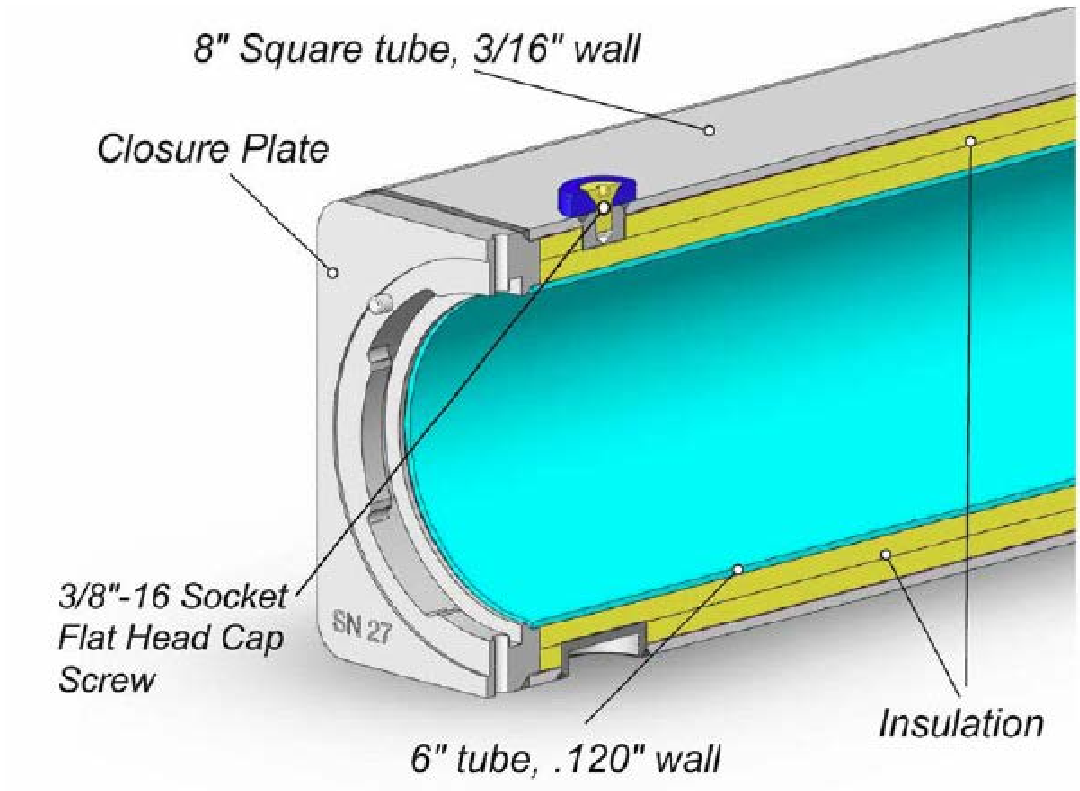


Figure 27. Top End of Single Element ATR Fresh Fuel Shipping Container

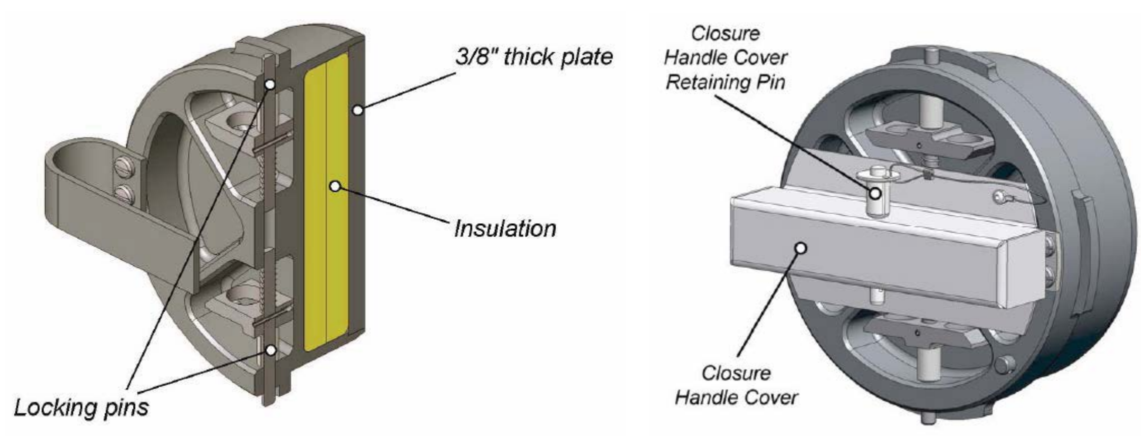


Figure 28. Single Element ATR Fresh Fuel Shipping Container Closure Device

The single element ATR FFSC is designed to be used for transport of an intact ATR fuel element or loose ATR fuel plates. In the case of intact elements, the ATR fuel element is placed within a Fuel Handling Enclosure (FHE), as shown in Figure 25, which is then inserted into the FFSC. The FHE is a hinged thin gauge aluminum weldment which encloses the fuel element.

In the case of loose ATR fuel plates, the plates are placed within a Loose Fuel Plate Basket, see Figure 29, which is then inserted into the FFSC. The aluminum basket maintains the fuel plates within a defined dimensional configuration. When loaded with loose fuel plates, the single element ATR FFSC is limited to a maximum of 600 g U-235 as loose ATR fuel plates. This also applies to flat (non-curved) ATR fuel plates that are identical to the curved plates, with respect to fuel loading, but exist only as loose plates.

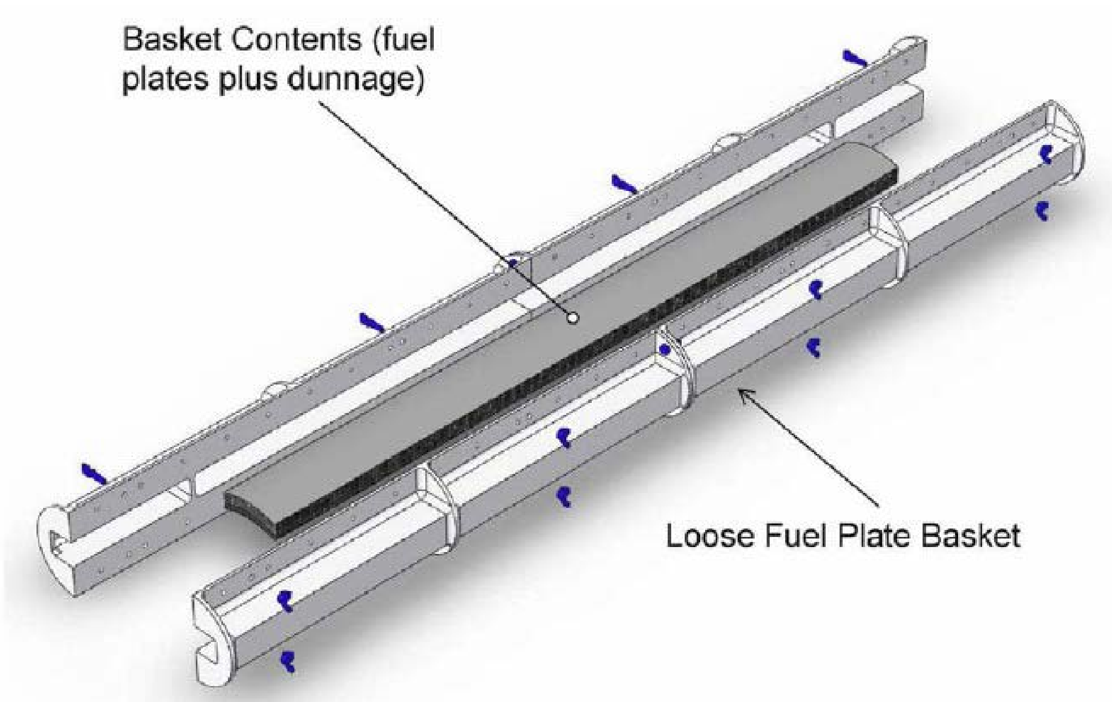


Figure 29. Single Element ATR Fresh Fuel Shipping Container Loose Fuel Plate Basket

The following cases are taken from Reference 23 and are used to evaluate single ATR elements in the FFSCs for ELF elements. These cases are listed as Cases 1 and 2 in Table 17.

- Case 1: Case drybox05 of Table 2, Reference 23. Dry infinite array of Single Element Shipping Containers each containing a single ATR element. The insulation is neglected, i.e., its thickness is zero.

- Case 2: Case wetbox05b of Table 2, Reference 23. Flooded infinite 3-d array of Single Element Shipping Containers each containing a single ATR Fuel element. The insulation thickness is 1 in.

Results for these cases are given in Table 17. The Mod 0.1 and Mk1B ELF elements are less reactive than the HEU elements for the dry array cases given in Case 1. The Mod 0.1 ELF results for the flooded array of Case 2 are more reactive than the HEU result by 2.22% though the k_{eff}'s are too small to be of concern to criticality safety. The results of the cases in this table do not require changes to the existing HEU controls as they are much less than the 0.95 limit. The CSI calculated for HEU fuel storage is also applicable to ELF elements.

The last set of cases in Table 17 give results for HEU Mark IV elements for comparison with Mark VII results from Reference 23. Results from this reference are given in the "Description" column of the table. The Mark IV result for the unmoderated case, Case 1, is ~4.1% less reactive than that for the Mark VII, whereas for the moderated case, Case 2, the Mark IV reactivity is ~2.7σ Δk smaller. This latter difference is consistent with the results in Section 6.1.4 (all moderated cases) where the difference is not significant. The difference for the unmoderated case shows the Mark IV element to be significantly less reactive than the Mark VII reactivity.

Table 17. HEU and ELF Results for Evaluated Single Element ATR FFSCs

Case (MCNP Input File)	**Description**	**$k_{eff} \pm \sigma$**	**$k_{eff} + 2\sigma$**	**Δk/k, (HEU – ELF) / HEU, %**
Case 1, Mark VII HEU and ELF elements; HEU $k_{eff} + 2\sigma$ = 0.7872				
drybox05	HEU results from Reference 23	0.7862 ± 0.0005	0.7872	–
drybox05	Previous case but MCNP5, version 1.51	0.7871 ± 0.0003	0.7876	–
dryboxl05	Mod 0.1 ELF elements, nominal thickness fuel meat	0.7291 ± 0.0002	0.7296	7.36%
dryboxlt05	Mod 0.1 ELF elements, thicker fuel meat	0.7513 ± 0.0002	0.7517	4.56%
drybx11lt05	Mk1B ELF elements, thicker fuel meat	0.7833 ± 0.0003	0.7838	0.48%
Case 2, Mark VII HEU and Mod 0.1 ELF elements; HEU $k_{eff} + 2\sigma$ = 0.6285				
wetbox05b	HEU results from Reference 23	0.6265 ± 0.0010	0.6285	–
wetbox05b	Previous case but MCNP5, version 1.51	0.6252 ± 0.0006	0.6265	–
wetboxl05b	Mod 0.1 ELF elements, nominal thickness fuel meat	0.6324 ± 0.0006	0.6336	-1.13%
wetboxlt05b	Mod 0.1 ELF elements, thicker fuel meat	0.6392 ± 0.0006	0.6404	-2.22%
Cases 1 and 2, Mark IV HEU results				
drybox43_05	Case 1; Mark VII result is $k_{eff} + 2\sigma$=0.7872	0.7540 ± 0.0003	0.7546	–
wetbox43_05b	Case 2; Mark VII result is $k_{eff} + 2\sigma$=0.6285	0.6245 ± 0.0007	0.6258	–

a HEU values of k_{eff} and σ were obtained with MCNP version older than MCNP5, version 1.51.

Additional cases similar to those in References 23 and 30 are investigated with differing moderation. This is done by varying the water density and differentially flooding the compartments of the shipping container. All cases have some amount of moderation and the reactivity of the Mark VII elements is greater than that of the Mark IV elements, though the magnitude of the difference is smaller than that for Case 1. The results for these cases are shown in Appendix D, Table D-7.

6.1.6.7 Analysis for ATR Fuel Storage in FAST[31]

The CSE that contains the contingency analysis for fissile fuel handling and storage at the Fluorinel Dissolution Process and Fuel Storage (FAST) facility is given in Reference 29, which includes spent ATR fuel. The Fuel Storage Area (FSA) is a large facility designed to store and handle spent nuclear fuel under water. The layout of the facility, shown in Figure 30, includes six storage pools, two unloading pools, two isolation pools, an underwater transfer channel that connects pools, an above-grade cask receiving and decontamination area, and various support areas. The fuel storage pool area consists of six interconnected fuel storage pools divided by concrete walls, containing underwater fuel storage racks. Each pool measures 31 ft (north to south) by 46.5 ft (east to west), resulting in a floor area of approximately 1,442 ft^2 for each pool. Storage Pools 1 and 2 (the southern-most storage pools) are 41 ft deep, and the remaining storage pools are 31 ft deep with nominal water depths of 40 ft and 30 ft, respectively.

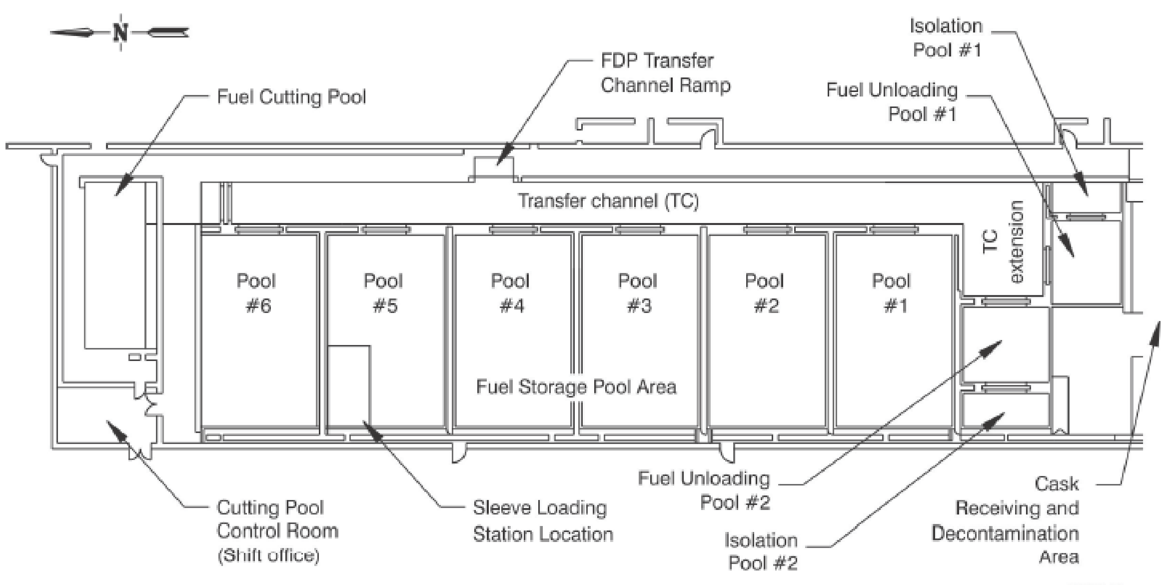


Figure 30. Facility Layout for the CPP-666 Fuel Storage Area

Storage racks are used for fuel storage in the FSA of which there are five different designs. The nominal heights of the storage racks are 20 ft in Storage Pool 1 and the other storage racks are 10 ft. The rack ports vary in size from 8 in. square to 18 in. square. The different types of racks and their capacities provide storage for many fuel types, accommodating different fuel sizes, material compositions, and distribution of overall fuel receipts. ATR fuel is stored in aluminum

FAST racks in Pool 6 whose dimensions are 7.33 ft × 7.33 ft × 10.38 ft high positioned in 8 in. square ports with a space of 8-1/8 in. between ports.

The FAST aluminum racks are constructed of Type T6061 aluminum. The storage port depth is 10.25 ft. The spacing between the edge of the rack and the peripheral ports is 6-1/4 in. The port wall thickness is 0.080 in. Each port has a hinged lid with an attached handling fixture. The FAST aluminum rack is illustrated in Figure 31, showing the rack design features and nominal dimensions. The rack provides 25 ports in a 5 × 5 array and there are 12 aluminum FAST racks in Storage Pool 6 giving a total of 300 ports.

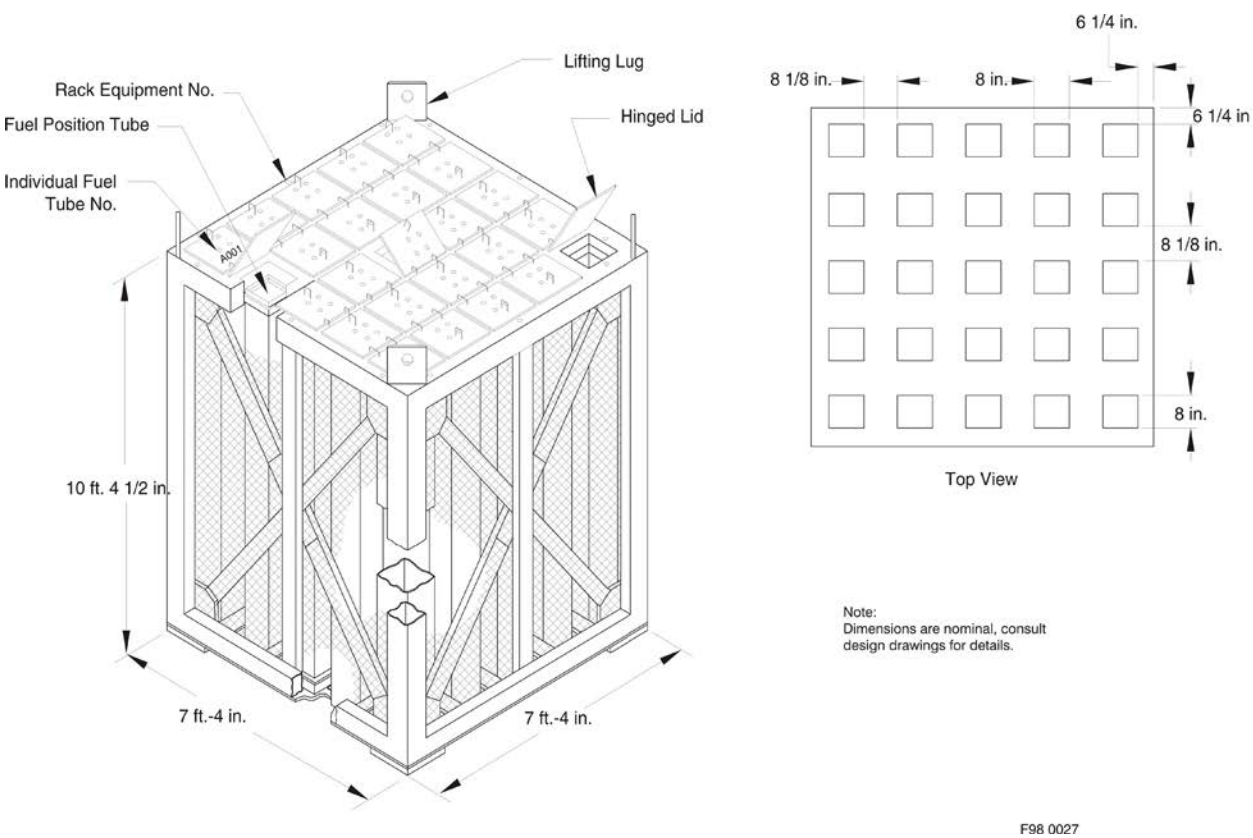


Figure 31. Sketch of the 8 in. FAST Aluminum Storage Rack for Storage Pool 6

The fuel storage limits for the 10 ft. high aluminum racks are:

- The parameter set for aluminum rack storage derived from the calculations is a k_{eff} of 0.91 (maximum), a U-235 linear loading limit of 5.0 kg/ft (maximum), and a water volume fraction (WVF) of 0.00 (minimum), i.e., there is no limit on WVF.

- The reactivity effect of placing fuel on top of the rack array is included. The parameter set includes the assumption of a 6 in. water gap between the fueled array and the fuel slab.

The approved fuel list for CPP-666 FSA states that end-to-end stacking of buckets with each bucket containing up to 4 ATR elements is an approved configuration in the 10 ft. tall, 8 in. aluminum rack port.[32] An approved bucket design that accommodates four ATR elements is given in ICP Design Drawing 097342. The design height of the bucket is 55.31 in., which allows for the stacking of two buckets in the 10 ft tall aluminum racks with more than 6 in. of space for water above the stacked fuel arrays.

This is supported by the fuel-specific CSEs of References 17 and 24. The latter evaluation modeled generic fuel elements of infinite length in an infinite planar array of fuel position tubes. Each fuel position tube contained a 2 × 2 array of generic fuel elements. The fuel element array is water moderated to give most reactive conditions. Results from this model are used to derive a maximum $k_{eff} < 0.9$ for HEU ATR fuel. Reference 17 found a most reactive configuration of four flooded and fully water-reflected HEU elements of finite length. This configuration, designated Configuration E, is shown in Figure 32, has a 0.25 cm spacing between fuel elements and a k_{eff} of 0.817 ± 0.002.

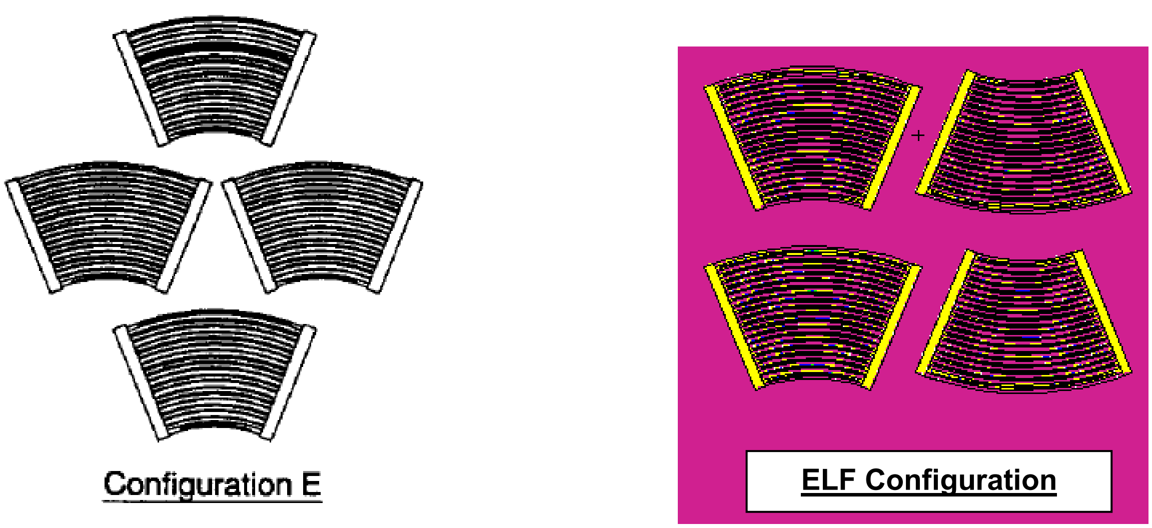


Figure 32. Configurations to Evaluate Four Element ATR Arrays

For the ELF fuel, both four element configurations shown in Figure 32 are evaluated to determine the most reactive array. The configuration labeled "ELF Configuration" is a four element variation of the seven element configuration shown in Figure 4. As is done for the seven element configuration, the spacing between elements is varied until the most reactive array is found. Except for cases that compare ELF and previous HEU results, the ELF fuel elements are infinite in length so as to bound any array stacking.

Table 18 is a summary of the most reactive results for three different sets. The first set reports the previous HEU results and gives results for the nominal and thicker fuel meat finite length Mod 0.1 ELF elements. The model used in the second set is the same as that used in the first set, except the elements are of infinite length and the Mk1B thicker fuel meat fuel is also evaluated. The last set uses the same infinite length element model as the second set, but the elements are modeled in an infinite planar array with dimensions of the port rack, i.e., the fuel fits in an eight in. square port in a square array with an 8.125 in. edge-to-edge spacing. The materials that composes the fuel buckets and port racks are replaced by water. In all cases the fuel is positioned in the "ELF Configuration" of Figure 32 as none of the more reactive Configuration E arrays fit in the 8 in. port. Even with the "ELF Configuration," some portion of the outermost element side plates is "cut" by MCNP, neglecting a relatively small amount of aluminum but in no case is any fuel neglected. This is conservative as it allows the more reactive, larger-spaced element arrays to be considered. Results are determined for both configurations of Figure 32 for the first two sets of the table. A complete set of results are given in Table D-8.

Table 18. Most Reactive Results for HEU and ELF Four Element Arrays

Case (MCNP Input File)	**Description**	**$k_{eff} \pm \sigma$**	**$k_{eff} + 2\sigma$**
Most reactive cases for four ATR elements using configurations of Figure 22 with finite length fuel elements; water flooded and reflected			
configuration E	HEU results[a] for Configuration E from Reference 17	0.817 ± 0.0020	0.821
heu_Ex4_.25	Previous case but MCNP5, version 1.51	0.8217 ± 0.0007	0.8231
leub_4b_1.8	Mod 0.1 ELF elements, nominal thickness fuel; "ELF Configuration"	0.8142 ± 0.0006	0.8154
leubT_4e_0.8	Mod 0.1 ELF elements, thicker fuel meat; Configuration E	0.8216 ± 0.0007	0.8229
Same as previous set but ELF elements are infinite in length			
leub_4e_0.6I	Mod 0.1 ELF nominal thickness fuel meat; Configuration E	0.8270 ± 0.0006	0.8281
leubT_4b_1.8I	Mod 0.1 ELF thicker fuel meat; "ELF Configuration"	0.8341 ± 0.0007	0.8354
l11bT_4b_1.8I	Mk1B ELF thicker fuel meat; "ELF Configuration"	0.8426 ± 0.0006	0.8439
Same element model as previous set, but elements are in an infinite planar array with dimensions of the 8 in. port rack; fuel buckets and port materials are replaced with water			
leub_4b_1.6P	Mod 0.1 ELF elements, nominal thickness fuel; "ELF Configuration"	0.8357 ± 0.0007	0.8371
leubT_4b_1.6P	Mod 0.1 ELF thicker fuel meat; "ELF Configuration"	0.8443 ± 0.0006	0.8456
l11bT_4b_1.6P	Mk1B ELF thicker fuel meat; "ELF Configuration"	0.8516 ± 0.0006	0.8528

a HEU values of k_{eff} and σ were obtained with MCNP version older than MCNP5, version 1.51.

The ELF elements are shown to be slightly more reactive than the HEU elements but clearly meet the acceptance limit of $k_{eff} + 2\sigma \leq 0.91$. Given this and the U-235 linear loading of ~0.45 kg/ft for the thicker fuel meat Mk1B ELF elements should allow ELF storage in the CPP-666 Fuel Storage Area.

7. Credited Controls and Assumptions

This CSE evaluated cases from previous CSEs that developed controls for the handling, storage and transportation of HEU ATR elements for the LEU Mod 0.1, Mk1A and Mk1B ELF elements.

7.1 Important Assumptions

The ATR U-10Mo ELF fuel is described in Section 2.2.2.

7.2 Engineered Controls

No additional engineered controls**.**

7.3 Administrative Controls

1) For the purposes of criticality safety, the LEU ELF elements are bound by the criticality controls derived for HEU ATR elements.

Note 1. This applies to the LEU Mod 0.1, Mk1A and Mk1B element designs. It should be noted that Mk1A and Mk1B have been selected as the conceptual design cases for the ATR Conversion project and were previously referred to as Mod 0.10 and Mod 0.11, respectively.

2) Mark VII element results are equivalent from a criticality safety point of view to Mark IV, V and VI results.

8. Summary

MCNP models for Mod 0.1, Mk1A and Mk1B ELF elements have been developed and used to evaluate a select number of existing HEU models. These existing models are taken from previous CSEs that are used to develop ATR handling, storage and transportation controls for ATR HEU elements. The reactivities of the three different ELF elements designs are compared. These are the original design, Mod 0.1 and the two latest optimized designs, Mk1A and Mk1B. These latter two designs have been selected as the conceptual design cases for the ATR Conversion project and were previously referred to as Mod 0.10 and Mod 0.11, respectively. Results are given for the design fuel meat thicknesses of each plate (nominal fuel meat thickness) and for a 0.001 in. (1 mil) thicker fuel meat to conservatively account for fuel meat thickness manufacturing tolerance uncertainties.

Two different array configurations with varying spacing between elements are evaluated for seven water moderated and reflected HEU and ELF fuels elements. The most reactive k_{eff} (near-critical) for HEU elements exceeds that of the most reactive ELF configurations (Mk1A and Mk1B) by an average of 0.0126 Δk and 0.0062 Δk for nominal and thicker fuel meat elements, respectively. As the spacing between elements increases, i.e., non-optimal spacing, the ELF fuels are found to be more reactive than the HEU fuel. For single elements, k_{eff}s for the ELF fuels exceed the HEU value by 0.0163 Δk and 0.0220 Δk for the nominal and thicker fuel meat Mk1A and Mk1B ELF elements. For criticality safety concerns the Mk1A and Mk1B reactivities are found to be essentially identical.

The conclusion of this CSE is that for many cases the HEU ATR element bounds the nominal and thicker fuel meat ELF elements. For the remaining cases where the ELF reactivity is greater than that of the HEU fuel, the margin below the acceptance limit is sufficient to allow HEU controls to be applied to the ELF elements. While other array configurations and additional cases may be slightly more reactive than those evaluated here, this would not affect the conclusion of this CSE. Should a larger total fissionable mass ELF element be the ultimate ATR LEU Conversion element then additional evaluations would be necessary.

The ELF elements by themselves, as well as the HEU and ELF elements mixed together (in proximity) are bound by the HEU ATR elements controls, and as such the ELF elements can be handled, stored and transferred using controls established for HEU ATR elements. This also applies to any existing CSI determinations that are derived for HEU ATR elements.

In many cases the Mark IV and VII reactivities are found to agree within statistics, but if there are statistically significant differences then the Mark VII is found to be more reactive. This also applies to Mark V and VI elements as the modeled Mark IV U-235 loading is 990 g. With uncertainties included this loading is slightly larger than that of the Mark V and VI elements.

9. References

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Appendix A: Materials & Compositions

number densities are listed as atoms/(cm·barn)

Table A-1. Material Specifications for Mark VII HEU UAl_x Plates
(These are used in Section 6.1.1)

	U-235	U-234	U-236	U-238	Al
U Isotope wt. abundances, →	93.00%	0.600%	0.350%	6.05%	–
Plate Number, ↓	**Number Densities**				
1	2.5479E-03	1.6508E-05	9.5481E-06	1.6366E-04	5.7424E-02
2	2.5425E-03	1.6474E-05	9.5280E-06	1.6331E-04	5.7430E-02
3	3.2098E-03	2.0797E-05	1.2029E-05	2.0617E-04	5.6628E-02
4	3.1890E-03	2.0662E-05	1.1951E-05	2.0484E-04	5.6653E-02
5	3.9232E-03	2.5419E-05	1.4702E-05	2.5199E-04	5.5771E-02
6	3.9305E-03	2.5466E-05	1.4729E-05	2.5246E-04	5.5762E-02
7	3.9302E-03	2.5465E-05	1.4728E-05	2.5245E-04	5.5762E-02
8	3.9300E-03	2.5464E-05	1.4728E-05	2.5243E-04	5.5763E-02
9	3.9299E-03	2.5463E-05	1.4727E-05	2.5242E-04	5.5763E-02
10	3.9297E-03	2.5461E-05	1.4726E-05	2.5241E-04	5.5763E-02
11	3.9295E-03	2.5461E-05	1.4726E-05	2.5240E-04	5.5763E-02
12	3.9294E-03	2.5460E-05	1.4725E-05	2.5239E-04	5.5763E-02
13	3.9293E-03	2.5459E-05	1.4725E-05	2.5239E-04	5.5764E-02
14	3.9292E-03	2.5458E-05	1.4725E-05	2.5238E-04	5.5764E-02
15	3.9342E-03	2.5491E-05	1.4743E-05	2.5270E-04	5.5758E-02
16	3.1992E-03	2.0728E-05	1.1989E-05	2.0549E-04	5.6641E-02
17	3.1965E-03	2.0711E-05	1.1979E-05	2.0532E-04	5.6644E-02
18	2.5639E-03	1.6612E-05	9.6080E-06	1.6468E-04	5.7405E-02
19	2.5362E-03	1.6433E-05	9.5044E-06	1.6291E-04	5.7438E-02

Table A-2. Material Specifications for Mark IV HEU Element

U Isotope wt. abundances					
U-235	**U-234**	**U-236**	**U-238**	**O**	**Al**
93.00%	0.60%	0.035%	6.05%	–	–
Number Densities (all Plates)					
3.1849E-03	2.0636E-05	1.1935E-05	2.0457E-04	9.1255E-03	4.9340E-02

Table A-3. Material Specifications for U-10Mo

Element / Isotope	U Isotope wt. abundances [a]	Number Density
U-235	19.75%	7.7745E-03
U-238	79.89%	3.1051E-02
U-234	0.130%	5.1393E-05
U-236	0.230%	9.0154E-05
Mo	–	9.6548E-03
density = 16.902 g/cm^3		

a Isotopic wt. abundances for U-234 and U-236 are taken to be half the maximum values give in Reference 33.

Table A-4. Material Specifications for Zr Cladding

Element	Number Density
Zr	4.3108E-02
density = 6.53 g/cm^3	

Table A-5. Material Specifications for Water

Element	Moles of Element/ Mole of Compound	Number Density, [atom/(cm·b)]
H	2	6.6874E-02
O	1	3.3437E-02
density = 1.0 g/cm^3		

Table A-6. Material Specifications for Al-6061

Element / Isotope	Number density
Mg	6.7060E-04
Si	3.4820E-04
Fe	2.0430E-04
Al-27	5.9018E-02
density = 2.7065 g/cm^3	

Appendix B: Typical Computer Model Input Listings

Sample Problem 1. This is case leub_1a of Table D-5, a single Mod 0.1 ELF element.

```
LEU ATR (ELF) element
c     cell cards for ATR assembly
601   5 0.100311        600 -601 -680 -681            u=1  imp:n=1
c     plate 1
602   515 4.862185E-02   602 -603  -682 -683 -692 693     u=1  imp:n=1
6021  30  4.310780E-02  6011 -602  -682 -683 -692 693     u=1  imp:n=1
6022  30  4.310780E-02   603 -6031 -682 -683 -692 693     u=1  imp:n=1
603   20  6.024110E-02   601 -604 -680 -681
                 (-6011:6031:692:-693:682:683)     u=1  imp:n=1
604   5 0.100311        604 -605 -680 -681            u=1  imp:n=1
c     plate 2
605   515 4.862185E-02   606 -607  -684 -685 -692 693     u=1  imp:n=1
6051  30  4.310780E-02  6051 -606  -684 -685 -692 693     u=1  imp:n=1
6052  30  4.310780E-02   607 -6071 -684 -685 -692 693     u=1  imp:n=1
606   20  6.024110E-02   605 -608 -680 -681
                 (-6051:6071:692:-693:684:685)     u=1  imp:n=1
607   5 0.100311        608 -609 -680 -681            u=1  imp:n=1
c     plate 3
608   515 4.862185E-02   610 -611  -684 -685 -692 693     u=1  imp:n=1
6081  30  4.310780E-02  6091 -610  -684 -685 -692 693     u=1  imp:n=1
6082  30  4.310780E-02   611 -6111 -684 -685 -692 693     u=1  imp:n=1
609   20  6.024110E-02   609 -612 -680 -681
                 (-6091:6111:692:-693:684:685)     u=1  imp:n=1
610   5 0.100311        612 -613 -680 -681            u=1  imp:n=1
c    plate 4
611   515 4.862185E-02   614 -615  -684 -685 -692 693     u=1  imp:n=1
6111  30  4.310780E-02  6131 -614  -684 -685 -692 693     u=1  imp:n=1
6112  30  4.310780E-02   615 -6151 -684 -685 -692 693     u=1  imp:n=1
612   20  6.024110E-02   613 -616 -680 -681
                 (-6131:6151:692:-693:684:685)     u=1  imp:n=1
613   5 0.100311        616 -617 -680 -681            u=1  imp:n=1
c    plate 5
614  515 4.862185E-02    618 -619 -684 -685 -692 693      u=1  imp:n=1
6141  30  4.310780E-02   6171 -618 -684 -685 -692 693      u=1  imp:n=1
6142  30  4.310780E-02   619 -6191 -684 -685 -692 693      u=1  imp:n=1
615  20  6.024110E-02    617 -620 -680 -681
                 (-6171:6191:692:-693:684:685)     u=1  imp:n=1
616  5 0.100311         620 -621 -680 -681            u=1  imp:n=1
c    plate 6
617  515 4.862185E-02    622 -623 -684 -685 -692 693      u=1  imp:n=1
6171  30  4.310780E-02   6211 -622 -684 -685 -692 693      u=1  imp:n=1
6172  30  4.310780E-02   623 -6231 -684 -685 -692 693      u=1  imp:n=1
618  20  6.024110E-02    621 -624 -680 -681
                 (-6211:6231:692:-693:684:685)     u=1  imp:n=1
619  5 0.100311         624 -625 -680 -681            u=1  imp:n=1
c    plate 7
620  515 4.862185E-02    626 -627 -684 -685 -692 693      u=1  imp:n=1
6201  30  4.310780E-02   6251 -626 -684 -685 -692 693      u=1  imp:n=1
6202  30  4.310780E-02   627 -6271 -684 -685 -692 693      u=1  imp:n=1
621  20  6.024110E-02    625 -628 -680 -681
                 (-6251:6271:692:-693:684:685)     u=1  imp:n=1
622  5 0.100311         628 -629 -680 -681            u=1  imp:n=1
c    plate 8
623  515 4.862185E-02    630 -631 -684 -685 -692 693      u=1  imp:n=1
6231  30  4.310780E-02   6291 -630 -684 -685 -692 693      u=1  imp:n=1
6232  30  4.310780E-02   631 -6311 -684 -685 -692 693      u=1  imp:n=1
624  20  6.024110E-02    629 -632 -680 -681
```

```
              (-6291:6311:692:-693:684:685)     u=1  imp:n=1
625   5 0.100311         632 -633 -680 -681              u=1  imp:n=1
c    plate 9
626   515 4.862185E-02    634 -635 -684 -685 -692 693      u=1  imp:n=1
6261  30  4.310780E-02   6331 -634 -684 -685 -692 693      u=1  imp:n=1
6262  30  4.310780E-02   635 -6351 -684 -685 -692 693      u=1  imp:n=1
627   20  6.024110E-02    633 -636 -680 -681
              (-6331:6351:692:-693:684:685)     u=1  imp:n=1
628   5 0.100311         636 -637 -680 -681              u=1  imp:n=1
c    plate 10
629   515 4.862185E-02    638 -639 -684 -685 -692 693      u=1  imp:n=1
6291  30  4.310780E-02   6371 -638 -684 -685 -692 693      u=1  imp:n=1
6292  30  4.310780E-02   639 -6391 -684 -685 -692 693      u=1  imp:n=1
630   20  6.024110E-02    637 -640 -680 -681
              (-6371:6391:692:-693:684:685)     u=1  imp:n=1
631   5 0.100311         640 -641 -680 -681              u=1  imp:n=1
c    plate 11
632   515 4.862185E-02    642 -643  -684 -685 -692 693     u=1  imp:n=1
6321  30  4.310780E-02   6411 -642 -684 -685 -692 693      u=1  imp:n=1
6322  30  4.310780E-02   643 -6431 -684 -685 -692 693      u=1  imp:n=1
633   20  6.024110E-02    641 -644 -680 -681
              (-6411:6431:692:-693:684:685)     u=1  imp:n=1
634   5 0.100311         644 -645 -680 -681              u=1  imp:n=1
c    plate 12
635   515 4.862185E-02    646 -647 -684 -685 -692 693      u=1  imp:n=1
6351  30  4.310780E-02   6451 -646 -684 -685 -692 693      u=1  imp:n=1
6352  30  4.310780E-02   647 -6471 -684 -685 -692 693      u=1  imp:n=1
636   20  6.024110E-02    645 -648 -680 -681
              (-6451:6471:692:-693:684:685)     u=1  imp:n=1
637   5 0.100311         648 -649 -680 -681              u=1  imp:n=1
c     plate 13
638   515 4.862185E-02    650 -651 -684 -685 -692 693      u=1  imp:n=1
6381  30  4.310780E-02   6491 -650 -684 -685 -692 693      u=1  imp:n=1
6382  30  4.310780E-02   651 -6511 -684 -685 -692 693      u=1  imp:n=1
639   20  6.024110E-02    649 -652 -680 -681
              (-6491:6511:692:-693:684:685)     u=1  imp:n=1
640   5 0.100311         652 -653 -680 -681              u=1  imp:n=1
c     plate 14
641   515 4.862185E-02    654 -655 -684 -685 -692 693      u=1  imp:n=1
6411  30  4.310780E-02   6531 -654 -684 -685 -692 693      u=1  imp:n=1
6412  30  4.310780E-02   655 -6551 -684 -685 -692 693      u=1  imp:n=1
642   20  6.024110E-02    653 -656 -680 -681
              (-6531:6551:692:-693:684:685)     u=1  imp:n=1
643   5 0.100311         656 -657 -680 -681              u=1  imp:n=1
c    plate 15
644   515 4.862185E-02    658 -659 -684 -685 -692 693      u=1  imp:n=1
6441  30  4.310780E-02   6571 -658 -684 -685 -692 693      u=1  imp:n=1
6442  30  4.310780E-02   659 -6591 -684 -685 -692 693      u=1  imp:n=1
645   20  6.024110E-02    657 -660 -680 -681
              (-6571:6591:692:-693:684:685)     u=1  imp:n=1
646   5 0.100311         660 -661 -680 -681              u=1  imp:n=1
c    plate 16
647   515 4.862185E-02    662 -663  -684 -685 -692 693     u=1  imp:n=1
6471  30  4.310780E-02   6611 -662  -684 -685 -692 693     u=1  imp:n=1
6472  30  4.310780E-02    663 -6631 -684 -685 -692 693     u=1  imp:n=1
648   20  6.024110E-02    661 -664 -680 -681
              (-6611:6631:692:-693:684:685)     u=1  imp:n=1
649   5 0.100311         664 -665 -680 -681              u=1  imp:n=1
c    plate 17
650   515 4.862185E-02    666 -667  -684 -685 -692 693     u=1  imp:n=1
6501  30  4.310780E-02   6651 -666  -684 -685 -692 693     u=1  imp:n=1
6502  30  4.310780E-02    667 -6671 -684 -685 -692 693     u=1  imp:n=1
651   20  6.024110E-02    665 -668 -680 -681
              (-6651:6671:692:-693:684:685)     u=1  imp:n=1
652   5 0.100311         668 -669 -680 -681              u=1  imp:n=1
```

```
c    plate 18
653   515 4.862185E-02    670 -671  -686 -687 -692 693     u=1  imp:n=1
6531  30  4.310780E-02   6691 -670  -686 -687 -692 693     u=1  imp:n=1
6532  30  4.310780E-02    671 -6711 -686 -687 -692 693     u=1  imp:n=1
654   20  6.024110E-02    669 -672 -680 -681
                  (-6691:6711:692:-693:686:687)     u=1  imp:n=1
655   5 0.100311          672 -673 -680 -681            u=1  imp:n=1
c    plate 19
656   515 4.862185E-02    674 -675  -682 -683 -692 693     u=1  imp:n=1
6561  30  4.310780E-02   6731 -674  -682 -683 -692 693     u=1  imp:n=1
6562  30  4.310780E-02    675 -6751 -682 -683 -692 693     u=1  imp:n=1
657   20  6.024110E-02    673 -676 -680 -681
                  (-6731:6751:692:-693:682:683)     u=1  imp:n=1
658   5 0.100311          676 -677 -680 -681            u=1  imp:n=1
c     side plates
659   20 6.024110E-02    (-600:677:680:681)             u=1  imp:n=1
c    cut-out elements and move
61    0    697 -698 -678 -679 -690 691 fill=1
                  trcl=(0  -10.5  0)      imp:n=1
104 5 0.100311   -110  111  -112  113 -114   115
              #61                        imp:n=1
105  0            110:-111:112:-113:114:-115   imp:n=0

c ******************************************************************
C     SURFACE SPECIFICATIONS
c     surface cards
600    cz 7.52855
c     radii for fuel plates
c    plate 1
601   cz 7.65810   $plate 1 inner radius
6011 cz 7.74700   $plate 1 inner Zr clad radius
602   cz 7.74954   $plate 1 inner fuel radius
603   cz 7.76986   $plate 1 outer fuel radius
6031  cz 7.77240   $plate 1 outer Zr clad radius
604   cz 7.86130   $plate 1 outer radius
c    plate 2
605   cz 8.05942   $plate 2 inner radius
6051 cz 8.10895   $plate 2 inner Zr clad radius
606   cz 8.11149   $plate 2 inner fuel radius
607   cz 8.13435   $plate 2 outer fuel radius
6071  cz 8.13689   $plate 2 outer Zr clad radius
608   cz 8.18642   $plate 2 outer radius
c    plate 3
609   cz 8.38454   $plate 3 inner radius
6091 cz 8.43280   $plate 3 inner Zr clad radius
610   cz 8.43534   $plate 3 inner fuel radius
611   cz 8.46074   $plate 3 outer fuel radius
6111  cz 8.46328   $plate 3 outer Zr clad radius
612   cz 8.51154   $plate 3 outer radius
c    plate 4
613   cz 8.70966   $plate 4 inner radius
6131 cz 8.75538   $plate 4 inner Zr clad radius
614   cz 8.75792   $plate 4 inner fuel radius
615   cz 8.78840   $plate 4 outer fuel radius
6151  cz 8.79094   $plate 4 outer Zr clad radius
616   cz 8.83666   $plate 4 outer radius
c    plate 5
617   cz 9.03478   $plate 5 inner radius
6171 cz 9.07923   $plate 5 inner Zr clad radius
618   cz 9.08177   $plate 5 inner fuel radius
619   cz 9.11479   $plate 5 outer fuel radius
6191  cz 9.11733   $plate 5 outer Zr clad radius
620   cz 9.16178   $plate 5 outer radius
c    plate 6
621   cz 9.35990   $plate 6 inner radius
```

```
6211 cz 9.40308   $plate 6 inner Zr clad radius
622   cz 9.40562   $plate 6 inner fuel radius
623   cz 9.44118   $plate 6 outer fuel radius
6231  cz 9.44372   $plate 6 outer Zr clad radius
624   cz 9.48690   $plate 6 outer radius
c    plate 7
625   cz 9.68502   $plate 7 inner radius
6251 cz 9.72693   $plate 7 inner Zr clad radius
626   cz 9.72947   $plate 7 inner fuel radius
627   cz 9.76757   $plate 7 outer fuel radius
6271  cz 9.77011   $plate 7 outer Zr clad radius
628   cz 9.81202   $plate 7 outer radius
c    plate 8
629   cz 10.01014   $plate 8 inner radius
6291 cz 10.05205   $plate 8 inner Zr clad radius
630   cz 10.05459   $plate 8 inner fuel radius
631   cz 10.09269   $plate 8 outer fuel radius
6311  cz 10.09523   $plate 8 outer Zr clad radius
632   cz 10.13714   $plate 8 outer radius
c    plate 9
633   cz 10.33526   $plate 9 inner radius
6331 cz 10.37717   $plate 9 inner Zr clad radius
634   cz 10.37971   $plate 9 inner fuel radius
635   cz 10.41781   $plate 9 outer fuel radius
6351  cz 10.42035   $plate 9 outer Zr clad radius
636   cz 10.46226   $plate 9 outer radius
c    plate 10
637   cz 10.66038   $plate 10 inner radius
6371 cz 10.70229   $plate 10 inner Zr clad radius
638   cz 10.70483   $plate 10 inner fuel radius
639   cz 10.74293   $plate 10 outer fuel radius
6391  cz 10.74547   $plate 10 outer Zr clad radius
640   cz 10.78738   $plate 10 outer radius
c    plate 11
641   cz 10.98550   $plate 11 inner radius
6411 cz 11.02741   $plate 11 inner Zr clad radius
642   cz 11.02995   $plate 11 inner fuel radius
643   cz 11.06805   $plate 11 outer fuel radius
6431  cz 11.07059   $plate 11 outer Zr clad radius
644   cz 11.11250   $plate 11 outer radius
c    plate 12
645   cz 11.31062   $plate 12 inner radius
6451 cz 11.35253   $plate 12 inner Zr clad radius
646   cz 11.35507   $plate 12 inner fuel radius
647   cz 11.39317   $plate 12 outer fuel radius
6471  cz 11.39571   $plate 12 outer Zr clad radius
648   cz 11.43762   $plate 12 outer radius
c    plate 13
649   cz 11.63574   $plate 13 inner radius
6491 cz 11.67765   $plate 13 inner Zr clad radius
650   cz 11.68019   $plate 13 inner fuel radius
651   cz 11.71829   $plate 13 outer fuel radius
6511  cz 11.72083   $plate 13 outer Zr clad radius
652   cz 11.76274   $plate 13 outer radius
c    plate 14
653   cz 11.96086   $plate 14 inner radius
6531 cz 12.00404   $plate 14 inner Zr clad radius
654   cz 12.00658   $plate 14 inner fuel radius
655   cz 12.04214   $plate 14 outer fuel radius
6551  cz 12.04468   $plate 14 outer Zr clad radius
656   cz 12.08786   $plate 14 outer radius
c    plate 15
657   cz 12.28598   $plate 15 inner radius
6571 cz 12.33170   $plate 15 inner Zr clad radius
658   cz 12.33424   $plate 15 inner fuel radius
```

```
659   cz 12.36472   $plate 15 outer fuel radius
6591  cz 12.36726   $plate 15 outer Zr clad radius
660   cz 12.41298   $plate 15 outer radius
c    plate 16
661   cz 12.61110   $plate 16 inner radius
6611 cz 12.65809   $plate 16 inner Zr clad radius
662   cz 12.66063   $plate 16 inner fuel radius
663   cz 12.68857   $plate 16 outer fuel radius
6631  cz 12.69111   $plate 16 outer Zr clad radius
664   cz 12.73810   $plate 16 outer radius
c    plate 17
665   cz 12.93622   $plate 17 inner radius
6651 cz 12.98575   $plate 17 inner Zr clad radius
666   cz 12.98829   $plate 17 inner fuel radius
667   cz 13.01115   $plate 17 outer fuel radius
6671  cz 13.01369   $plate 17 outer Zr clad radius
668   cz 13.06322   $plate 17 outer radius
c    plate 18
669   cz 13.26134   $plate 18 inner radius
6691 cz 13.31214   $plate 18 inner Zr clad radius
670   cz 13.31468   $plate 18 inner fuel radius
671   cz 13.33500   $plate 18 outer fuel radius
6711  cz 13.33754   $plate 18 outer Zr clad radius
672   cz 13.38834   $plate 18 outer radius
c    plate 19
673   cz 13.58646   $plate 19 inner radius
6731 cz 13.70203   $plate 19 inner Zr clad radius
674   cz 13.70457   $plate 19 inner fuel radius
675   cz 13.72235   $plate 19 outer fuel radius
6751  cz 13.72489   $plate 19 outer Zr clad radius
676   cz 13.84046   $plate 19 outer radius
c
677    cz 14.01317  $outer diameter of element
c    surfaces for sides of plate and fuel region
678   p -2.414214 -1 0 -0.212395   $outside boundary of Al plate
679   p  2.414214 -1 0 -0.212395   $outside boundary of Al plate
680   p -2.414214 -1 0 -1.453578  $inside boundary of Al plate
681   p  2.414214 -1 0 -1.453578  $inside boundary of Al plate
682   p -2.414214 -1 0 -2.08412  $plate 1 and 19 fuel meat boundary
683   p  2.414214 -1 0 -2.08412  $plate 1 and 19 fuel meat boundary
684   p -2.414214 -1 0 -2.08412  $plate 2 through 17 fuel meat boundary
685   p  2.414214 -1 0 -2.08412  $plate 2 through 17 fuel meat boundary
686   p -2.414214 -1 0 -2.08412  $plate 18 fuel meat boundary
687   p  2.414214 -1 0 -2.08412  $plate 18 fuel meat boundary
690   pz  62.8650   $top of fuel element, 49.5" total
691   pz -62.8650   $bottom of fuel element
692   pz  60.960    $top of fuel meat, 48.0" total
693   pz -60.960    $bottom of fuel meat
697   cz  7.52856   $inner radius of element
698   cz 14.00302   $outer radius of element
160   cz  10000.    $just a big surface
c ************************************************************
*110  px  65.2630                        $ storage rack
*111  px -65.2630
*112  py  44.8468
*113  py -44.8468
114  pz  100.0                           $ water reflector
115  pz -100.0

mode n
C    WATER  dens=1.0000 g/cc  $   atm. den.:   .100284
m5    1001       6.6874E-02  $ H
      8016       3.3437E-02  $ O
      nlib=.50c
mt5   lwtr.01t
```

```
c     fuel plates
m515    92235       7.7745E-03
        92238       3.1051E-02
        92234       5.1393E-05
        92236       9.0154E-05
        42000.51c   9.6548E-03
c       42092       1.5761E-03
c       42094       9.8495E-04
c       42095       1.6967E-03
c       42096       1.7799E-03
c       42097       1.0202E-03
c       42098       2.5813E-03
c       42100       1.0319E-03
        nlib=.50c
c     material for cladding and support (Al6061)
m20    13027     5.9018E-02 $ Al (impurities less than 0.5% neglected)
       12000     6.7060e-04 $ Mg
c      12024     5.2971E-04
c      12025     6.7060E-05
c      12026     7.3833E-05
       14000     3.4820E-04 $ Si
c      14028     3.2114E-04 $ Si
c      14029     1.6261E-05
c      14030     1.0794E-05
       26000.55c 2.0430E-04 $ Fe
c      26054     1.1952E-05 $ Fe
c      26056     1.8745E-04
c      26057     4.3312E-06
c      26058     5.7205E-07
       nlib=.50c
c
m30 $ 40090      2.2179E-02
c     40091      4.8367E-03
c     40092      7.3930E-03
c     40094      7.4921E-03
c     40096      1.2070E-03
      40000.56c  4.31078E-02
      nlib=.50c
c                          RC
c
kcode  6500  1.0  55  305
c
ksrc  0.2    -2.8     0.00  -0.2    -2.8     0.0
      3.7    2.6     0.00  -3.7     2.6     0.0
      2.7    -1.1     0.00  -2.7    -1.1     0.0
      2.1    -2.6     0.00  -2.1    -2.6     0.0
print
```

Sample Problem 2. This is case l.11_1a of Table D-5, a single Mk1B ELF element.

```
LEU ATR (ELF_0.11) element
c     cell cards for ATR assembly
601    5 0.100311         600 -601 -680 -681              u=1  imp:n=1
c     plate 1
602    515 4.862185E-02   602 -603  -682 -683 -692 693     u=1  imp:n=1
6021   30  4.310780E-02  6011 -602  -682 -683 -692 693     u=1  imp:n=1
6022   30  4.310780E-02   603 -6031 -682 -683 -692 693     u=1  imp:n=1
603    20  6.024110E-02   601 -604 -680 -681
                    (-6011:6031:692:-693:682:683)      u=1  imp:n=1
604    5 0.100311         604 -605 -680 -681              u=1  imp:n=1
c     plate 2
605    515 4.862185E-02   606 -607  -684 -685 -692 693     u=1  imp:n=1
```

```
6051   30  4.310780E-02  6051 -606  -684 -685 -692 693     u=1  imp:n=1
6052   30  4.310780E-02   607 -6071 -684 -685 -692 693     u=1  imp:n=1
606    20  6.024110E-02   605 -608 -680 -681
                   (-6051:6071:692:-693:684:685)     u=1  imp:n=1
607    5 0.100311         608 -609 -680 -681             u=1  imp:n=1
c      plate 3
608    515 4.862185E-02   610 -611  -684 -685 -692 693     u=1  imp:n=1
6081   30  4.310780E-02  6091 -610  -684 -685 -692 693     u=1  imp:n=1
6082   30  4.310780E-02   611 -6111 -684 -685 -692 693     u=1  imp:n=1
609    20  6.024110E-02   609 -612 -680 -681
                   (-6091:6111:692:-693:684:685)     u=1  imp:n=1
610    5 0.100311         612 -613 -680 -681             u=1  imp:n=1
c     plate 4
611    515 4.862185E-02   614 -615  -684 -685 -692 693     u=1  imp:n=1
6111   30  4.310780E-02  6131 -614  -684 -685 -692 693     u=1  imp:n=1
6112   30  4.310780E-02   615 -6151 -684 -685 -692 693     u=1  imp:n=1
612    20  6.024110E-02   613 -616 -680 -681
                   (-6131:6151:692:-693:684:685)     u=1  imp:n=1
613    5 0.100311         616 -617 -680 -681             u=1  imp:n=1
c     plate 5
614   515 4.862185E-02    618 -619 -684 -685 -692 693     u=1  imp:n=1
6141  30  4.310780E-02   6171 -618 -684 -685 -692 693     u=1  imp:n=1
6142  30  4.310780E-02   619 -6191 -684 -685 -692 693     u=1  imp:n=1
615   20  6.024110E-02   617 -620 -680 -681
                   (-6171:6191:692:-693:684:685)     u=1  imp:n=1
616   5 0.100311          620 -621 -680 -681             u=1  imp:n=1
c     plate 6
617   515 4.862185E-02    622 -623 -684 -685 -692 693     u=1  imp:n=1
6171  30  4.310780E-02   6211 -622 -684 -685 -692 693     u=1  imp:n=1
6172  30  4.310780E-02   623 -6231 -684 -685 -692 693     u=1  imp:n=1
618   20  6.024110E-02   621 -624 -680 -681
                   (-6211:6231:692:-693:684:685)     u=1  imp:n=1
619   5 0.100311          624 -625 -680 -681             u=1  imp:n=1
c     plate 7
620   515 4.862185E-02    626 -627 -684 -685 -692 693     u=1  imp:n=1
6201  30  4.310780E-02   6251 -626 -684 -685 -692 693     u=1  imp:n=1
6202  30  4.310780E-02   627 -6271 -684 -685 -692 693     u=1  imp:n=1
621   20  6.024110E-02   625 -628 -680 -681
                   (-6251:6271:692:-693:684:685)     u=1  imp:n=1
622   5 0.100311          628 -629 -680 -681             u=1  imp:n=1
c     plate 8
623   515 4.862185E-02    630 -631 -684 -685 -692 693     u=1  imp:n=1
6231  30  4.310780E-02   6291 -630 -684 -685 -692 693     u=1  imp:n=1
6232  30  4.310780E-02   631 -6311 -684 -685 -692 693     u=1  imp:n=1
624   20  6.024110E-02   629 -632 -680 -681
                   (-6291:6311:692:-693:684:685)     u=1  imp:n=1
625   5 0.100311          632 -633 -680 -681             u=1  imp:n=1
c     plate 9
626   515 4.862185E-02    634 -635 -684 -685 -692 693     u=1  imp:n=1
6261  30  4.310780E-02   6331 -634 -684 -685 -692 693     u=1  imp:n=1
6262  30  4.310780E-02   635 -6351 -684 -685 -692 693     u=1  imp:n=1
627   20  6.024110E-02   633 -636 -680 -681
                   (-6331:6351:692:-693:684:685)     u=1  imp:n=1
628   5 0.100311          636 -637 -680 -681             u=1  imp:n=1
c     plate 10
629   515 4.862185E-02    638 -639 -684 -685 -692 693     u=1  imp:n=1
6291  30  4.310780E-02   6371 -638 -684 -685 -692 693     u=1  imp:n=1
6292  30  4.310780E-02   639 -6391 -684 -685 -692 693     u=1  imp:n=1
630   20  6.024110E-02   637 -640 -680 -681
                   (-6371:6391:692:-693:684:685)     u=1  imp:n=1
631   5 0.100311          640 -641 -680 -681             u=1  imp:n=1
c     plate 11
632   515 4.862185E-02    642 -643  -684 -685 -692 693     u=1  imp:n=1
6321  30  4.310780E-02   6411 -642 -684 -685 -692 693     u=1  imp:n=1
6322  30  4.310780E-02   643 -6431 -684 -685 -692 693     u=1  imp:n=1
```

```
633   20  6.024110E-02    641 -644 -680 -681
                   (-6411:6431:692:-693:684:685)     u=1  imp:n=1
634   5 0.100311          644 -645 -680 -681              u=1  imp:n=1
c     plate 12
635   515 4.862185E-02    646 -647 -684 -685 -692 693      u=1  imp:n=1
6351  30  4.310780E-02   6451 -646 -684 -685 -692 693      u=1  imp:n=1
6352  30  4.310780E-02   647 -6471 -684 -685 -692 693      u=1  imp:n=1
636   20  6.024110E-02    645 -648 -680 -681
                   (-6451:6471:692:-693:684:685)     u=1  imp:n=1
637   5 0.100311          648 -649 -680 -681              u=1  imp:n=1
c     plate 13
638   515 4.862185E-02    650 -651 -684 -685 -692 693      u=1  imp:n=1
6381  30  4.310780E-02   6491 -650 -684 -685 -692 693      u=1  imp:n=1
6382  30  4.310780E-02   651 -6511 -684 -685 -692 693      u=1  imp:n=1
639   20  6.024110E-02    649 -652 -680 -681
                   (-6491:6511:692:-693:684:685)     u=1  imp:n=1
640   5 0.100311          652 -653 -680 -681              u=1  imp:n=1
c     plate 14
641   515 4.862185E-02    654 -655 -684 -685 -692 693      u=1  imp:n=1
6411  30  4.310780E-02   6531 -654 -684 -685 -692 693      u=1  imp:n=1
6412  30  4.310780E-02   655 -6551 -684 -685 -692 693      u=1  imp:n=1
642   20  6.024110E-02    653 -656 -680 -681
                   (-6531:6551:692:-693:684:685)     u=1  imp:n=1
643   5 0.100311          656 -657 -680 -681              u=1  imp:n=1
c     plate 15
644   515 4.862185E-02    658 -659 -684 -685 -692 693      u=1  imp:n=1
6441  30  4.310780E-02   6571 -658 -684 -685 -692 693      u=1  imp:n=1
6442  30  4.310780E-02   659 -6591 -684 -685 -692 693      u=1  imp:n=1
645   20  6.024110E-02    657 -660 -680 -681
                   (-6571:6591:692:-693:684:685)     u=1  imp:n=1
646   5 0.100311          660 -661 -680 -681              u=1  imp:n=1
c     plate 16
647   515 4.862185E-02    662 -663  -684 -685 -692 693     u=1  imp:n=1
6471  30  4.310780E-02   6611 -662  -684 -685 -692 693     u=1  imp:n=1
6472  30  4.310780E-02    663 -6631 -684 -685 -692 693     u=1  imp:n=1
648   20  6.024110E-02    661 -664 -680 -681
                   (-6611:6631:692:-693:684:685)     u=1  imp:n=1
649   5 0.100311          664 -665 -680 -681              u=1  imp:n=1
c     plate 17
650   515 4.862185E-02    666 -667  -684 -685 -692 693     u=1  imp:n=1
6501  30  4.310780E-02   6651 -666  -684 -685 -692 693     u=1  imp:n=1
6502  30  4.310780E-02    667 -6671 -684 -685 -692 693     u=1  imp:n=1
651   20  6.024110E-02    665 -668 -680 -681
                   (-6651:6671:692:-693:684:685)     u=1  imp:n=1
652   5 0.100311          668 -669 -680 -681              u=1  imp:n=1
c     plate 18
653   515 4.862185E-02    670 -671  -686 -687 -692 693     u=1  imp:n=1
6531  30  4.310780E-02   6691 -670  -686 -687 -692 693     u=1  imp:n=1
6532  30  4.310780E-02    671 -6711 -686 -687 -692 693     u=1  imp:n=1
654   20  6.024110E-02    669 -672 -680 -681
                   (-6691:6711:692:-693:686:687)     u=1  imp:n=1
655   5 0.100311          672 -673 -680 -681              u=1  imp:n=1
c     plate 19
656   515 4.862185E-02    674 -675  -682 -683 -692 693     u=1  imp:n=1
6561  30  4.310780E-02   6731 -674  -682 -683 -692 693     u=1  imp:n=1
6562  30  4.310780E-02    675 -6751 -682 -683 -692 693     u=1  imp:n=1
657   20  6.024110E-02    673 -676 -680 -681
                   (-6731:6751:692:-693:682:683)     u=1  imp:n=1
658   5 0.100311          676 -677 -680 -681              u=1  imp:n=1
c     side plates
659   20 6.024110E-02    (-600:677:680:681)               u=1  imp:n=1
c     cut-out elements and move
61    0    697 -698 -678 -679 -690 691 fill=1
                    trcl=(0  -10.5  0)       imp:n=1
104 5 0.100311   -110  111  -112  113 -114   115
```

```
            #61                     imp:n=1
105  0           110:-111:112:-113:114:-115   imp:n=0

c *****************************************************************
C     SURFACE SPECIFICATIONS
c     surface cards
600    cz 7.52855
c     radii for fuel plates
c    plate 1
601   cz 7.65810   $plate 1 inner radius
6011 cz 7.74446   $plate 1 inner Zr clad radius
602   cz 7.74700   $plate 1 inner fuel radius
603   cz 7.77240   $plate 1 outer fuel radius
6031  cz 7.77494   $plate 1 outer Zr clad radius
604   cz 7.86130   $plate 1 outer radius
c    plate 2
605   cz 8.05942   $plate 2 inner radius
6051 cz 8.10768   $plate 2 inner Zr clad radius
606   cz 8.11022   $plate 2 inner fuel radius
607   cz 8.13562   $plate 2 outer fuel radius
6071  cz 8.13816   $plate 2 outer Zr clad radius
608   cz 8.18642   $plate 2 outer radius
c    plate 3
609   cz 8.38454   $plate 3 inner radius
6091 cz 8.42899   $plate 3 inner Zr clad radius
610   cz 8.43153   $plate 3 inner fuel radius
611   cz 8.46455   $plate 3 outer fuel radius
6111  cz 8.46709   $plate 3 outer Zr clad radius
612   cz 8.51154   $plate 3 outer radius
c    plate 4
613   cz 8.70966   $plate 4 inner radius
6131 cz 8.75411   $plate 4 inner Zr clad radius
614   cz 8.75665   $plate 4 inner fuel radius
615   cz 8.78967   $plate 4 outer fuel radius
6151  cz 8.79221   $plate 4 outer Zr clad radius
616   cz 8.83666   $plate 4 outer radius
c    plate 5
617   cz 9.03478   $plate 5 inner radius
6171 cz 9.07669   $plate 5 inner Zr clad radius
618   cz 9.07923   $plate 5 inner fuel radius
619   cz 9.11733   $plate 5 outer fuel radius
6191  cz 9.11987   $plate 5 outer Zr clad radius
620   cz 9.16178   $plate 5 outer radius
c    plate 6
621   cz 9.35990   $plate 6 inner radius
6211 cz 9.40181   $plate 6 inner Zr clad radius
622   cz 9.40435   $plate 6 inner fuel radius
623   cz 9.44245   $plate 6 outer fuel radius
6231  cz 9.44499   $plate 6 outer Zr clad radius
624   cz 9.48690   $plate 6 outer radius
c    plate 7
625   cz 9.68502   $plate 7 inner radius
6251 cz 9.72312   $plate 7 inner Zr clad radius
626   cz 9.72566   $plate 7 inner fuel radius
627   cz 9.77138   $plate 7 outer fuel radius
6271  cz 9.77392   $plate 7 outer Zr clad radius
628   cz 9.81202   $plate 7 outer radius
c    plate 8
629   cz 10.01014   $plate 8 inner radius
6291 cz 10.04824   $plate 8 inner Zr clad radius
630   cz 10.05078   $plate 8 inner fuel radius
631   cz 10.09650   $plate 8 outer fuel radius
6311  cz 10.09904   $plate 8 outer Zr clad radius
632   cz 10.13714   $plate 8 outer radius
c    plate 9
```

```
633   cz 10.33526   $plate 9 inner radius
6331 cz 10.37336   $plate 9 inner Zr clad radius
634   cz 10.37590   $plate 9 inner fuel radius
635   cz 10.42162   $plate 9 outer fuel radius
6351  cz 10.42416   $plate 9 outer Zr clad radius
636   cz 10.46226   $plate 9 outer radius
c    plate 10
637   cz 10.66038   $plate 10 inner radius
6371 cz 10.69848   $plate 10 inner Zr clad radius
638   cz 10.70102   $plate 10 inner fuel radius
639   cz 10.74674   $plate 10 outer fuel radius
6391  cz 10.74928   $plate 10 outer Zr clad radius
640   cz 10.78738   $plate 10 outer radius
c    plate 11
641   cz 10.98550   $plate 11 inner radius
6411 cz 11.02360   $plate 11 inner Zr clad radius
642   cz 11.02614   $plate 11 inner fuel radius
643   cz 11.07186   $plate 11 outer fuel radius
6431  cz 11.07440   $plate 11 outer Zr clad radius
644   cz 11.11250   $plate 11 outer radius
c    plate 12
645   cz 11.31062   $plate 12 inner radius
6451 cz 11.34872   $plate 12 inner Zr clad radius
646   cz 11.35126   $plate 12 inner fuel radius
647   cz 11.39698   $plate 12 outer fuel radius
6471  cz 11.39952   $plate 12 outer Zr clad radius
648   cz 11.43762   $plate 12 outer radius
c    plate 13
649   cz 11.63574   $plate 13 inner radius
6491 cz 11.67765   $plate 13 inner Zr clad radius
650   cz 11.68019   $plate 13 inner fuel radius
651   cz 11.71829   $plate 13 outer fuel radius
6511  cz 11.72083   $plate 13 outer Zr clad radius
652   cz 11.76274   $plate 13 outer radius
c    plate 14
653   cz 11.96086   $plate 14 inner radius
6531 cz 12.00531   $plate 14 inner Zr clad radius
654   cz 12.00785   $plate 14 inner fuel radius
655   cz 12.04087   $plate 14 outer fuel radius
6551  cz 12.04341   $plate 14 outer Zr clad radius
656   cz 12.08786   $plate 14 outer radius
c    plate 15
657   cz 12.28598   $plate 15 inner radius
6571 cz 12.33043   $plate 15 inner Zr clad radius
658   cz 12.33297   $plate 15 inner fuel radius
659   cz 12.36599   $plate 15 outer fuel radius
6591  cz 12.36853   $plate 15 outer Zr clad radius
660   cz 12.41298   $plate 15 outer radius
c    plate 16
661   cz 12.61110   $plate 16 inner radius
6611 cz 12.65555   $plate 16 inner Zr clad radius
662   cz 12.65809   $plate 16 inner fuel radius
663   cz 12.69111   $plate 16 outer fuel radius
6631  cz 12.69365   $plate 16 outer Zr clad radius
664   cz 12.73810   $plate 16 outer radius
c    plate 17
665   cz 12.93622   $plate 17 inner radius
6651 cz 12.98448   $plate 17 inner Zr clad radius
666   cz 12.98702   $plate 17 inner fuel radius
667   cz 13.01242   $plate 17 outer fuel radius
6671  cz 13.01496   $plate 17 outer Zr clad radius
668   cz 13.06322   $plate 17 outer radius
c    plate 18
669   cz 13.26134   $plate 18 inner radius
6691 cz 13.31214   $plate 18 inner Zr clad radius
```

```
670   cz 13.31468   $plate 18 inner fuel radius
671   cz 13.33500   $plate 18 outer fuel radius
6711  cz 13.33754   $plate 18 outer Zr clad radius
672   cz 13.38834   $plate 18 outer radius
c    plate 19
673   cz 13.58646   $plate 19 inner radius
6731 cz 13.70076   $plate 19 inner Zr clad radius
674   cz 13.70330   $plate 19 inner fuel radius
675   cz 13.72362   $plate 19 outer fuel radius
6751  cz 13.72616   $plate 19 outer Zr clad radius
676   cz 13.84046   $plate 19 outer radius
c
677    cz 14.01317  $outer diameter of element
c    surfaces for sides of plate and fuel region
678   p -2.414214 -1 0 -0.212395   $outside boundary of Al plate
679   p  2.414214 -1 0 -0.212395   $outside boundary of Al plate
680   p -2.414214 -1 0 -1.453578  $inside boundary of Al plate
681   p  2.414214 -1 0 -1.453578  $inside boundary of Al plate
682   p -2.414214 -1 0 -2.08412  $plate 1 and 19 fuel meat boundary
683   p  2.414214 -1 0 -2.08412  $plate 1 and 19 fuel meat boundary
684   p -2.414214 -1 0 -2.08412  $plate 2 through 17 fuel meat boundary
685   p  2.414214 -1 0 -2.08412  $plate 2 through 17 fuel meat boundary
686   p -2.414214 -1 0 -2.08412  $plate 18 fuel meat boundary
687   p  2.414214 -1 0 -2.08412  $plate 18 fuel meat boundary
690   pz  62.8650   $top of fuel element, 49.5" total
691   pz -62.8650   $bottom of fuel element
692   pz  60.960    $top of fuel meat, 48.0" total
693   pz -60.960    $bottom of fuel meat
697   cz  7.52856   $inner radius of element
698   cz 14.00302   $outer radius of element
160   cz  10000.    $just a big surface
c ************************************************************
*110  px  65.2630                          $ storage rack
*111  px -65.2630
*112  py  44.8468
*113  py -44.8468
114  pz  100.0                             $ water reflector
115  pz -100.0

mode n
C    WATER  dens=1.0000 g/cc  $   atm. den.:   .100284
m5     1001       6.6874E-02  $ H
      8016      3.3437E-02  $ O
      nlib=.50c
mt5   lwtr.01t
c    fuel plates
m515    92235       7.7745E-03
       92238       3.1051E-02
       92234       5.1393E-05
       92236       9.0154E-05
       42000.51c   9.6548E-03
c       42092       1.5761E-03
c       42094       9.8495E-04
c       42095       1.6967E-03
c       42096       1.7799E-03
c       42097       1.0202E-03
c       42098       2.5813E-03
c       42100       1.0319E-03
       nlib=.50c
c    material for cladding and support (Al6061)
m20    13027     5.9018E-02 $ Al (impurities less than 0.5% neglected)
      12000     6.7060e-04 $ Mg
c     12024     5.2971E-04
c     12025     6.7060E-05
c     12026     7.3833E-05
```

```
      14000     3.4820E-04 $ Si
c      14028     3.2114E-04 $ Si
c      14029     1.6261E-05
c      14030     1.0794E-05
      26000.55c 2.0430E-04 $ Fe
c      26054     1.1952E-05 $ Fe
c      26056     1.8745E-04
c      26057     4.3312E-06
c      26058     5.7205E-07
      nlib=.50c
c
m30 $ 40090      2.2179E-02
c     40091      4.8367E-03
c     40092      7.3930E-03
c     40094      7.4921E-03
c     40096      1.2070E-03
     40000.56c  4.31078E-02
     nlib=.50c
c                           RC
c
kcode  6500  1.0  55  305
c
ksrc  0.2    -2.8     0.00  -0.2    -2.8     0.0
     3.7     2.6     0.00  -3.7     2.6     0.0
     2.7    -1.1     0.00  -2.7    -1.1     0.0
     2.1    -2.6     0.00  -2.1    -2.6     0.0
print
```

Sample Problem 3. This is case tolHhaT11_36 of Table 12, 36 Mk1B thicker fuel meat elements and 4 HEU elements.

```
LEU ATR (thicker, 1 mil mod0.11) element
c    cell cards for LEU ATR assembly
601   5 0.100311        600 -601 -680 -681           u=1  imp:n=1
c    plate 1
602   515 4.862185E-02   602 -603  -682 -683 -692 693    u=1  imp:n=1
6021  30  4.310780E-02  6011 -602  -682 -683 -692 693    u=1  imp:n=1
6022  30  4.310780E-02   603 -6031 -682 -683 -692 693    u=1  imp:n=1
603   20  6.024110E-02   601 -604 -680 -681
                (-6011:6031:692:-693:682:683)    u=1  imp:n=1
604   5 0.100311        604 -605 -680 -681           u=1  imp:n=1
c    plate 2
605   515 4.862185E-02   606 -607  -684 -685 -692 693    u=1  imp:n=1
6051  30  4.310780E-02  6051 -606  -684 -685 -692 693    u=1  imp:n=1
6052  30  4.310780E-02   607 -6071 -684 -685 -692 693    u=1  imp:n=1
606   20  6.024110E-02   605 -608 -680 -681
                (-6051:6071:692:-693:684:685)    u=1  imp:n=1
607   5 0.100311        608 -609 -680 -681           u=1  imp:n=1
c    plate 3
608   515 4.862185E-02   610 -611  -684 -685 -692 693    u=1  imp:n=1
6081  30  4.310780E-02  6091 -610  -684 -685 -692 693    u=1  imp:n=1
6082  30  4.310780E-02   611 -6111 -684 -685 -692 693    u=1  imp:n=1
609   20  6.024110E-02   609 -612 -680 -681
                (-6091:6111:692:-693:684:685)    u=1  imp:n=1
610   5 0.100311        612 -613 -680 -681           u=1  imp:n=1
c    plate 4
611   515 4.862185E-02   614 -615  -684 -685 -692 693    u=1  imp:n=1
6111  30  4.310780E-02  6131 -614  -684 -685 -692 693    u=1  imp:n=1
6112  30  4.310780E-02   615 -6151 -684 -685 -692 693    u=1  imp:n=1
612   20  6.024110E-02   613 -616 -680 -681
                (-6131:6151:692:-693:684:685)    u=1  imp:n=1
613   5 0.100311        616 -617 -680 -681           u=1  imp:n=1
c    plate 5
614   515 4.862185E-02   618 -619 -684 -685 -692 693     u=1  imp:n=1
6141  30  4.310780E-02   6171 -618 -684 -685 -692 693    u=1  imp:n=1
6142  30  4.310780E-02   619 -6191 -684 -685 -692 693    u=1  imp:n=1
615   20  6.024110E-02   617 -620 -680 -681
                (-6171:6191:692:-693:684:685)    u=1  imp:n=1
616   5 0.100311        620 -621 -680 -681           u=1  imp:n=1
c    plate 6
617   515 4.862185E-02   622 -623 -684 -685 -692 693     u=1  imp:n=1
6171  30  4.310780E-02   6211 -622 -684 -685 -692 693    u=1  imp:n=1
6172  30  4.310780E-02   623 -6231 -684 -685 -692 693    u=1  imp:n=1
618   20  6.024110E-02   621 -624 -680 -681
                (-6211:6231:692:-693:684:685)    u=1  imp:n=1
619   5 0.100311        624 -625 -680 -681           u=1  imp:n=1
c    plate 7
620   515 4.862185E-02   626 -627 -684 -685 -692 693     u=1  imp:n=1
6201  30  4.310780E-02   6251 -626 -684 -685 -692 693    u=1  imp:n=1
6202  30  4.310780E-02   627 -6271 -684 -685 -692 693    u=1  imp:n=1
621   20  6.024110E-02   625 -628 -680 -681
                (-6251:6271:692:-693:684:685)    u=1  imp:n=1
622   5 0.100311        628 -629 -680 -681           u=1  imp:n=1
c    plate 8
623   515 4.862185E-02   630 -631 -684 -685 -692 693     u=1  imp:n=1
6231  30  4.310780E-02   6291 -630 -684 -685 -692 693    u=1  imp:n=1
6232  30  4.310780E-02   631 -6311 -684 -685 -692 693    u=1  imp:n=1
624   20  6.024110E-02   629 -632 -680 -681
                (-6291:6311:692:-693:684:685)    u=1  imp:n=1
625   5 0.100311        632 -633 -680 -681           u=1  imp:n=1
c    plate 9
```

```
626   515 4.862185E-02    634 -635 -684 -685 -692 693      u=1  imp:n=1
6261  30  4.310780E-02   6331 -634 -684 -685 -692 693      u=1  imp:n=1
6262  30  4.310780E-02   635 -6351 -684 -685 -692 693      u=1  imp:n=1
627   20  6.024110E-02   633 -636 -680 -681
                  (-6331:6351:692:-693:684:685)     u=1  imp:n=1
628   5 0.100311         636 -637 -680 -681             u=1  imp:n=1
c    plate 10
629   515 4.862185E-02    638 -639 -684 -685 -692 693      u=1  imp:n=1
6291  30  4.310780E-02   6371 -638 -684 -685 -692 693      u=1  imp:n=1
6292  30  4.310780E-02   639 -6391 -684 -685 -692 693      u=1  imp:n=1
630   20  6.024110E-02   637 -640 -680 -681
                  (-6371:6391:692:-693:684:685)     u=1  imp:n=1
631   5 0.100311         640 -641 -680 -681             u=1  imp:n=1
c    plate 11
632   515 4.862185E-02    642 -643  -684 -685 -692 693     u=1  imp:n=1
6321  30  4.310780E-02   6411 -642  -684 -685 -692 693     u=1  imp:n=1
6322  30  4.310780E-02   643 -6431  -684 -685 -692 693     u=1  imp:n=1
633   20  6.024110E-02   641 -644 -680 -681
                  (-6411:6431:692:-693:684:685)     u=1  imp:n=1
634   5 0.100311         644 -645 -680 -681             u=1  imp:n=1
c    plate 12
635   515 4.862185E-02    646 -647 -684 -685 -692 693      u=1  imp:n=1
6351  30  4.310780E-02   6451 -646 -684 -685 -692 693      u=1  imp:n=1
6352  30  4.310780E-02   647 -6471 -684 -685 -692 693      u=1  imp:n=1
636   20  6.024110E-02   645 -648 -680 -681
                  (-6451:6471:692:-693:684:685)     u=1  imp:n=1
637   5 0.100311         648 -649 -680 -681             u=1  imp:n=1
c     plate 13
638   515 4.862185E-02    650 -651 -684 -685 -692 693      u=1  imp:n=1
6381  30  4.310780E-02   6491 -650 -684 -685 -692 693      u=1  imp:n=1
6382  30  4.310780E-02   651 -6511 -684 -685 -692 693      u=1  imp:n=1
639   20  6.024110E-02   649 -652 -680 -681
                  (-6491:6511:692:-693:684:685)     u=1  imp:n=1
640   5 0.100311         652 -653 -680 -681             u=1  imp:n=1
c     plate 14
641   515 4.862185E-02    654 -655 -684 -685 -692 693      u=1  imp:n=1
6411  30  4.310780E-02   6531 -654 -684 -685 -692 693      u=1  imp:n=1
6412  30  4.310780E-02   655 -6551 -684 -685 -692 693      u=1  imp:n=1
642   20  6.024110E-02   653 -656 -680 -681
                  (-6531:6551:692:-693:684:685)     u=1  imp:n=1
643   5 0.100311         656 -657 -680 -681             u=1  imp:n=1
c    plate 15
644   515 4.862185E-02    658 -659 -684 -685 -692 693      u=1  imp:n=1
6441  30  4.310780E-02   6571 -658 -684 -685 -692 693      u=1  imp:n=1
6442  30  4.310780E-02   659 -6591 -684 -685 -692 693      u=1  imp:n=1
645   20  6.024110E-02   657 -660 -680 -681
                  (-6571:6591:692:-693:684:685)     u=1  imp:n=1
646   5 0.100311         660 -661 -680 -681             u=1  imp:n=1
c    plate 16
647   515 4.862185E-02    662 -663  -684 -685 -692 693     u=1  imp:n=1
6471  30  4.310780E-02   6611 -662  -684 -685 -692 693     u=1  imp:n=1
6472  30  4.310780E-02    663 -6631 -684 -685 -692 693     u=1  imp:n=1
648   20  6.024110E-02   661 -664 -680 -681
                  (-6611:6631:692:-693:684:685)     u=1  imp:n=1
649   5 0.100311         664 -665 -680 -681             u=1  imp:n=1
c    plate 17
650   515 4.862185E-02    666 -667  -684 -685 -692 693     u=1  imp:n=1
6501  30  4.310780E-02   6651 -666  -684 -685 -692 693     u=1  imp:n=1
6502  30  4.310780E-02    667 -6671 -684 -685 -692 693     u=1  imp:n=1
651   20  6.024110E-02   665 -668 -680 -681
                  (-6651:6671:692:-693:684:685)     u=1  imp:n=1
652   5 0.100311         668 -669 -680 -681             u=1  imp:n=1
c    plate 18
653   515 4.862185E-02    670 -671  -686 -687 -692 693     u=1  imp:n=1
6531  30  4.310780E-02   6691 -670  -686 -687 -692 693     u=1  imp:n=1
```

```
6532  30  4.310780E-02    671 -6711 -686 -687 -692 693     u=1  imp:n=1
654   20  6.024110E-02    669 -672 -680 -681
                    (-6691:6711:692:-693:686:687)      u=1  imp:n=1
655   5 0.100311          672 -673 -680 -681              u=1  imp:n=1
c    plate 19
656   515 4.862185E-02    674 -675  -682 -683 -692 693     u=1  imp:n=1
6561  30  4.310780E-02   6731 -674  -682 -683 -692 693     u=1  imp:n=1
6562  30  4.310780E-02    675 -6751 -682 -683 -692 693     u=1  imp:n=1
657   20  6.024110E-02    673 -676 -680 -681
                    (-6731:6751:692:-693:682:683)      u=1  imp:n=1
658   5 0.100311          676 -677 -680 -681              u=1  imp:n=1
c     side plates
659   20 6.024110E-02    (-600:677:680:681)              u=1  imp:n=1
c    cut-out LEU elements and put in Al tube
61   0             697 -698 -678 -679  fill=1  imp:n=1  $ ATR element
                    trcl=(0  -10.5  0)    u=2
62  5 0.100311   -100  #61                   u=2 imp:n=1
63  22  -2.7      100 -103                   u=2 imp:n=1  $ Al wall
64  5 0.100311    103                        u=2 imp:n=1  $water around
c     cell cards for HEU ATR assembly
c     plate 1
701    5 0.100311          700 -701 -780 -781             u=11 imp:n=1
702    101 6.016162E-02   702 -703 -782 -783 -792 793      u=11 imp:n=1
703    20  6.024110E-02   701 -704 -780 -781 #702         u=11 imp:n=1
704    5 0.100311          704 -705 -780 -781             u=11 imp:n=1
c     plate 2
705    102 6.016181E-02   706 -707 -784 -785 -792 793      u=11 imp:n=1
706    20  6.024110E-02   705 -708 -780 -781 #705         u=11 imp:n=1
707    5 0.100311          708 -709 -780 -781             u=11 imp:n=1
c     plate 3
708    103 6.007680E-02   710 -711 -784 -785 -792 793      u=11 imp:n=1
709    20  6.024110E-02   709 -712 -780 -781 #708         u=11 imp:n=1
710    5 0.100311          712 -713 -780 -781             u=11 imp:n=1
c    plate 4
711    104 6.007945E-02   714 -715 -784 -785 -792 793      u=11 imp:n=1
712    20  6.024110E-02   713 -716 -780 -781 #711         u=11 imp:n=1
713    5 0.100311          716 -717 -780 -781             u=11 imp:n=1
c    plate 5
714    105 5.998631E-02   718 -719 -784 -785 -792 793      u=11 imp:n=1
715    20  6.024110E-02   717 -720 -780 -781 #714         u=11 imp:n=1
716    5 0.100311          720 -721 -780 -781             u=11 imp:n=1
c    plate 6
717   106 5.998515E-02    722 -723 -784 -785 -792 793      u=11 imp:n=1
718   20  6.024110E-02    721 -724 -780 -781 #717         u=11 imp:n=1
719   5 0.100311          724 -725 -780 -781              u=11 imp:n=1
c    plate 7
720   107 5.998484E-02    726 -727 -784 -785 -792 793      u=11 imp:n=1
721   20  6.024110E-02    725 -728 -780 -781  #720        u=11 imp:n=1
722   5 0.100311          728 -729 -780 -781              u=11 imp:n=1
c    plate 8
723   108 5.998562E-02    730 -731 -784 -785 -792 793      u=11 imp:n=1
724   20  6.024110E-02    729 -732 -780 -781 #723         u=11 imp:n=1
725   5 0.100311          732 -733 -780 -781              u=11 imp:n=1
c    plate 9
726   109 5.998551E-02    734 -735 -784 -785 -792 793      u=11 imp:n=1
727   20  6.024110E-02    733 -736 -780 -781 #726         u=11 imp:n=1
728   5 0.100311          736 -737 -780 -781              u=11 imp:n=1
c    plate 10
729  110 5.998530E-02     738 -739 -784 -785 -792 793      u=11 imp:n=1
730  20  6.024110E-02     737 -740 -780 -781 #729         u=11 imp:n=1
731   5 0.100311          740 -741 -780 -781              u=11 imp:n=1
c    plate 11
732  111 5.998509E-02     742 -743 -784 -785 -792 793     u=11 imp:n=1
733  20  6.024110E-02     741 -744 -780 -781  #732        u=11 imp:n=1
734   5 0.100311          744 -745 -780 -781              u=11 imp:n=1
```

```
c    plate 12
735   112 5.998498E-02    746 -747 -784 -785 -792 793     u=11 imp:n=1
736   20  6.024110E-02    745 -748 -780 -781 #735         u=11 imp:n=1
737   5 0.100311          748 -749 -780 -781              u=11 imp:n=1
c     plate 13
738   113 5.998587E-02    750 -751 -784 -785 -792 793     u=11 imp:n=1
739   20  6.024110E-02    749 -752 -780 -781 #738         u=11 imp:n=1
740   5 0.100311          752 -753 -780 -781              u=11 imp:n=1
c     plate 14
741   114 5.998576E-02    754 -755 -784 -785 -792 793     u=11 imp:n=1
742   20  6.024110E-02    753 -756 -780 -781  #741        u=11 imp:n=1
743   5 0.100311          756 -757 -780 -781              u=11 imp:n=1
c    plate 15
744   115 5.998513E-02    758 -759 -784 -785 -792 793     u=11 imp:n=1
745   20  6.024110E-02    757 -760 -780 -781 #744         u=11 imp:n=1
746   5 0.100311          760 -761 -780 -781              u=11 imp:n=1
c    plate 16
747   116 6.007841E-02    762 -763 -784 -785 -792 793     u=11 imp:n=1
748   20  6.024110E-02    761 -764 -780 -781 #747         u=11 imp:n=1
749   5 0.100311          764 -765 -780 -781              u=11 imp:n=1
c    plate 17
750   117 6.007851E-02    766 -767 -784 -785 -792 793     u=11 imp:n=1
751   20  6.024110E-02    765 -768 -780 -781  #750        u=11 imp:n=1
752   5 0.100311          768 -769 -780 -781              u=11 imp:n=1
c    plate 18
753   118 6.015980E-02    770 -771 -786 -787 -792 793     u=11 imp:n=1
754   20  6.024110E-02    769 -772 -780 -781 #753         u=11 imp:n=1
755   5 0.100311          772 -773 -780 -781              u=11 imp:n=1
c    plate 19
756   119 6.016305E-02    774 -775 -782 -783 -792 793     u=11 imp:n=1
757   20  6.024110E-02    773 -776 -780 -781 #756         u=11 imp:n=1
758   5 0.100311          776 -777 -780 -781              u=11 imp:n=1
c     side plates
759   20 6.024110E-02    (-700:777:780:781)               u=11 imp:n=1
c    cut-out HEU elements and put in Al tube
65   0            797 -798 -778 -779  fill=11 imp:n=1  $ ATR element
                   trcl=(0  -10.5  0)    u=4
66  5 0.100311   -100  #65                  u=4 imp:n=1
67  22  -2.7      100 -103                  u=4 imp:n=1  $ Al wall
68  5 0.100311    103                       u=4 imp:n=1  $water around
c
69  0           -160                        u=9 imp:n=1
100 5 0.100311 -120 122 -124 125 -123 121 lat=2 u=3 imp:n=1 fill=-5:5 -6:5 0:0
                 3  3  3  3  3  3  3  3  3  3  3  $LEU is u=2, HEU is u=4
                 3  3  3  3  3  3  3  3  3  3  3
                 3  3  3  3  3  3  3  3  2  4  3 $bottom
                 3  3  3  3  3  3  2  2  2  2  3
                 3  3  3  3  2  2  2  2  2  2  3
                 3  3  2  2  2  2  2  2  2  4  3
                 3  4  2  2  2  2  2  2  2  3  3 $C
                 3  2  2  2  2  2  2  3  3  3  3
                 3  2  2  2  2  3  3  3  3  3  3
                 3  4  2  3  3  3  3  3  3  3  3 $top
                 3  3  3  3  3  3  3  3  3  3  3
                 3  3  3  3  3  3  3  3  3  3  3
101   0  -110 111 -112 113 -690 691 fill=3 (0 7.62 0) imp:n=1
102   5 0.100311 -110 111 -112 113  690 -114 imp:n=1
103   5 0.100311 -110 111 -112 113 -691  115 imp:n=1
105  0            110:-111:112:-113:114:-115   imp:n=0

c ******************************************************************
C    LEU SURFACE SPECIFICATIONS
c    surface cards
600    cz 7.52855
c    radii for fuel plates
```

```
c    plate 1
601   cz 7.65810   $plate 1 inner radius
6011 cz 7.74319   $plate 1 inner Zr clad radius
602   cz 7.74573   $plate 1 inner fuel radius
603   cz 7.77367   $plate 1 outer fuel radius
6031  cz 7.77621   $plate 1 outer Zr clad radius
604   cz 7.86130   $plate 1 outer radius
c    plate 2
605   cz 8.05942   $plate 2 inner radius
6051 cz 8.10641   $plate 2 inner Zr clad radius
606   cz 8.10895   $plate 2 inner fuel radius
607   cz 8.13689   $plate 2 outer fuel radius
6071  cz 8.13943   $plate 2 outer Zr clad radius
608   cz 8.18642   $plate 2 outer radius
c    plate 3
609   cz 8.38454   $plate 3 inner radius
6091 cz 8.42772   $plate 3 inner Zr clad radius
610   cz 8.43026   $plate 3 inner fuel radius
611   cz 8.46582   $plate 3 outer fuel radius
6111  cz 8.46836   $plate 3 outer Zr clad radius
612   cz 8.51154   $plate 3 outer radius
c    plate 4
613   cz 8.70966   $plate 4 inner radius
6131 cz 8.75284   $plate 4 inner Zr clad radius
614   cz 8.75538   $plate 4 inner fuel radius
615   cz 8.79094   $plate 4 outer fuel radius
6151  cz 8.79348   $plate 4 outer Zr clad radius
616   cz 8.83666   $plate 4 outer radius
c    plate 5
617   cz 9.03478   $plate 5 inner radius
6171 cz 9.07542   $plate 5 inner Zr clad radius
618   cz 9.07796   $plate 5 inner fuel radius
619   cz 9.11860   $plate 5 outer fuel radius
6191  cz 9.12114   $plate 5 outer Zr clad radius
620   cz 9.16178   $plate 5 outer radius
c    plate 6
621   cz 9.35990   $plate 6 inner radius
6211 cz 9.40054   $plate 6 inner Zr clad radius
622   cz 9.40308   $plate 6 inner fuel radius
623   cz 9.44372   $plate 6 outer fuel radius
6231  cz 9.44626   $plate 6 outer Zr clad radius
624   cz 9.48690   $plate 6 outer radius
c    plate 7
625   cz 9.68502   $plate 7 inner radius
6251 cz 9.72185   $plate 7 inner Zr clad radius
626   cz 9.72439   $plate 7 inner fuel radius
627   cz 9.77265   $plate 7 outer fuel radius
6271  cz 9.77519   $plate 7 outer Zr clad radius
628   cz 9.81202   $plate 7 outer radius
c    plate 8
629   cz 10.01014   $plate 8 inner radius
6291 cz 10.04697   $plate 8 inner Zr clad radius
630   cz 10.04951   $plate 8 inner fuel radius
631   cz 10.09777   $plate 8 outer fuel radius
6311  cz 10.10031   $plate 8 outer Zr clad radius
632   cz 10.13714   $plate 8 outer radius
c    plate 9
633   cz 10.33526   $plate 9 inner radius
6331 cz 10.37209   $plate 9 inner Zr clad radius
634   cz 10.37463   $plate 9 inner fuel radius
635   cz 10.42289   $plate 9 outer fuel radius
6351  cz 10.42543   $plate 9 outer Zr clad radius
636   cz 10.46226   $plate 9 outer radius
c    plate 10
637   cz 10.66038   $plate 10 inner radius
```

```
6371 cz 10.69721   $plate 10 inner Zr clad radius
638   cz 10.69975   $plate 10 inner fuel radius
639   cz 10.74801   $plate 10 outer fuel radius
6391  cz 10.75055   $plate 10 outer Zr clad radius
640   cz 10.78738   $plate 10 outer radius
c    plate 11
641   cz 10.98550   $plate 11 inner radius
6411 cz 11.02233   $plate 11 inner Zr clad radius
642   cz 11.02487   $plate 11 inner fuel radius
643   cz 11.07313   $plate 11 outer fuel radius
6431  cz 11.07567   $plate 11 outer Zr clad radius
644   cz 11.11250   $plate 11 outer radius
c    plate 12
645   cz 11.31062   $plate 12 inner radius
6451 cz 11.34745   $plate 12 inner Zr clad radius
646   cz 11.34999   $plate 12 inner fuel radius
647   cz 11.39825   $plate 12 outer fuel radius
6471  cz 11.40079   $plate 12 outer Zr clad radius
648   cz 11.43762   $plate 12 outer radius
c    plate 13
649   cz 11.63574   $plate 13 inner radius
6491 cz 11.67638   $plate 13 inner Zr clad radius
650   cz 11.67892   $plate 13 inner fuel radius
651   cz 11.71956   $plate 13 outer fuel radius
6511  cz 11.72210   $plate 13 outer Zr clad radius
652   cz 11.76274   $plate 13 outer radius
c    plate 14
653   cz 11.96086   $plate 14 inner radius
6531 cz 12.00404   $plate 14 inner Zr clad radius
654   cz 12.00658   $plate 14 inner fuel radius
655   cz 12.04214   $plate 14 outer fuel radius
6551  cz 12.04468   $plate 14 outer Zr clad radius
656   cz 12.08786   $plate 14 outer radius
c    plate 15
657   cz 12.28598   $plate 15 inner radius
6571 cz 12.32916   $plate 15 inner Zr clad radius
658   cz 12.33170   $plate 15 inner fuel radius
659   cz 12.36726   $plate 15 outer fuel radius
6591  cz 12.36980   $plate 15 outer Zr clad radius
660   cz 12.41298   $plate 15 outer radius
c    plate 16
661   cz 12.61110   $plate 16 inner radius
6611 cz 12.65428   $plate 16 inner Zr clad radius
662   cz 12.65682   $plate 16 inner fuel radius
663   cz 12.69238   $plate 16 outer fuel radius
6631  cz 12.69492   $plate 16 outer Zr clad radius
664   cz 12.73810   $plate 16 outer radius
c    plate 17
665   cz 12.93622   $plate 17 inner radius
6651 cz 12.98321   $plate 17 inner Zr clad radius
666   cz 12.98575   $plate 17 inner fuel radius
667   cz 13.01369   $plate 17 outer fuel radius
6671  cz 13.01623   $plate 17 outer Zr clad radius
668   cz 13.06322   $plate 17 outer radius
c    plate 18
669   cz 13.26134   $plate 18 inner radius
6691 cz 13.31087   $plate 18 inner Zr clad radius
670   cz 13.31341   $plate 18 inner fuel radius
671   cz 13.33627   $plate 18 outer fuel radius
6711  cz 13.33881   $plate 18 outer Zr clad radius
672   cz 13.38834   $plate 18 outer radius
c    plate 19
673   cz 13.58646   $plate 19 inner radius
6731 cz 13.69949   $plate 19 inner Zr clad radius
674   cz 13.70203   $plate 19 inner fuel radius
```

```
675   cz 13.72489   $plate 19 outer fuel radius
6751  cz 13.72743   $plate 19 outer Zr clad radius
676   cz 13.84046   $plate 19 outer radius
c
677    cz 14.01317  $outer diameter of element
c    surfaces for sides of plate and fuel region
678   p -2.414214 -1 0 -0.212395   $outside boundary of Al plate
679   p  2.414214 -1 0 -0.212395   $outside boundary of Al plate
680   p -2.414214 -1 0 -1.453578  $inside boundary of Al plate
681   p  2.414214 -1 0 -1.453578  $inside boundary of Al plate
682   p -2.414214 -1 0 -2.08412  $plate 1 and 19 fuel meat boundary
683   p  2.414214 -1 0 -2.08412  $plate 1 and 19 fuel meat boundary
684   p -2.414214 -1 0 -2.08412  $plate 2 through 17 fuel meat boundary
685   p  2.414214 -1 0 -2.08412  $plate 2 through 17 fuel meat boundary
686   p -2.414214 -1 0 -2.08412  $plate 18 fuel meat boundary
687   p  2.414214 -1 0 -2.08412  $plate 18 fuel meat boundary
690   pz  62.8650   $top of fuel element, 49.5" total
691   pz -62.8650   $bottom of fuel element
692   pz  60.960    $top of fuel meat, 48.0" total
693   pz -60.960    $bottom of fuel meat
697   cz  7.52856   $inner radius of element
698   cz 14.00302   $outer radius of element
C     HEU SURFACE SPECIFICATIONS
c     surface cards
700    cz 7.52855
c     radius for fuel plates
c     plate 1
701    cz 7.6581    $plate 1 inner radius
702    cz 7.7343    $plate 1 fuel meat inner
703    cz 7.7851    $plate 1 fuel meat outer
704    cz 7.8613    $plate 1 outer radius
c     plate 2
705    cz 8.05942   $plate 2 inner radius
706    cz 8.09752   $plate 2 fuel meat inner
707    cz 8.14832   $plate 2 fuel meat outer
708    cz 8.18642   $plate 2 outer radius
c     plate 3
709    cz 8.38454   $plate 3 inner radius
710    cz 8.42264   $plate 3 fuel meat inner
711    cz 8.47344   $plate 3 fuel meat outer
712    cz 8.51154   $plate 3 outer radius
c     plate 4
713    cz 8.70966   $plate 4 inner radius
714    cz 8.74776   $plate 4 fuel meat inner
715    cz 8.79856   $plate 4 fuel meat outer
716    cz 8.83666   $plate 4 outer radius
c     plate 5
717    cz 9.03478   $plate 5 inner radius
718    cz 9.07288   $plate 5 fuel meat inner
719    cz 9.12368   $plate 5 fuel meat outer
720    cz 9.16178   $plate 5 outer radius
c     plate 6
721    cz 9.3599    $plate 6 inner radius
722    cz 9.398     $plate 6 fuel meat inner
723    cz 9.4488    $plate 6 fuel meat outer
724    cz 9.4869    $plate 6 outer radius
c     plate 7
725    cz 9.68502   $plate 7 inner radius
726    cz 9.72312   $plate 7 fuel meat inner
727    cz 9.77392   $plate 7 fuel meat outer
728    cz 9.81202   $plate 7 outer radius
c     plate 8
729    cz 10.01014  $plate 8 inner radius
730    cz 10.04824  $plate 8 fuel meat inner
731    cz 10.09904  $plate 8 fuel meat outer
```

```
732   cz 10.13714  $plate 8 outer radius
c     plate 9
733   cz 10.33526  $plate 9 inner radius
734   cz 10.37336  $plate 9 fuel meat inner
735   cz 10.42416  $plate 9 fuel meat outer
736   cz 10.46226  $plate 9 outer radius
c     plate 10
737   cz 10.66038  $plate 10 inner radius
738   cz 10.69848  $plate 10 fuel meat inner
739   cz 10.74928  $plate 10 fuel meat outer
740   cz 10.78738  $plate 10 outer radius
c     plate 11
741   cz 10.98550  $plate 11 inner radius
742   cz 11.02360  $plate 11 fuel meat inner
743   cz 11.07440  $plate 11 fuel meat outer
744   cz 11.11250  $plate 11 outer radius
c     plate 12
745   cz 11.31062  $plate 12 inner radius
746   cz 11.34872  $plate 12 fuel meat inner
747   cz 11.39952  $plate 12 fuel meat outer
748   cz 11.43762  $plate 12 outer radius
c     plate 13
749   cz 11.63574  $plate 13 inner radius
750   cz 11.67384  $plate 13 fuel meat inner
751   cz 11.72464  $plate 13 fuel meat outer
752   cz 11.76274  $plate 13 outer radius
c     plate 14
753   cz 11.96086  $plate 14 inner radius
754   cz 11.99896  $plate 14 fuel meat inner
755   cz 12.04976  $plate 14 fuel meat outer
756   cz 12.08786  $plate 14 outer radius
c     plate 15
757   cz 12.28598  $plate 15 inner radius
758   cz 12.32408  $plate 15 fuel meat inner
759   cz 12.37488  $plate 15 fuel meat outer
760   cz 12.41298  $plate 15 outer radius
c     plate 16
761   cz 12.61110  $plate 16 inner radius
762   cz 12.64920  $plate 16 fuel meat inner
763   cz 12.70000  $plate 16 fuel meat outer
764   cz 12.73810  $plate 16 outer radius
c     plate 17
765   cz 12.93622  $plate 17 inner radius
766   cz 12.97432  $plate 17 fuel meat inner
767   cz 13.02512  $plate 17 fuel meat outer
768   cz 13.06322  $plate 17 outer radius
c     plate 18
769   cz 13.26134  $plate 18 inner radius
770   cz 13.29944  $plate 18 fuel meat inner
771   cz 13.35024  $plate 18 fuel meat outer
772   cz 13.38834  $plate 18 outer radius
c     plate 19
773   cz 13.58646  $plate 19 inner radius
774   cz 13.68806  $plate 19 fuel meat inner
775   cz 13.73886  $plate 19 fuel meat outer
776   cz 13.84046  $plate 19 outer radius
777   cz 14.01317  $outer diameter of element
c     surfaces for sides of plate and fuel region
778   p -2.414214 -1 0 -0.212395   $outside boundary of Al plate
779   p  2.414214 -1 0 -0.212395   $outside boundary of Al plate
780   p -2.414214 -1 0 -1.453578  $inside boundary of Al plate
781   p  2.414214 -1 0 -1.453578  $inside boundary of Al plate
782   p -2.414214 -1 0 -2.747859  $plate 1 and 19 fuel meat boundary
783   p  2.414214 -1 0 -2.747859  $plate 1 and 19 fuel meat boundary
784   p -2.414214 -1 0 -2.084125  $plate 2 through 17 fuel meat boundary
```

```
785   p  2.414214 -1 0 -2.084125  $plate 2 through 17 fuel meat boundary
786   p -2.414214 -1 0 -2.216872  $plate 18 fuel meat boundary
787   p  2.414214 -1 0 -2.216872  $plate 18 fuel meat boundary
792   pz  60.960    $top of fuel meat, 48" total
793   pz -60.960    $bottom of fuel meat
797   cz  7.52856   $inner radius of element
798   cz 14.00302   $outer radius of element
160   cz  10000.    $just a big surface
c ************************************************************
100  cz   6.35                          $ compartment ID
101  cz   6.668                          $ inner Al wall
102  cz   6.718                          $ cadmium poison
103  cz   6.843                          $ outer Al wall
*110  px  65.2630                          $ storage rack
*111  px -65.2630
*112  py  44.8468
*113  py -44.8468
114  pz  100.0                            $ water reflector
115  pz -100.0
c following are (irregular) hex surface cards
120  p  1.73205081     1    0   16.3327
121  p -1.73205081     1    0  -16.3327
122  p  1.73205081     1    0  -16.3327
123  p -1.73205081     1    0   16.3327
124  py  7.62
125  py -7.62

mode n
C    WATER  dens=1.0000 g/cc  $   atm. den.:   .100284
m5     1001       6.6874E-02  $ H
      8016       3.3437E-02  $ O
      nlib=.50c
mt5   lwtr.01t
c     fuel plates
m515    92235       7.7745E-03
       92238       3.1051E-02
       92234       5.1393E-05
       92236       9.0154E-05
       42000.51c   9.6548E-03
c       42092       1.5761E-03
c       42094       9.8495E-04
c       42095       1.6967E-03
c       42096       1.7799E-03
c       42097       1.0202E-03
c       42098       2.5813E-03
c       42100       1.0319E-03
       nlib=.50c
c     HEU fuel plates
m101    92235       2.5479E-03
       92238       1.6366E-04
       92234       1.6508E-05
       92236       9.5481E-06
       13027       5.7424E-02
       nlib=.50c
m102    92235       2.5425E-03
       92238       1.6331E-04
       92234       1.6474E-05
       92236       9.5280E-06
       13027       5.7430E-02
       nlib=.50c
m103    92235       3.2098E-03
       92238       2.0617E-04
       92234       2.0797E-05
       92236       1.2029E-05
       13027       5.6628E-02
```

```
      nlib=.50c
m104   92235     3.1890E-03
       92238     2.0484E-04
       92234     2.0662E-05
       92236     1.1951E-05
       13027     5.6653E-02
      nlib=.50c
m105   92235     3.9232E-03
       92238     2.5199E-04
       92234     2.5419E-05
       92236     1.4702E-05
       13027     5.5771E-02
      nlib=.50c
m106   92235     3.9305E-03
       92238     2.5246E-04
       92234     2.5466E-05
       92236     1.4729E-05
       13027     5.5762E-02
      nlib=.50c
m107   92235     3.9302E-03
       92238     2.5245E-04
       92234     2.5465E-05
       92236     1.4728E-05
       13027     5.5762E-02
      nlib=.50c
m108   92235     3.9300E-03
       92238     2.5243E-04
       92234     2.5464E-05
       92236     1.4728E-05
       13027     5.5763E-02
      nlib=.50c
m109   92235     3.9299E-03
       92238     2.5242E-04
       92234     2.5463E-05
       92236     1.4727E-05
       13027     5.5763E-02
      nlib=.50c
m110   92235     3.9297E-03
       92238     2.5241E-04
       92234     2.5461E-05
       92236     1.4726E-05
       13027     5.5763E-02
      nlib=.50c
m111   92235     3.9295E-03
       92238     2.5240E-04
       92234     2.5461E-05
       92236     1.4726E-05
       13027     5.5763E-02
      nlib=.50c
m112   92235     3.9294E-03
       92238     2.5239E-04
       92234     2.5460E-05
       92236     1.4725E-05
       13027     5.5763E-02
      nlib=.50c
m113   92235     3.9293E-03
       92238     2.5239E-04
       92234     2.5459E-05
       92236     1.4725E-05
       13027     5.5764E-02
      nlib=.50c
m114   92235     3.9292E-03
       92238     2.5238E-04
       92234     2.5458E-05
       92236     1.4725E-05
```

```
       13027      5.5764E-02
       nlib=.50c
m115    92235      3.9342E-03
       92238      2.5270E-04
       92234      2.5491E-05
       92236      1.4743E-05
       13027      5.5758E-02
       nlib=.50c
m116    92235      3.1992E-03
       92238      2.0549E-04
       92234      2.0728E-05
       92236      1.1989E-05
       13027      5.6641E-02
       nlib=.50c
m117    92235      3.1965E-03
       92238      2.0532E-04
       92234      2.0711E-05
       92236      1.1979E-05
       13027      5.6644E-02
       nlib=.50c
m118    92235      2.5639E-03
       92238      1.6468E-04
       92234      1.6612E-05
       92236      9.6080E-06
       13027      5.7405E-02
       nlib=.50c
m119    92235      2.5362E-03
       92238      1.6291E-04
       92234      1.6433E-05
       92236      9.5044E-06
       13027      5.7438E-02
       nlib=.50c
c     material for cladding and support (Al6061)
m20    13027     5.9018E-02 $ Al (impurities less than 0.5% neglected)
      12000     6.7060e-04 $ Mg
c      12024     5.2971E-04
c      12025     6.7060E-05
c      12026     7.3833E-05
      14000     3.4820E-04 $ Si
c      14028     3.2114E-04 $ Si
c      14029     1.6261E-05
c      14030     1.0794E-05
      26000.55c 2.0430E-04 $ Fe
c      26054     1.1952E-05 $ Fe
c      26056     1.8745E-04
c      26057     4.3312E-06
c      26058     5.7205E-07
      nlib=.50c
c
m30 $ 40090      2.2179E-02
c     40091      4.8367E-03
c     40092      7.3930E-03
c     40094      7.4921E-03
c     40096      1.2070E-03
     40000.56c  4.31078E-02
     nlib=.50c
m22  13027.50c 1                                    $ aluminum
c                          RC
c
kcode  6500  1.0  55  305
c
ksrc  0.2    -2.8     0.00  -0.2    -2.8     0.0
     3.7     2.6     0.00  -3.7     2.6     0.0
     2.7    -1.1     0.00  -2.7    -1.1     0.0
     2.1    -2.6     0.00  -2.1    -2.6     0.0
```

```
    0.32     7.39     0.00 0.32     -7.39     0.00
    15.23   -15.25     0.00 -15.23   15.25     0.00
   -15.23   -15.25     0.00  15.23   15.25     0.00
   -28.95    -7.12     0.00  28.95    7.12     0.00
    28.95    -7.12     0.00 -28.95    7.12     0.00
print
```

Sample Problem 4. This is case wetbox43_05b of Table 17, a Mark IV element case

```
ATR Fresh Fuel Shipping Container - Single Element Type
c   box: actual length
c       all steel tube, body & walls included
c       6" OD SS-304 inner tube body included
c       3/16" SS-304 outer wall included
c       1/4" & 7/8" end walls included
c       no insulation
c   array is infinite array of dry boxes
c LEE: note this uses average "B" values
c     cell cards for ATR assembly
601    5 0.100311         600 -601 -680 -681              u=1  imp:n=1
602    993 6.188754E-02   602 -603 -682 -683 -692 693     u=1  imp:n=1
603    20  6.024110E-02   601 -604 -680 -681 #602         u=1  imp:n=1
604    5 0.100311         604 -605 -680 -681              u=1  imp:n=1
c     plate 2
605    993 6.188754E-02   606 -607 -684 -685 -692 693     u=1  imp:n=1
606    20  6.024110E-02   605 -608 -680 -681 #605         u=1  imp:n=1
607    5 0.100311         608 -609 -680 -681              u=1  imp:n=1
c     plate 3
608    993 6.188754E-02   610 -611 -684 -685 -692 693     u=1  imp:n=1
609    20  6.024110E-02   609 -612 -680 -681 #608         u=1  imp:n=1
610    5 0.100311         612 -613 -680 -681              u=1  imp:n=1
c    plate 4
611    993 6.188754E-02   614 -615 -684 -685 -692 693     u=1  imp:n=1
612    20  6.024110E-02   613 -616 -680 -681 #611         u=1  imp:n=1
613    5 0.100311         616 -617 -680 -681              u=1  imp:n=1
c    plate 5
614    993 6.188754E-02   618 -619 -684 -685 -692 693     u=1  imp:n=1
615    20  6.024110E-02   617 -620 -680 -681 #614         u=1  imp:n=1
616    5 0.100311         620 -621 -680 -681              u=1  imp:n=1
c    plate 6
617   993 6.188754E-02    622 -623 -684 -685 -692 693     u=1  imp:n=1
618   20  6.024110E-02    621 -624 -680 -681 #617         u=1  imp:n=1
619   5 0.100311          624 -625 -680 -681              u=1  imp:n=1
c    plate 7
620   993 6.188754E-02    626 -627 -684 -685 -692 693     u=1  imp:n=1
621   20  6.024110E-02    625 -628 -680 -681  #620        u=1  imp:n=1
622   5 0.100311          628 -629 -680 -681              u=1  imp:n=1
c    plate 8
623   993 6.188754E-02    630 -631 -684 -685 -692 693     u=1  imp:n=1
624   20  6.024110E-02    629 -632 -680 -681 #623         u=1  imp:n=1
625   5 0.100311          632 -633 -680 -681              u=1  imp:n=1
c    plate 9
626   993 6.188754E-02    634 -635 -684 -685 -692 693     u=1  imp:n=1
627   20  6.024110E-02    633 -636 -680 -681 #626         u=1  imp:n=1
628   5 0.100311          636 -637 -680 -681              u=1  imp:n=1
c    plate 10
629  993 6.188754E-02     638 -639 -684 -685 -692 693     u=1  imp:n=1
630  20  6.024110E-02     637 -640 -680 -681 #629         u=1  imp:n=1
631   5 0.100311          640 -641 -680 -681              u=1  imp:n=1
c    plate 11
632  993 6.188754E-02     642 -643  -684 -685 -692 693    u=1  imp:n=1
633  20  6.024110E-02     641 -644 -680 -681  #632        u=1  imp:n=1
634   5 0.100311          644 -645 -680 -681              u=1  imp:n=1
```

```
c    plate 12
635   993 6.188754E-02    646 -647 -684 -685 -692 693     u=1  imp:n=1
636   20  6.024110E-02    645 -648 -680 -681 #635         u=1  imp:n=1
637   5 0.100311          648 -649 -680 -681              u=1  imp:n=1
c    plate 13
638   993 6.188754E-02    650 -651 -684 -685 -692 693     u=1  imp:n=1
639   20  6.024110E-02    649 -652 -680 -681 #638         u=1  imp:n=1
640   5 0.100311          652 -653 -680 -681              u=1  imp:n=1
c    plate 14
641   993 6.188754E-02    654 -655 -684 -685 -692 693     u=1  imp:n=1
642   20  6.024110E-02    653 -656 -680 -681  #641        u=1  imp:n=1
643   5 0.100311          656 -657 -680 -681              u=1  imp:n=1
c    plate 15
644   993 6.188754E-02    658 -659 -684 -685 -692 693     u=1  imp:n=1
645   20  6.024110E-02    657 -660 -680 -681 #644         u=1  imp:n=1
646   5 0.100311          660 -661 -680 -681              u=1  imp:n=1
c    plate 16
647   993 6.188754E-02    662 -663 -684 -685 -692 693     u=1  imp:n=1
648   20  6.024110E-02    661 -664 -680 -681 #647         u=1  imp:n=1
649   5 0.100311          664 -665 -680 -681              u=1  imp:n=1
c    plate 17
650   993 6.188754E-02    666 -667 -684 -685 -692 693     u=1  imp:n=1
651   20  6.024110E-02    665 -668 -680 -681  #650        u=1  imp:n=1
652   5 0.100311          668 -669 -680 -681              u=1  imp:n=1
c    plate 18
653   993 6.188754E-02    670 -671 -686 -687 -692 693     u=1  imp:n=1
654   20  6.024110E-02    669 -672 -680 -681 #653         u=1  imp:n=1
655   5 0.100311          672 -673 -680 -681              u=1  imp:n=1
c    plate 19
656   993 6.188754E-02    674 -675 -682 -683 -692 693     u=1  imp:n=1
657   20  6.024110E-02    673 -676 -680 -681 #656         u=1  imp:n=1
658   5 0.100311          676 -677 -680 -681              u=1  imp:n=1
c    side plates
659   20 6.024110E-02    (-600:677:680:681)               u=1  imp:n=1
c    cut-out elements and move
61    0    697 -698 -678 -679 -690 691 fill=1
                    trcl=(0  -10.5  0)      u=2  imp:n=1
62   5 0.100311  -100 -101   102  #61           u=2  imp:n=1
63  24   8.625-2 -103 -104   105  (100:101:-102)  u=2  imp:n=1 $ FFSC inner tube
64  25   2.863-3 -110 -111   112  (103:104:-105)  u=2  imp:n=1 $ FFSC thermal insulation
65   5 0.100311   110:111:-112                  u=2  imp:n=1
66   5 0.100311  -140  141  -142  143 -111  112
                                      fill=2 imp:n=1
67  24   8.625-2 -150  151  -152  153 -154  155               $ FFSC
           (140:-141:142:-143:111:-112) imp:n=1
68   0          150:-151:152:-153:154:-155  imp:n=0

c ****************************************************************
C    SURFACE SPECIFICATIONS
c    surface cards
600    cz 7.52855
c    radius for fuel plates
c    plate 1
601    cz 7.6581    $plate 1 inner radius
602    cz 7.7343    $plate 1 fuel meat inner
603    cz 7.7851    $plate 1 fuel meat outer
604    cz 7.8613    $plate 1 outer radius
c    plate 2
605    cz 8.05942   $plate 2 inner radius
606    cz 8.09752   $plate 2 fuel meat inner
607    cz 8.14832   $plate 2 fuel meat outer
608    cz 8.18642   $plate 2 outer radius
c    plate 3
609    cz 8.38454   $plate 3 inner radius
610    cz 8.42264   $plate 3 fuel meat inner
```

```
611    cz 8.47344   $plate 3 fuel meat outer
612    cz 8.51154   $plate 3 outer radius
c    plate 4
613    cz 8.70966   $plate 4 inner radius
614    cz 8.74776   $plate 4 fuel meat inner
615    cz 8.79856   $plate 4 fuel meat outer
616    cz 8.83666   $plate 4 outer radius
c    plate 5
617    cz 9.03478   $plate 5 inner radius
618    cz 9.07288   $plate 5 fuel meat inner
619    cz 9.12368   $plate 5 fuel meat outer
620    cz 9.16178   $plate 5 outer radius
c    plate 6
621    cz 9.3599    $plate 6 inner radius
622    cz 9.398     $plate 6 fuel meat inner
623    cz 9.4488    $plate 6 fuel meat outer
624    cz 9.4869    $plate 6 outer radius
c    plate 7
625    cz 9.68502   $plate 7 inner radius
626    cz 9.72312   $plate 7 fuel meat inner
627    cz 9.77392   $plate 7 fuel meat outer
628    cz 9.81202   $plate 7 outer radius
c    plate 8
629    cz 10.01014  $plate 8 inner radius
630    cz 10.04824  $plate 8 fuel meat inner
631    cz 10.09904  $plate 8 fuel meat outer
632    cz 10.13714  $plate 8 outer radius
c    plate 9
633    cz 10.33526  $plate 9 inner radius
634    cz 10.37336  $plate 9 fuel meat inner
635    cz 10.42416  $plate 9 fuel meat outer
636    cz 10.46226  $plate 9 outer radius
c    plate 10
637    cz 10.66038  $plate 10 inner radius
638    cz 10.69848  $plate 10 fuel meat inner
639    cz 10.74928  $plate 10 fuel meat outer
640    cz 10.78738  $plate 10 outer radius
c    plate 11
641    cz 10.98550  $plate 11 inner radius
642    cz 11.02360  $plate 11 fuel meat inner
643    cz 11.07440  $plate 11 fuel meat outer
644    cz 11.11250  $plate 11 outer radius
c    plate 12
645    cz 11.31062  $plate 12 inner radius
646    cz 11.34872  $plate 12 fuel meat inner
647    cz 11.39952  $plate 12 fuel meat outer
648    cz 11.43762  $plate 12 outer radius
c    plate 13
649    cz 11.63574  $plate 13 inner radius
650    cz 11.67384  $plate 13 fuel meat inner
651    cz 11.72464  $plate 13 fuel meat outer
652    cz 11.76274  $plate 13 outer radius
c    plate 14
653    cz 11.96086  $plate 14 inner radius
654    cz 11.99896  $plate 14 fuel meat inner
655    cz 12.04976  $plate 14 fuel meat outer
656    cz 12.08786  $plate 14 outer radius
c    plate 15
657    cz 12.28598  $plate 15 inner radius
658    cz 12.32408  $plate 15 fuel meat inner
659    cz 12.37488  $plate 15 fuel meat outer
660    cz 12.41298  $plate 15 outer radius
c    plate 16
661    cz 12.61110  $plate 16 inner radius
662    cz 12.64920  $plate 16 fuel meat inner
```

```
663    cz 12.70000  $plate 16 fuel meat outer
664    cz 12.73810  $plate 16 outer radius
c     plate 17
665    cz 12.93622  $plate 17 inner radius
666    cz 12.97432  $plate 17 fuel meat inner
667    cz 13.02512  $plate 17 fuel meat outer
668    cz 13.06322  $plate 17 outer radius
c     plate 18
669    cz 13.26134  $plate 18 inner radius
670    cz 13.29944  $plate 18 fuel meat inner
671    cz 13.35024  $plate 18 fuel meat outer
672    cz 13.38834  $plate 18 outer radius
c     plate 19
673    cz 13.58646  $plate 19 inner radius
674    cz 13.68806  $plate 19 fuel meat inner
675    cz 13.73886  $plate 19 fuel meat outer
676    cz 13.84046  $plate 19 outer radius
677    cz 14.01317  $outer diameter of element
c     surfaces for sides of plate and fuel region
678   p -2.414214 -1 0 -0.212395  $outside boundary of Al plate
679   p  2.414214 -1 0 -0.212395  $outside boundary of Al plate
680   p -2.414214 -1 0 -1.453578  $inside boundary of Al plate
681   p  2.414214 -1 0 -1.453578  $inside boundary of Al plate
682   p -2.414214 -1 0 -2.747859  $plate 1 and 19 fuel meat boundary
683   p  2.414214 -1 0 -2.747859  $plate 1 and 19 fuel meat boundary
684   p -2.414214 -1 0 -2.084125  $plate 2 through 17 fuel meat boundary
685   p  2.414214 -1 0 -2.084125  $plate 2 through 17 fuel meat boundary
686   p -2.414214 -1 0 -2.216872  $plate 18 fuel meat boundary
687   p  2.414214 -1 0 -2.216872  $plate 18 fuel meat boundary
690   pz  62.8650   $top of fuel element, 49.5" total
691   pz -62.8650   $bottom of fuel element
692   pz  60.960    $top of fuel meat, 48" total
693   pz -60.960    $bottom of fuel meat
697   cz  7.52856   $inner radius of element
698   cz 14.00302   $outer radius of element
160   cz  10000.    $just a big surface
c ***************************************************************
1    p   -2.4142    -1   0   -0.2490         $ left side plate  - outside
3    p    2.4142    -1   0   -0.2490         $ right side plate - outside
11   cz   7.529                              $ fuel element IR
88   cz  14.0155                             $ 20th water region
89   pz  60.96                               $ top    of fuel element
90   pz -60.96                               $ bottom of fuel element
c ***************************************************************
c ************    Fresh Fuel Shipping Container    *************
c ***************************************************************
100  cz   7.3152                             $ FFSC body - 6" OD tube
101  pz  86.2076                             $          - 0.12" wall
102  pz -86.2076
103  cz   7.620
104  pz  87.1601
105  pz -87.1601
110  cz  10.160                              $ thermal insulation
111  pz  89.7001
112  pz -89.7001
140  px   9.68375                            $ FFSC outer wall
141  px  -9.68375
142  py   9.68375
143  py  -9.68375
*150  px  10.160                             $ FFSC outer dimensions
*151  px -10.160
*152  py  10.160
*153  py -10.160
*154  pz  90.3351
*155  pz -91.9226
```

```
mode n
C    WATER  dens=1.0000 g/cc  $   atm. den.:   .100284
m5    1001      6.6874E-02  $ H
      8016      3.3437E-02  $ O
      nlib=.50c
mt5   lwtr.01t
c     fuel plates
m993  92235.50c  3.1849E-03  92234.50c  2.0636E-05  92236.50c  1.1935E-05  $ U-235=990.0, 93%
     92238.50c  2.0457E-04   8016.50c  9.1255E-03  13027.50c  4.9340E-02 $ 93%
c       nlib=.50c
c     material for cladding and support (Al6061)
m20    13027     5.9018E-02 $ Al (impurities less than 0.5% neglected)
      12000     6.7060e-04 $ Mg
c      12024     5.2971E-04
c      12025     6.7060E-05
c      12026     7.3833E-05
      14000     3.4820E-04 $ Si
c      14028     3.2114E-04 $ Si
c      14029     1.6261E-05
c      14030     1.0794E-05
      26000.55c 2.0430E-04 $ Fe
c      26054     1.1952E-05 $ Fe
c      26056     1.8745E-04
c      26057     4.3312E-06
c      26058     5.7205E-07
      nlib=.50c
c                          RC
m24  26000.55c 5.936e-2   14000.50c 1.743e-2   28000.50c 0.772e-2     $ SS-304
    25055.50c 0.174e-2
m25  13027.50c 5.6780e-4  14000.50c 4.8166e-4   8016.50c 1.8139e-3    $ thermal insulation
c
kcode  6500  1.0  55  305
c
ksrc  0.2    -2.8     0.00  -0.2    -2.8     0.0
     3.7     2.6     0.00  -3.7     2.6     0.0
     2.7    -1.1     0.00  -2.7    -1.1     0.0
     2.1    -2.6     0.00  -2.1    -2.6     0.0
print
```

Appendix C: Engineering Inputs

A copy of the Engineering Work Request is included:

Engineering Work Request

Plan ID: 4441

CC'd To: J.Taylor@inl.gov,

Attachments:

Employee Information (all fields in this section are required)**:**

1. S Number:	110081	**2. Requester's Name:**	Evan Nef	**3. Email:**	Evan.Nef@inl.gov
4. Mail Stop:	3425	**5. Work Phone:**	(208)526-3621	**6. Location:**	REC
7. Home Org:	W120	**8. Work Org:**	W120	**9. Work Mgr:**	Langenwalter, Tracy A
10.Submitted by:	Evan Nef	**11.Phone Number:**	(208)526-3621	**12.Submitted Date:**	08/08/2013

Project Information:

13. Project Title:	ATR LEU Conversion Criticality Pre-Conceptual Analyses
14. Project Number:	
15. Charge Number:	101820132
16. Requested Service:	Calculation or Analysis
17. Work Area:	REC
18. Quality Level: (required field)	2
19. Date of Request:	08/08/2013
20. System Engineer or Contact:	Nef, Evan C
21. Estimated Cost:	50000
22. Requested Start Date:	08/08/2013
23. Requested Finish Date:	09/30/2013

24. Work Scope: (Upon what is this effort based? Design Criteria, Conceptual Design Report, TFRs, Other)
Based on the "LEU ATR Fuel Criticality Safety Review" by Leland M. Montierth dated August 2013, re-evaluate the identified CSE's for use with the proposed LEU fuel elements Enhanced LEU Fuel (ELF) as identified in TEV-1792. Evaluation to identify if the existing CSE is sufficient for use with the ELF element, or if changes are required and what analyses are needed to justify the use of the ELF element.

25. Identify Potential Problems or Safety Issues:
None

26. Reference Documents:(What Specific Documents, other than DOE 420, Engineering Standards (STD-139), etc., effect this effort?)
INL engineering standards and LWP's. QLD-ATR-Comp-211 & 212.

27. Deliverables: (What products are required from this effort? Please be specific.)
ECAR summarizing the evaluations.

28. Additional Comments:
Have been coordinating this work with Todd Taylor--project would prefer to continue using his staff for this activity. Please perform technical check and peer reviews on the ECAR for additional level of rigor.

Appendix D: Fuel Element Array Results

The value of $k_{eff} + 2\sigma$ in each set that is highlighted in yellow is the most reactive value.

The results in Table D-1are for the HEU ATR elements. The water moderated and reflected single element results are given in the first set of the table. The comparison case (from Reference 17) results are given in the second set. Results for the configuration array shown in Figure 4 with different spacings are given in the third set of the table.

Table D-1. Results for Mark VII HEU ATR Element Configurations

Case (MCNP Input File)	Description	$k_{eff} \pm \sigma$	$k_{eff} + 2\sigma$
A single water moderated and reflected ATR element			
heu_1a	Single water moderated and reflected ATR element	0.4481 ± 0.0006	0.4492
An array of 7 ATR elements like Configuration A in Figure 3			
heu_7a	Elements are water moderated and reflected	0.9904 ± 0.0007	0.9917
An array of 7 ATR elements to investigate element spacing, see Figure 4			
heu_7b	Adjacent elements are touching; see Figure 4a	0.9653 ± 0.0007	0.9666
heu_7b_.2	Previous case, but spacing between elements is 0.2 cm	0.9775 ± 0.0007	0.9789
heu_7b_.4	Case heu_7b, but spacing between elements is 0.4 cm	0.9841 ± 0.0007	0.9855
heu_7b_.6	Case heu_7b, but spacing between elements is 0.6 cm	0.9897 ± 0.0006	0.9910
heu_7b_.8	Case heu_7b, but spacing between elements is 0.8 cm	0.9957 ± 0.0006	0.9969
heu_7b_.9	Case heu_7b, but spacing between elements is 0.9 cm	0.9955 ± 0.0007	0.9969
heu_7b_1	Previous case, but spacing is 1.0 cm; see Figure 4b	0.9957 ± 0.0006	0.9969
heu_7b_1.1	Case heu_7b, but spacing between elements is 1.1 cm	0.9960 ± 0.0007	0.9975
heu_7b_1.2	Case heu_7b, but spacing between elements is 1.2 cm	0.9961 ± 0.0006	0.9974
heu_7b_1.4	Case heu_7b, but spacing between elements is 1.4 cm	0.9932 ± 0.0007	0.9946
heu_7b_1.6	Case heu_7b, but spacing between elements is 1.6 cm	0.9892 ± 0.0007	0.9905
heu_7b_1.8	Case heu_7b, but spacing between elements is 1.8 cm	0.9833 ± 0.0006	0.9846
heu_7b_2	Case heu_7b, but spacing between elements is 2.0 cm	0.9771 ± 0.0006	0.9783
heu_7b_2.5	Case heu_7b, but spacing between elements is 2.5 cm	0.9581 ± 0.0006	0.9593
heu_7b_3.0	Case heu_7b, but spacing between elements is 3.0 cm	0.9291 ± 0.0006	0.9303
heu_7b_3.5	Case heu_7b, but spacing between elements is 3.5 cm	0.8980 ± 0.0006	0.8992
heu_7b_4.0	Case heu_7b, but spacing between elements is 4.0 cm	0.8645 ± 0.0006	0.8658
heu_7b_4.5	Case heu_7b, but spacing between elements is 4.5 cm	0.8304 ± 0.0006	0.8316
heu_7b_5.0	Case heu_7b, but spacing between elements is 5.0 cm	0.7953 ± 0.0006	0.7964
heu_7b_5.5	Case heu_7b, but spacing between elements is 5.5 cm	0.7630 ± 0.0006	0.7642
heu_7b_6.0	Case heu_7b, but spacing between elements is 6.0 cm	0.7326 ± 0.0006	0.7338

0.4492 0.4492

Results for the array configuration shown in Figure 5 with different spacings are given in Table D-2.

Table D-2. Results for Mark VII HEU ATR Elements in Configurations Shown in Figure 5

Case (MCNP Input File)	Description	$k_{eff} \pm \sigma$	$k_{eff} + 2\sigma$
Elements in configuration similar to Configuration B of Table 6 with varying spacing			
heu_7c_ma	Elements are at closest approach, see Figure 5a	0.9859 ± 0.0006	0.9871
heu_7c_0	Similar to previous case, but center element is moved upwards towards the center, and radius of outer ring is increased slightly	0.9968 ± 0.0006	0.9981
heu_7c_0.1	Case heu_7c_0, but outer radius is increased by 0.1 cm	0.9973 ± 0.0007	0.9986
heu_7c_0.2	Case heu_7c_0, but outer radius is increased by 0.2 cm, see Figure 5b	0.9977 ± 0.0007	0.9991
heu_7c_0.3	Case heu_7c_0, but outer radius is increased by 0.3 cm	0.9954 ± 0.0006	0.9967
heu_7c_0.4	Case heu_7c_0, but outer radius is increased by 0.4 cm	0.9955 ± 0.0006	0.9968
heu_7c_0.6	Case heu_7c_0, but outer radius is increased by 0.6 cm	0.9922 ± 0.0006	0.9935
heu_7c_0.8	Case heu_7c_0, but outer radius is increased by 0.8 cm	0.9868 ± 0.0007	0.9881
heu_7c_1.0	Case heu_7c_0, but outer radius is increased by 1.0 cm	0.9813 ± 0.0007	0.9827
heu_7c_1.2	Case heu_7c_0, but outer radius is increased by 1.2 cm	0.9733 ± 0.0006	0.9745
heu_7c_1.5	Case heu_7c_0, but outer radius is increased by 1.5 cm	0.9628 ± 0.0006	0.9641
heu_7c_2.0	Case heu_7c_0, but outer radius is increased by 2.0 cm	0.9377 ± 0.0007	0.9391
heu_7c_2.5	Case heu_7c_0, but outer radius is increased by 2.5 cm	0.9083 ± 0.0006	0.9095
heu_7c_3.0	Case heu_7c_0, but outer radius is increased by 3.0 cm	0.8781 ± 0.0006	0.8793
heu_7c_3.5	Case heu_7c_0, but outer radius is increased by 3.5 cm	0.8451 ± 0.0006	0.8463
heu_7c_4.0	Case heu_7c_0, but outer radius is increased by 4.0 cm	0.8119 ± 0.0006	0.8131
heu_7c_4.5	Case heu_7c_0, but outer radius is increased by 4.5 cm	0.7809 ± 0.0006	0.7821
heu_7c_5.0	Case heu_7c_0, but outer radius is increased by 5.0 cm	0.7520 ± 0.0006	0.7532
heu_7c_5.5	Case heu_7c_0, but outer radius is increased by 5.5 cm	0.7223 ± 0.0006	0.7235
heu_7c_6.0	Case heu_7c_0, but outer radius is increased by 6.0 cm	0.6964 ± 0.0006	0.6975

Results similar to those in Table D-1 and Table D-2 are given for Mark IV elements in Table D-3 and Table D-4

Table D-3. Results for Mark IV HEU ATR Element Configurations

Case (MCNP Input File)	Description	$k_{eff} \pm \sigma$	$k_{eff} + 2\sigma$
A single water moderated and reflected ATR element			
heu43_1a	Single water moderated and reflected ATR element	0.4469 ± 0.0006	0.4481
An array of 7 ATR elements like Configuration A in Figure 3			
heu43_7a	Elements are water moderated and reflected	0.9880 ± 0.0007	0.9893
An array of 7 ATR elements to investigate element spacing, see Figure 4			
heu43_7b	Adjacent elements are touching; see Figure 4a	0.9646 ± 0.0007	0.9661
heu43_7b_.2	Previous case, but spacing between elements is 0.2 cm	0.9738 ± 0.0006	0.9750
heu43_7b_.4	Case heu43_7b, but spacing between elements is 0.4 cm	0.9828 ± 0.0006	0.9840
heu43_7b_.6	Case heu43_7b, but spacing between elements is 0.6 cm	0.9890 ± 0.0007	0.9904

Case (MCNP Input File)	Description	$k_{eff} \pm \sigma$	$k_{eff} + 2\sigma$
heu43_7b_.8	Case heu43_7b, but spacing between elements is 0.8 cm	0.9926 ± 0.0006	0.9938
heu43_7b_.9	Case heu43_7b, but spacing between elements is 0.9 cm	0.9929 ± 0.0007	0.9943
heu43_7b_1	Case heu43_7b, but spacing between elements is 1.0 cm	0.9937 ± 0.0007	0.9950
heu43_7b_1.1	Case heu43_7b, but spacing between elements is 1.1 cm	0.9949 ± 0.0006	0.9961
heu43_7b_1.2	Case heu43_7b, but spacing between elements is 1.2 cm	0.9946 ± 0.0007	0.9959
heu43_7b_1.4	Case heu43_7b, but spacing between elements is 1.4 cm	0.9913 ± 0.0006	0.9926
heu43_7b_1.6	Case heu43_7b, but spacing between elements is 1.6 cm	0.9866 ± 0.0007	0.9880
heu43_7b_1.8	Case heu43_7b, but spacing between elements is 1.8 cm	0.9834 ± 0.0006	0.9846
heu43_7b_2	Case heu43_7b, but spacing between elements is 2.0 cm	0.9741 ± 0.0007	0.9754
heu43_7b_2.5	Case heu43_7b, but spacing between elements is 2.5 cm	0.9567 ± 0.0007	0.9580
heu43_7b_3.0	Case heu43_7b, but spacing between elements is 3.0 cm	0.9283 ± 0.0006	0.9295
heu43_7b_3.5	Case heu43_7b, but spacing between elements is 3.5 cm	0.8963 ± 0.0007	0.8976
heu43_7b_4.0	Case heu43_7b, but spacing between elements is 4.0 cm	0.8636 ± 0.0006	0.8648
heu43_7b_4.5	Case heu43_7b, but spacing between elements is 4.5 cm	0.8289 ± 0.0007	0.8302
heu43_7b_5.0	Case heu43_7b, but spacing between elements is 5.0 cm	0.7963 ± 0.0006	0.7976
heu43_7b_5.5	Case heu43_7b, but spacing between elements is 5.5 cm	0.7620 ± 0.0006	0.7631
heu43_7b_6.0	Case heu43_7b, but spacing between elements is 6.0 cm	0.7314 ± 0.0006	0.7327

Table D-4. Results for Mark IV HEU ATR Elements in Configurations Shown in Figure 5

Case (MCNP Input File)	Description	$k_{eff} \pm \sigma$	$k_{eff} + 2\sigma$
Elements in configuration similar to Configuration B of Table 6 with varying spacing			
heu43_7c_ma	Elements are at closest approach, see Figure 5a	0.9851 ± 0.0007	0.9865
heu43_7c_0	Similar to previous case, but center element is moved upwards towards the center, and radius of outer ring is increased slightly	0.9958 ± 0.0007	0.9972
heu43_7c_0.1	Case heu43_7c_0, but outer radius is increased by 0.1 cm	0.9959 ± 0.0007	0.9972
heu43_7c_0.2	Case heu43_7c_0, but outer radius is increased by 0.2 cm, see Figure 5b	0.9953 ± 0.0007	0.9966
heu43_7c_0.3	Case heu43_7c_0, but outer radius is increased by 0.3 cm	0.9943 ± 0.0007	0.9956
heu43_7c_0.4	Case heu43_7c_0, but outer radius is increased by 0.4 cm	0.9939 ± 0.0007	0.9952
heu43_7c_0.6	Case heu43_7c_0, but outer radius is increased by 0.6 cm	0.9902 ± 0.0007	0.9916
heu43_7c_0.8	Case heu43_7c_0, but outer radius is increased by 0.8 cm	0.9864 ± 0.0007	0.9877
heu43_7c_1.0	Case heu43_7c_0, but outer radius is increased by 1.0 cm	0.9800 ± 0.0007	0.9814
heu43_7c_1.2	Case heu43_7c_0, but outer radius is increased by 1.2 cm	0.9721 ± 0.0007	0.9734
heu43_7c_1.5	Case heu43_7c_0, but outer radius is increased by 1.5 cm	0.9598 ± 0.0007	0.9611
heu43_7c_2.0	Case heu43_7c_0, but outer radius is increased by 2.0 cm	0.9364 ± 0.0006	0.9376
heu43_7c_2.5	Case heu43_7c_0, but outer radius is increased by 2.5 cm	0.9058 ± 0.0007	0.9071
heu43_7c_3.0	Case heu43_7c_0, but outer radius is increased by 3.0 cm	0.8764 ± 0.0007	0.8777
heu43_7c_3.5	Case heu43_7c_0, but outer radius is increased by 3.5 cm	0.8436 ± 0.0006	0.8448
heu43_7c_4.0	Case heu43_7c_0, but outer radius is increased by 4.0 cm	0.8112 ± 0.0006	0.8125
heu43_7c_4.5	Case heu43_7c_0, but outer radius is increased by 4.5 cm	0.7799 ± 0.0006	0.7812
heu43_7c_5.0	Case heu43_7c_0, but outer radius is increased by 5.0 cm	0.7489 ± 0.0006	0.7501

heu43_7c_5.5	Case heu43_7c_0, but outer radius is increased by 5.5 cm	0.7224 ± 0.0006	0.7236
heu43_7c_6.0	Case heu43_7c_0, but outer radius is increased by 6.0 cm	0.6944 ± 0.0006	0.6956

Results similar to those given in Table D-1 and Table D-2 are given for the nominal and thicker fuel meat U-10Mo ELF elements in Table D-5 and Table D-6, respectively.

Table D-5. Results for Nominal Fuel Meat Thickness U-10Mo ELF Element Configurations

Case (MCNP Input File)	Description	$k_{eff} \pm \sigma$	$k_{eff} + 2\sigma$
A single water moderated and reflected ATR ELF element			
leub_1a	Single water moderated and reflected ATR Mod 0.1 element	0.4561 ± 0.0006	0.4572
l.10_1a	Single water moderated and reflected ATR Mk1A element	0.4642 ± 0.0005	0.4653
l.11_1a	Single water moderated and reflected ATR Mk1B element	0.4645 ± 0.0005	0.4656
An array of 7 ELF elements similar to Configuration A in Figure 3			
leub_7a	Mod 0.1 elements are water moderated and reflected	0.9626 ± 0.0006	0.9638
l.10_7a	Mk1A elements are water moderated and reflected	0.9717 ± 0.0006	0.9730
l.11_7a	Mk1B elements are water moderated and reflected	0.9734 ± 0.0006	0.9747
An array of 7 Mod 0.1 elements to investigate element spacing, see Figure 4			
leub_7b	Adjacent elements are touching; see Figure 4a	0.9265 ± 0.0007	0.9278
leub_7b_.2	Previous case, but spacing between elements is 0.2 cm	0.9399 ± 0.0007	0.9414
leub_7b_.4	Case leub_7b, but spacing between elements is 0.4 cm	0.9504 ± 0.0007	0.9517
leub_7b_.6	Case leub_7b, but spacing between elements is 0.6 cm	0.9581 ± 0.0006	0.9593
leub_7b_.8	Case leub_7b, but spacing between elements is 0.8 cm	0.9641 ± 0.0006	0.9653
leub_7b_.9	Case leub_7b, but spacing between elements is 0.9 cm	0.9666 ± 0.0006	0.9679
leub_7b_1	Case leub_7b, but spacing between elements is 1.0 cm	0.9699 ± 0.0006	0.9711
leub_7b_1.1	Case leub_7b, but spacing between elements is 1.1 cm	0.9711 ± 0.0006	0.9724
leub_7b_1.2	Case leub_7b, but spacing between elements is 1.2 cm	0.9723 ± 0.0007	0.9736
leub_7b_1.4	Case leub_7b, but spacing between elements is 1.4 cm	0.9725 ± 0.0006	0.9737
leub_7b_1.6	Case leub_7b, but spacing between elements is 1.6 cm	0.9702 ± 0.0006	0.9715
leub_7b_1.8	Case leub_7b, but spacing between elements is 1.8 cm	0.9689 ± 0.0006	0.9702
leub_7b_2	Case leub_7b, but spacing between elements is 2.0 cm	0.9635 ± 0.0007	0.9648
leub_7b_2.5	Case leub_7b, but spacing between elements is 2.5 cm	0.9455 ± 0.0006	0.9467
leub_7b_3.0	Case leub_7b, but spacing between elements is 3.0 cm	0.9226 ± 0.0006	0.9239
leub_7b_3.5	Case leub_7b, but spacing between elements is 3.5 cm	0.8940 ± 0.0006	0.8952
leub_7b_4.0	Case leub_7b, but spacing between elements is 4.0 cm	0.8637 ± 0.0006	0.8650
leub_7b_4.5	Case leub_7b, but spacing between elements is 4.5 cm	0.8310 ± 0.0006	0.8322
leub_7b_5.0	Case leub_7b, but spacing between elements is 5.0 cm	0.7986 ± 0.0006	0.7998
leub_7b_5.5	Case leub_7b, but spacing between elements is 5.5 cm	0.7666 ± 0.0006	0.7678
leub_7b_6.0	Case leub_7b, but spacing between elements is 6.0 cm	0.7359 ± 0.0006	0.7372
An array of 7 Mk1A elements to investigate element spacing, see Figure 4			
l.10_7b	Adjacent elements are touching; see Figure 4a	0.9340 ± 0.0007	0.93537

Case (MCNP Input File)	Description	$k_{eff} \pm \sigma$	$k_{eff} + 2\sigma$
I.10_7b_.2	Previous case, but spacing between elements is 0.2 cm	0.9466 ± 0.0007	0.9480
I.10_7b_.4	Case I.10_7b, but spacing between elements is 0.4 cm	0.9586 ± 0.0007	0.9600
I.10_7b_.6	Case I.10_7b, but spacing between elements is 0.6 cm	0.9667 ± 0.0006	0.9680
I.10_7b_.8	Case I.10_7b, but spacing between elements is 0.8 cm	0.9747 ± 0.0007	0.9761
I.10_7b_.9	Case I.10_7b, but spacing between elements is 0.9 cm	0.9770 ± 0.0007	0.9783
I.10_7b_1	Case I.10_7b, but spacing between elements is 1.0 cm	0.9788 ± 0.0007	0.9802
I.10_7b_1.1	Case I.10_7b, but spacing between elements is 1.1 cm	0.9817 ± 0.0007	0.9830
I.10_7b_1.2	Case I.10_7b, but spacing between elements is 1.2 cm	0.9818 ± 0.0007	0.9831
I.10_7b_1.4	Case I.10_7b, but spacing between elements is 1.4 cm	0.9832 ± 0.0007	0.9845
I.10_7b_1.6	Case I.10_7b, but spacing between elements is 1.6 cm	0.9819 ± 0.0006	0.9831
I.10_7b_1.8	Case I.10_7b, but spacing between elements is 1.8 cm	0.9789 ± 0.0006	0.9801
I.10_7b_2	Case I.10_7b, but spacing between elements is 2.0 cm	0.9753 ± 0.0006	0.9765
I.10_7b_2.5	Case I.10_7b, but spacing between elements is 2.5 cm	0.9571 ± 0.0007	0.9584
I.10_7b_3.0	Case I.10_7b, but spacing between elements is 3.0 cm	0.9349 ± 0.0006	0.9361
I.10_7b_3.5	Case I.10_7b, but spacing between elements is 3.5 cm	0.9069 ± 0.0006	0.9081
I.10_7b_4.0	Case I.10_7b, but spacing between elements is 4.0 cm	0.8759 ± 0.0006	0.8771
I.10_7b_4.5	Case I.10_7b, but spacing between elements is 4.5 cm	0.8424 ± 0.0006	0.8436
I.10_7b_5.0	Case I.10_7b, but spacing between elements is 5.0 cm	0.8100 ± 0.0006	0.8113
I.10_7b_5.5	Case I.10_7b, but spacing between elements is 5.5 cm	0.7795 ± 0.0006	0.7808
I.10_7b_6.0	Case I.10_7b, but spacing between elements is 6.0 cm	0.7482 ± 0.0006	0.7495
An array of 7 Mk1B elements to investigate element spacing, see Figure 4			
I.11_7b	Adjacent elements are touching; see Figure 4a	0.9329 ± 0.0007	0.9342
I.11_7b_.2	Previous case, but spacing between elements is 0.2 cm	0.9479 ± 0.0006	0.9491
I.11_7b_.4	Case I.11_7b, but spacing between elements is 0.4 cm	0.9586 ± 0.0007	0.9599
I.11_7b_.6	Case I.11_7b, but spacing between elements is 0.6 cm	0.9673 ± 0.0007	0.9686
I.11_7b_.8	Case I.11_7b, but spacing between elements is 0.8 cm	0.9752 ± 0.0007	0.9766
I.11_7b_.9	Case I.11_7b, but spacing between elements is 0.9 cm	0.9776 ± 0.0007	0.9789
I.11_7b_1	Case I.11_7b, but spacing between elements is 1.0 cm	0.9795 ± 0.0008	0.9810
I.11_7b_1.1	Case I.11_7b, but spacing between elements is 1.1 cm	0.9815 ± 0.0006	0.9828
I.11_7b_1.2	Case I.11_7b, but spacing between elements is 1.2 cm	0.9824 ± 0.0006	0.9836
I.11_7b_1.4	Case I.11_7b, but spacing between elements is 1.4 cm	0.9839 ± 0.0007	0.9852
I.11_7b_1.6	Case I.11_7b, but spacing between elements is 1.6 cm	0.9816 ± 0.0006	0.9829
I.11_7b_1.8	Case I.11_7b, but spacing between elements is 1.8 cm	0.9803 ± 0.0007	0.9816
I.11_7b_2	Case I.11_7b, but spacing between elements is 2.0 cm	0.9757 ± 0.0006	0.9770
I.11_7b_2.5	Case I.11_7b, but spacing between elements is 2.5 cm	0.9574 ± 0.0006	0.9586
I.11_7b_3.0	Case I.11_7b, but spacing between elements is 3.0 cm	0.9353 ± 0.0006	0.9365
I.11_7b_3.5	Case I.11_7b, but spacing between elements is 3.5 cm	0.9072 ± 0.0006	0.9084
I.11_7b_4.0	Case I.11_7b, but spacing between elements is 4.0 cm	0.8764 ± 0.0006	0.8776
I.11_7b_4.5	Case I.11_7b, but spacing between elements is 4.5 cm	0.8426 ± 0.0006	0.8439
I.11_7b_5.0	Case I.11_7b, but spacing between elements is 5.0 cm	0.8108 ± 0.0006	0.8120
I.11_7b_5.5	Case I.11_7b, but spacing between elements is 5.5 cm	0.7802 ± 0.0006	0.7815
I.11_7b_6.0	Case I.11_7b, but spacing between elements is 6.0 cm	0.7493 ± 0.0005	0.7504
Mod 0.1 elements in configuration similar to Configuration B of Table 6 with varying spacing			
leub_7c_ma	Elements are at closest approach, see Figure 5a	0.9522 ± 0.0006	0.9535

Case (MCNP Input File)	Description	$k_{eff} \pm \sigma$	$k_{eff} + 2\sigma$
leub_7c_0	Similar to previous case, but center element is moved upwards towards the center, and radius of outer ring is increased slightly	0.9713 ± 0.0007	0.9726
leub_7c_0.1	Case leub_7c_0, but outer radius is increased by 0.1 cm	0.9719 ± 0.0006	0.9731
leub_7c_0.2	Case leub_7c_0, but outer radius is increased by 0.2 cm	0.9729 ± 0.0007	0.9742
leub_7c_0.3	Case leub_7c_0, but outer radius is increased by 0.3 cm	0.9734 ± 0.0007	0.9747
leub_7c_0.4	Case leub_7c_0, but outer radius is increased by 0.4 cm	0.9741 ± 0.0006	0.9753
leub_7c_0.6	Case leub_7c_0, but outer radius is increased by 0.6 cm	0.9729 ± 0.0007	0.9742
leub_7c_0.8	Case leub_7c_0, but outer radius is increased by 0.8 cm	0.9714 ± 0.0007	0.9727
leub_7c_1.0	Case leub_7c_0, but outer radius is increased by 1.0 cm	0.9673 ± 0.0007	0.9686
leub_7c_1.2	Case leub_7c_0, but outer radius is increased by 1.2 cm	0.9638 ± 0.0007	0.9651
leub_7c_1.5	Case leub_7c_0, but outer radius is increased by 1.5 cm	0.9528 ± 0.0006	0.9540
leub_7c_2.0	Case leub_7c_0, but outer radius is increased by 2.0 cm	0.9325 ± 0.0007	0.9339
leub_7c_2.5	Case leub_7c_0, but outer radius is increased by 2.5 cm	0.9073 ± 0.0006	0.9086
leub_7c_3.0	Case leub_7c_0, but outer radius is increased by 3.0 cm	0.8801 ± 0.0006	0.8814
leub_7c_3.5	Case leub_7c_0, but outer radius is increased by 3.5 cm	0.8500 ± 0.0006	0.8512
leub_7c_4.0	Case leub_7c_0, but outer radius is increased by 4.0 cm	0.8183 ± 0.0006	0.8195
leub_7c_4.5	Case leub_7c_0, but outer radius is increased by 4.5 cm	0.7878 ± 0.0006	0.7890
leub_7c_5.0	Case leub_7c_0, but outer radius is increased by 5.0 cm	0.7595 ± 0.0006	0.7607
leub_7c_5.5	Case leub_7c_0, but outer radius is increased by 5.5 cm	0.7317 ± 0.0006	0.7329
leub_7c_6.0	Case leub_7c_0, but outer radius is increased by 6.0 cm	0.7048 ± 0.0006	0.7059
Mk1A elements in configuration similar to Configuration B of Table 6 with varying spacing			
l.10_7c_ma	Elements are at closest approach, see Figure 5a	0.9601 ± 0.0006	0.9614
l.10_7c_0	Similar to previous case, but center element is moved upwards towards the center, and radius of outer ring is increased slightly	0.9800 ± 0.0007	0.9813
l.10_7c_0.1	Case l.10_7c_0, but outer radius is increased by 0.1 cm	0.9813 ± 0.0007	0.9826
l.10_7c_0.2	Case l.10_7c_0, but outer radius is increased by 0.2 cm	0.9824 ± 0.0007	0.9837
l.10_7c_0.3	Case l.10_7c_0, but outer radius is increased by 0.3 cm	0.9839 ± 0.0007	0.9853
l.10_7c_0.4	Case l.10_7c_0, but outer radius is increased by 0.4 cm	0.9854 ± 0.0006	0.9867
l.10_7c_0.6	Case l.10_7c_0, but outer radius is increased by 0.6 cm	0.9846 ± 0.0006	0.9859
l.10_7c_0.8	Case l.10_7c_0, but outer radius is increased by 0.8 cm	0.9832 ± 0.0007	0.9845
l.10_7c_1.0	Case l.10_7c_0, but outer radius is increased by 1.0 cm	0.9785 ± 0.0007	0.9798
l.10_7c_1.2	Case l.10_7c_0, but outer radius is increased by 1.2 cm	0.9742 ± 0.0006	0.9755
l.10_7c_1.5	Case l.10_7c_0, but outer radius is increased by 1.5 cm	0.9674 ± 0.0006	0.9686
l.10_7c_2.0	Case l.10_7c_0, but outer radius is increased by 2.0 cm	0.9464 ± 0.0006	0.9476
l.10_7c_2.5	Case l.10_7c_0, but outer radius is increased by 2.5 cm	0.9221 ± 0.0006	0.9234
l.10_7c_3.0	Case l.10_7c_0, but outer radius is increased by 3.0 cm	0.8937 ± 0.0006	0.8950
l.10_7c_3.5	Case l.10_7c_0, but outer radius is increased by 3.5 cm	0.8627 ± 0.0006	0.8639
l.10_7c_4.0	Case l.10_7c_0, but outer radius is increased by 4.0 cm	0.8333 ± 0.0007	0.8346
l.10_7c_4.5	Case l.10_7c_0, but outer radius is increased by 4.5 cm	0.8023 ± 0.0006	0.8035
l.10_7c_5.0	Case l.10_7c_0, but outer radius is increased by 5.0 cm	0.7725 ± 0.0006	0.7737
l.10_7c_5.5	Case l.10_7c_0, but outer radius is increased by 5.5 cm	0.7453 ± 0.0006	0.7465
l.10_7c_6.0	Case l.10_7c_0, but outer radius is increased by 6.0 cm	0.7173 ± 0.0006	0.7184
Mk1B elements in configuration similar to Configuration B of Table 6 with varying spacing			
l.11_7c_ma	Elements are at closest approach, see Figure 5a	0.9616 ± 0.0007	0.9630

Case (MCNP Input File)	Description	$k_{eff} \pm \sigma$	$k_{eff} + 2\sigma$
I.11_7c_0	Similar to previous case, but center element is moved upwards towards the center, and radius of outer ring is increased slightly	0.9792 ± 0.0007	0.9806
I.11_7c_0.1	Case I.11_7c_0, but outer radius is increased by 0.1 cm	0.9804 ± 0.0007	0.9818
I.11_7c_0.2	Case I.11_7c_0, but outer radius is increased by 0.2 cm	0.9830 ± 0.0007	0.9843
I.11_7c_0.3	Case I.11_7c_0, but outer radius is increased by 0.3 cm	0.9824 ± 0.0006	0.9837
I.11_7c_0.4	Case I.11_7c_0, but outer radius is increased by 0.4 cm	0.9841 ± 0.0007	0.9854
I.11_7c_0.6	Case I.11_7c_0, but outer radius is increased by 0.6 cm	0.9850 ± 0.0006	0.9863
I.11_7c_0.8	Case I.11_7c_0, but outer radius is increased by 0.8 cm	0.9833 ± 0.0006	0.9845
I.11_7c_1.0	Case I.11_7c_0, but outer radius is increased by 1.0 cm	0.9796 ± 0.0006	0.9808
I.11_7c_1.2	Case I.11_7c_0, but outer radius is increased by 1.2 cm	0.9748 ± 0.0006	0.9761
I.11_7c_1.5	Case I.11_7c_0, but outer radius is increased by 1.5 cm	0.9674 ± 0.0006	0.9686
I.11_7c_2.0	Case I.11_7c_0, but outer radius is increased by 2.0 cm	0.9453 ± 0.0006	0.9465
I.11_7c_2.5	Case I.11_7c_0, but outer radius is increased by 2.5 cm	0.9215 ± 0.0006	0.9228
I.11_7c_3.0	Case I.11_7c_0, but outer radius is increased by 3.0 cm	0.8929 ± 0.0006	0.8940
I.11_7c_3.5	Case I.11_7c_0, but outer radius is increased by 3.5 cm	0.8641 ± 0.0006	0.8653
I.11_7c_4.0	Case I.11_7c_0, but outer radius is increased by 4.0 cm	0.8329 ± 0.0006	0.8341
I.11_7c_4.5	Case I.11_7c_0, but outer radius is increased by 4.5 cm	0.8026 ± 0.0006	0.8038
I.11_7c_5.0	Case I.11_7c_0, but outer radius is increased by 5.0 cm	0.7726 ± 0.0006	0.7738
I.11_7c_5.5	Case I.11_7c_0, but outer radius is increased by 5.5 cm	0.7426 ± 0.0006	0.7438
I.11_7c_6.0	Case I.11_7c_0, but outer radius is increased by 6.0 cm	0.7183 ± 0.0006	0.7195

Table D-6. Results for the Thicker Fuel Meat U-10Mo ELF ATR Element Configurations

Case (MCNP Input File)	Description	$k_{eff} \pm \sigma$	$k_{eff} + 2\sigma$
A single water moderated and reflected ATR ELF thicker fuel meat element			
leubt_1a	Single water moderated and reflected ATR Mod 0.1 element	0.4624 ± 0.0006	0.4635
I.10t_1a	Single water moderated and reflected ATR Mk1A element	0.4694 ± 0.0005	0.4705
I.11t_1a	Single water moderated and reflected ATR Mk1B element	0.4707 ± 0.0006	0.4719
An array of 7 ELF thicker fuel meat elements similar to Configuration A in Figure 3			
leubt_7a	Mod 0.1 elements are water moderated and reflected	0.9695 ± 0.0007	0.9709
I.10t_7a	Mk1A elements are water moderated and reflected	0.9783 ± 0.0007	0.9796
I.11t_7a	Mk1B elements are water moderated and reflected	0.9784 ± 0.0006	0.9796
An array of 7 Mod 0.1 thicker fuel meat elements to investigate element spacing, see Figure 4			
leubt_7b	Adjacent elements are touching; see Figure 4a	0.9329 ± 0.0007	0.9342
leubt_7b_.2	Case leubt_7b, but spacing between elements is 0.2 cm	0.9442 ± 0.0006	0.9455
leubt_7b_.4	Case leubt_7b, but spacing between elements is 0.4 cm	0.9566 ± 0.0007	0.9580
leubt_7b_.6	Case leubt_7b, but spacing between elements is 0.6 cm	0.9650 ± 0.0007	0.9663
leubt_7b_.8	Case leubt_7b, but spacing between elements is 0.8 cm	0.9723 ± 0.0007	0.9736
leubt_7b_.9	Case leubt_7b, but spacing between elements is 0.9 cm	0.9756 ± 0.0007	0.9769
leubt_7b_1	Case leubt_7b, but spacing between elements is 1.0 cm	0.9770 ± 0.0007	0.9784
leubt_7b_1.1	Case leubt_7b, but spacing between elements is 1.1 cm	0.9788 ± 0.0006	0.9800
leubt_7b_1.2	Case leubt_7b, but spacing between elements is 1.2 cm	0.9800 ± 0.0006	0.9812

Case (MCNP Input File)	Description	$k_{eff} \pm \sigma$	$k_{eff} + 2\sigma$
leubt_7b_1.4	Case leubt_7b, but spacing between elements is 1.4 cm	0.9809 ± 0.0007	0.9822
leubt_7b_1.6	Case leubt_7b, but spacing between elements is 1.6 cm	0.9800 ± 0.0007	0.9813
leubt_7b_1.8	Case leubt_7b, but spacing between elements is 1.8 cm	0.9772 ± 0.0006	0.9783
leubt_7b_2	Case leubt_7b, but spacing between elements is 2.0 cm	0.9732 ± 0.0006	0.9744
leubt_7b_2.5	Case leubt_7b, but spacing between elements is 2.5 cm	0.9567 ± 0.0006	0.9579
leubt_7b_3.0	Case leubt_7b, but spacing between elements is 3.0 cm	0.9321 ± 0.0007	0.9334
leubt_7b_3.5	Case leubt_7b, but spacing between elements is 3.5 cm	0.9054 ± 0.0006	0.9066
leubt_7b_4.0	Case leubt_7b, but spacing between elements is 4.0 cm	0.8735 ± 0.0006	0.8748
leubt_7b_4.5	Case leubt_7b, but spacing between elements is 4.5 cm	0.8407 ± 0.0006	0.8419
leubt_7b_5.0	Case leubt_7b, but spacing between elements is 5.0 cm	0.8083 ± 0.0006	0.8095
leubt_7b_5.5	Case leubt_7b, but spacing between elements is 5.5 cm	0.7767 ± 0.0005	0.7778
leubt_7b_6.0	Case leubt_7b, but spacing between elements is 6.0 cm	0.7462 ± 0.0006	0.7473
An array of 7 Mk1A thicker fuel meat elements to investigate element spacing, see Figure 4			
l.10t_7b	Adjacent elements are touching; see Figure 4a	0.9401 ± 0.0007	0.9414
l.10t_7b_.2	Case l.10t_7b, but spacing between elements is 0.2 cm	0.9509 ± 0.0006	0.9522
l.10t_7b_.4	Case l.10t_7b, but spacing between elements is 0.4 cm	0.9632 ± 0.0007	0.9647
l.10t_7b_.6	Case l.10t_7b, but spacing between elements is 0.6 cm	0.9736 ± 0.0007	0.9749
l.10t_7b_.8	Case l.10t_7b, but spacing between elements is 0.8 cm	0.9806 ± 0.0007	0.9819
l.10t_7b_.9	Case l.10t_7b, but spacing between elements is 0.9 cm	0.9830 ± 0.0006	0.9843
l.10t_7b_1	Case l.10t_7b, but spacing between elements is 1.0 cm	0.9854 ± 0.0007	0.9868
l.10t_7b_1.1	Case l.10t_7b, but spacing between elements is 1.1 cm	0.9865 ± 0.0006	0.9877
l.10t_7b_1.2	Case l.10t_7b, but spacing between elements is 1.2 cm	0.9877 ± 0.0007	0.9890
l.10t_7b_1.4	Case l.10t_7b, but spacing between elements is 1.4 cm	0.9884 ± 0.0007	0.9897
l.10t_7b_1.6	Case l.10t_7b, but spacing between elements is 1.6 cm	0.9886 ± 0.0006	0.9898
l.10t_7b_1.8	Case l.10t_7b, but spacing between elements is 1.8 cm	0.9882 ± 0.0006	0.9895
l.10t_7b_2	Case l.10t_7b, but spacing between elements is 2.0 cm	0.9842 ± 0.0006	0.9855
l.10t_7b_2.5	Case l.10t_7b, but spacing between elements is 2.5 cm	0.9674 ± 0.0006	0.9686
l.10t_7b_3.0	Case l.10t_7b, but spacing between elements is 3.0 cm	0.9441 ± 0.0006	0.9453
l.10t_7b_3.5	Case l.10t_7b, but spacing between elements is 3.5 cm	0.9150 ± 0.0006	0.9161
l.10t_7b_4.0	Case l.10t_7b, but spacing between elements is 4.0 cm	0.8847 ± 0.0006	0.8859
l.10t_7b_4.5	Case l.10t_7b, but spacing between elements is 4.5 cm	0.8522 ± 0.0006	0.8533
l.10t_7b_5.0	Case l.10t_7b, but spacing between elements is 5.0 cm	0.8188 ± 0.0006	0.8200
l.10t_7b_5.5	Case l.10t_7b, but spacing between elements is 5.5 cm	0.7877 ± 0.0006	0.7888
l.10t_7b_6.0	Case l.10t_7b, but spacing between elements is 6.0 cm	0.7565 ± 0.0006	0.7577
An array of 7 Mk1B thicker fuel meat elements to investigate element spacing, see Figure 4			
l.11t_7b	Adjacent elements are touching; see Figure 4a	0.9388 ± 0.0007	0.9402
l.11t_7b_.2	Case l.11t_7b, but spacing between elements is 0.2 cm	0.9531 ± 0.0006	0.9544
l.11t_7b_.4	Case l.11t_7b, but spacing between elements is 0.4 cm	0.9644 ± 0.0006	0.9657
l.11t_7b_.6	Case l.11t_7b, but spacing between elements is 0.6 cm	0.9730 ± 0.0007	0.9743
l.11t_7b_.8	Case l.11t_7b, but spacing between elements is 0.8 cm	0.9810 ± 0.0006	0.9823
l.11t_7b_.9	Case l.11t_7b, but spacing between elements is 0.9 cm	0.9833 ± 0.0007	0.9846
l.11t_7b_1	Case l.11t_7b, but spacing between elements is 1.0 cm	0.9853 ± 0.0007	0.9866
l.11t_7b_1.1	Case l.11t_7b, but spacing between elements is 1.1 cm	0.9878 ± 0.0007	0.9891
l.11t_7b_1.2	Case l.11t_7b, but spacing between elements is 1.2 cm	0.9891 ± 0.0007	0.9904
l.11t_7b_1.4	Case l.11t_7b, but spacing between elements is 1.4 cm	0.9908 ± 0.0006	0.9920

Case (MCNP Input File)	Description	$k_{eff} \pm \sigma$	$k_{eff} + 2\sigma$
l.11t_7b_1.6	Case l.11t_7b, but spacing between elements is 1.6 cm	0.9891 ± 0.0006	0.9904
l.11t_7b_1.8	Case l.11t_7b, but spacing between elements is 1.8 cm	0.9865 ± 0.0007	0.9879
l.11t_7b_2	Case l.11t_7b, but spacing between elements is 2.0 cm	0.9831 ± 0.0006	0.9843
l.11t_7b_2.5	Case l.11t_7b, but spacing between elements is 2.5 cm	0.9672 ± 0.0006	0.9685
l.11t_7b_3.0	Case l.11t_7b, but spacing between elements is 3.0 cm	0.9438 ± 0.0006	0.9450
l.11t_7b_3.5	Case l.11t_7b, but spacing between elements is 3.5 cm	0.9158 ± 0.0006	0.9171
l.11t_7b_4.0	Case l.11t_7b, but spacing between elements is 4.0 cm	0.8840 ± 0.0006	0.8853
l.11t_7b_4.5	Case l.11t_7b, but spacing between elements is 4.5 cm	0.8519 ± 0.0006	0.8532
l.11t_7b_5.0	Case l.11t_7b, but spacing between elements is 5.0 cm	0.8197 ± 0.0006	0.8210
l.11t_7b_5.5	Case l.11t_7b, but spacing between elements is 5.5 cm	0.7879 ± 0.0006	0.7891
l.11t_7b_6.0	Case l.11t_7b, but spacing between elements is 6.0 cm	0.7577 ± 0.0006	0.7589
Mod 0.1 thicker fuel meat elements in configuration similar to Configuration B of Table 6 with varying spacing			
leubt_7c_ma	Elements are at closest approach, see Figure 5a	0.9594 ± 0.0007	0.9607
leubt_7c_0	Similar to previous case, but center element is moved upwards towards the center, and radius of outer ring is increased slightly	0.9782 ± 0.0007	0.9796
leubt_7c_0.1	Case leubt_7c_0, but outer radius is increased by 0.1 cm	0.9798 ± 0.0006	0.9810
leubt_7c_0.2	Case leubt_7c_0, but outer radius is increased by 0.2 cm	0.9803 ± 0.0007	0.9816
leubt_7c_0.3	Case leubt_7c_0, but outer radius is increased by 0.3 cm	0.9805 ± 0.0006	0.9818
leubt_7c_0.4	Case leubt_7c_0, but outer radius is increased by 0.4 cm	0.9816 ± 0.0006	0.9828
leubt_7c_0.5	Case leubt_7c_0, but outer radius is increased by 0.5 cm	0.9816 ± 0.0007	0.9830
leubt_7c_0.6	Case leubt_7c_0, but outer radius is increased by 0.6 cm	0.9819 ± 0.0007	0.9832
leubt_7c_0.8	Case leubt_7c_0, but outer radius is increased by 0.8 cm	0.9807 ± 0.0006	0.9820
leubt_7c_1.0	Case leubt_7c_0, but outer radius is increased by 1.0 cm	0.9761 ± 0.0007	0.9774
leubt_7c_1.2	Case leubt_7c_0, but outer radius is increased by 1.2 cm	0.9720 ± 0.0006	0.9732
leubt_7c_1.5	Case leubt_7c_0, but outer radius is increased by 1.5 cm	0.9626 ± 0.0007	0.9639
leubt_7c_2.0	Case leubt_7c_0, but outer radius is increased by 2.0 cm	0.9431 ± 0.0006	0.9443
leubt_7c_2.5	Case leubt_7c_0, but outer radius is increased by 2.5 cm	0.9174 ± 0.0006	0.9185
leubt_7c_3.0	Case leubt_7c_0, but outer radius is increased by 3.0 cm	0.8891 ± 0.0006	0.8904
leubt_7c_3.5	Case leubt_7c_0, but outer radius is increased by 3.5 cm	0.8592 ± 0.0006	0.8604
leubt_7c_4.0	Case leubt_7c_0, but outer radius is increased by 4.0 cm	0.8290 ± 0.0006	0.8301
leubt_7c_4.5	Case leubt_7c_0, but outer radius is increased by 4.5 cm	0.7981 ± 0.0006	0.7994
leubt_7c_5.0	Case leubt_7c_0, but outer radius is increased by 5.0 cm	0.7686 ± 0.0006	0.7697
leubt_7c_5.5	Case leubt_7c_0, but outer radius is increased by 5.5 cm	0.7413 ± 0.0006	0.7425
leubt_7c_6.0	Case leubt_7c_0, but outer radius is increased by 6.0 cm	0.7123 ± 0.0006	0.7134
Mk1A thicker fuel meat elements in configuration similar to Configuration B of Table 6 with varying spacing			
l.10t_7c_ma	Elements are at closest approach, see Figure 5a	0.9677 ± 0.0007	0.9692
l.10t_7c_0	Similar to previous case, but center element is moved upwards towards the center, and radius of outer ring is increased slightly	0.9853 ± 0.0007	0.9867
l.10t_7c_0.1	Case l.10t_7c_0, but outer radius is increased by 0.1 cm	0.9864 ± 0.0007	0.9878
l.10t_7c_0.2	Case l.10t_7c_0, but outer radius is increased by 0.2 cm	0.9891 ± 0.0006	0.9903
l.10t_7c_0.3	Case l.10t_7c_0, but outer radius is increased by 0.3 cm	0.9907 ± 0.0007	0.9921
l.10t_7c_0.4	Case l.10t_7c_0, but outer radius is increased by 0.4 cm	0.9904 ± 0.0007	0.9918
l.10t_7c_0.6	Case l.10t_7c_0, but outer radius is increased by 0.6 cm	0.9924 ± 0.0007	0.9937
l.10t_7c_0.8	Case l.10t_7c_0, but outer radius is increased by 0.8 cm	0.9901 ± 0.0006	0.9913

Case (MCNP Input File)	Description	$k_{eff} \pm \sigma$	$k_{eff} + 2\sigma$
I.10t_7c_1.0	Case I.10t_7c_0, but outer radius is increased by 1.0 cm	0.9873 ± 0.0006	0.9886
I.10t_7c_1.2	Case I.10t_7c_0, but outer radius is increased by 1.2 cm	0.9832 ± 0.0007	0.9845
I.10t_7c_1.5	Case I.10t_7c_0, but outer radius is increased by 1.5 cm	0.9745 ± 0.0006	0.9757
I.10t_7c_2.0	Case I.10t_7c_0, but outer radius is increased by 2.0 cm	0.9530 ± 0.0006	0.9543
I.10t_7c_2.5	Case I.10t_7c_0, but outer radius is increased by 2.5 cm	0.9301 ± 0.0006	0.9312
I.10t_7c_3.0	Case I.10t_7c_0, but outer radius is increased by 3.0 cm	0.9015 ± 0.0006	0.9027
I.10t_7c_3.5	Case I.10t_7c_0, but outer radius is increased by 3.5 cm	0.8714 ± 0.0006	0.8725
I.10t_7c_4.0	Case I.10t_7c_0, but outer radius is increased by 4.0 cm	0.8411 ± 0.0006	0.8423
I.10t_7c_4.5	Case I.10t_7c_0, but outer radius is increased by 4.5 cm	0.8113 ± 0.0006	0.8125
I.10t_7c_5.0	Case I.10t_7c_0, but outer radius is increased by 5.0 cm	0.7808 ± 0.0006	0.7820
I.10t_7c_5.5	Case I.10t_7c_0, but outer radius is increased by 5.5 cm	0.7519 ± 0.0006	0.7530
I.10t_7c_6.0	Case I.10t_7c_0, but outer radius is increased by 6.0 cm	0.7260 ± 0.0006	0.7273
Mk1B thicker fuel meat elements in configuration similar to Configuration B of Table 6 with varying spacing			
I.11t_7c_ma	Elements are at closest approach, see Figure 5a	0.9668 ± 0.0006	0.9681
I.11t_7c_0	Similar to previous case, but center element is moved upwards towards the center, and radius of outer ring is increased slightly	0.9867 ± 0.0007	0.9880
I.11t_7c_0.1	Case I.11t_7c_0, but outer radius is increased by 0.1 cm	0.9879 ± 0.0006	0.9891
I.11t_7c_0.2	Case I.11t_7c_0, but outer radius is increased by 0.2 cm	0.9899 ± 0.0007	0.9913
I.11t_7c_0.3	Case I.11t_7c_0, but outer radius is increased by 0.3 cm	0.9891 ± 0.0007	0.9905
I.11t_7c_0.4	Case I.11t_7c_0, but outer radius is increased by 0.4 cm	0.9913 ± 0.0007	0.9926
I.11t_7c_0.6	Case I.11t_7c_0, but outer radius is increased by 0.6 cm	0.9909 ± 0.0006	0.9921
I.11t_7c_0.8	Case I.11t_7c_0, but outer radius is increased by 0.8 cm	0.9893 ± 0.0007	0.9907
I.11t_7c_1.0	Case I.11t_7c_0, but outer radius is increased by 1.0 cm	0.9859 ± 0.0007	0.9872
I.11t_7c_1.2	Case I.11t_7c_0, but outer radius is increased by 1.2 cm	0.9821 ± 0.0006	0.9833
I.11t_7c_1.5	Case I.11t_7c_0, but outer radius is increased by 1.5 cm	0.9735 ± 0.0006	0.9748
I.11t_7c_2.0	Case I.11t_7c_0, but outer radius is increased by 2.0 cm	0.9548 ± 0.0006	0.9561
I.11t_7c_2.5	Case I.11t_7c_0, but outer radius is increased by 2.5 cm	0.9310 ± 0.0006	0.9322
I.11t_7c_3.0	Case I.11t_7c_0, but outer radius is increased by 3.0 cm	0.9023 ± 0.0006	0.9036
I.11t_7c_3.5	Case I.11t_7c_0, but outer radius is increased by 3.5 cm	0.8721 ± 0.0006	0.8732
I.11t_7c_4.0	Case I.11t_7c_0, but outer radius is increased by 4.0 cm	0.8415 ± 0.0006	0.8427
I.11t_7c_4.5	Case I.11t_7c_0, but outer radius is increased by 4.5 cm	0.8099 ± 0.0006	0.8111
I.11t_7c_5.0	Case I.11t_7c_0, but outer radius is increased by 5.0 cm	0.7802 ± 0.0006	0.7815
I.11t_7c_5.5	Case I.11t_7c_0, but outer radius is increased by 5.5 cm	0.7522 ± 0.0006	0.7534
I.11t_7c_6.0	Case I.11t_7c_0, but outer radius is increased by 6.0 cm	0.7247 ± 0.0006	0.7259

The cases in Table D-7 are variations of cases wetbox05b and wetbox43_05b in Table 17 and examine varying degrees of moderation. For all cases in Table D-7 full density water is between the element plates and the moderation in the other parts of the FFSCs is varied as described in the “Description” column of the table. Results for Mark VII elements are given in the first set of the table, and Mark IV results are given in the second set for the same configurations. The largest reactivity cases are for void in the FFSC (elements are water flooded) and is greater than critical, which is to be expected for an infinite array. Of greatest interest is that the Mark VII elements are more reactive than the Mark IV elements for all cases.

Table D-7. Infinite Array Results for Mark IV and VII Elements in FFSCs

Case (MCNP Input File)	Description	$k_{eff} \pm \sigma$	$k_{eff} + 2\sigma$
Mark VII results similar to case wetbox05b ($k_{eff} + 2\sigma$=0.6285) **in Table 17, but void between insulation and outer tube, unless noted otherwise; full density water is between element plates; and varying water density is inside inner tube**			
wetbox_vii_05bp	Full density water in inner tube	0.7452 ± 0.0006	0.7464
wetbox_vii_05bp.6	Water density in inner tube is 60% of full density	0.8271 ± 0.0006	0.8283
wetbox_vii_05bp.3	Water density in inner tube is 30% of full density	0.9034 ± 0.0006	0.9046
wetbox_vii_05bp.0	Void inside inner tube; water between element plates	1.1550 ± 0.0006	1.1561
wetbox_vii_05bq.0	Previous case, but full density water is between insulation and outer tube	0.6648 ± 0.0006	0.6659
Mark IV results similar to case wetbox43_05b ($k_{eff} + 2\sigma$=0.6258) **in Table 17, but void between insulation and outer tube, unless noted otherwise; full density water is between element plates; and varying water density is inside inner tube**			
wetbox43_05bp	Full density water in inner tube	0.7426 ± 0.0006	0.7439
wetbox43_05bp.6	Water density in inner tube is 60% of full density	0.8233 ± 0.0007	0.8246
wetbox43_05bp.3	Water density in inner tube is 30% of full density	0.8970 ± 0.0006	0.8982
wetbox43_05bp.0	Void inside inner tube; water between element plates	1.1403 ± 0.0006	1.1414
wetbox43_05bq.0	Previous case, but full density water is between insulation and outer tube	0.6586 ± 0.0006	0.6598

Table D-8. Results for Four ELF Elements per Storage Position in an Infinite Array

Case (MCNP Input File)	Description	$k_{eff} \pm \sigma$	$k_{eff} + 2\sigma$
Finite length Mod 0.1 elements; "Configuration ELF" shown in Figure 22			
leub_4b	Adjacent elements are essentially touching	0.7687 ± 0.0007	0.7700
leub_4b_0.2	Case leub_4b, but spacing between elements is 0.2 cm	0.7777 ± 0.0006	0.7790
leub_4b_0.4	Case leub_4b, but spacing between elements is 0.4 cm	0.7874 ± 0.0006	0.7886
leub_4b_0.6	Case leub_4b, but spacing between elements is 0.6 cm	0.7952 ± 0.0006	0.7964
leub_4b_0.8	Case leub_4b, but spacing between elements is 0.8 cm	0.8014 ± 0.0007	0.8028
leub_4b_1.0	Case leub_4b, but spacing between elements is 1.0 cm	0.8069 ± 0.0007	0.8083
leub_4b_1.2	Case leub_4b, but spacing between elements is 1.2 cm	0.8099 ± 0.0006	0.8112
leub_4b_1.4	Case leub_4b, but spacing between elements is 1.4 cm	0.8138 ± 0.0006	0.8150
leub_4b_1.6	Case leub_4b, but spacing between elements is 1.6 cm	0.8137 ± 0.0006	0.8150
leub_4b_1.8	Case leub_4b, but spacing between elements is 1.8 cm	0.8142 ± 0.0006	0.8154
leub_4b_2.0	Case leub_4b, but spacing between elements is 2.0 cm	0.8122 ± 0.0006	0.8135
leub_4b_2.2	Case leub_4b, but spacing between elements is 2.2 cm	0.8093 ± 0.0007	0.8106
leub_4b_2.4	Case leub_4b, but spacing between elements is 2.4 cm	0.8062 ± 0.0006	0.8074
Finite length Mod 0.1 elements; Configuration E shown in Figure 22			
leub_4e	Adjacent elements are essentially touching	0.8062 ± 0.0007	0.8075
leub_4e_0.2	Case leub_4e, but spacing between elements is 0.2 cm	0.8074 ± 0.0007	0.8087

Case (MCNP Input File)	Description	$k_{eff} \pm \sigma$	$k_{eff} + 2\sigma$
leub_4e_0.4	Case leub_4e, but spacing between elements is 0.4 cm	0.8115 ± 0.0006	0.8128
leub_4e_0.6	Case leub_4e, but spacing between elements is 0.6 cm	0.8131 ± 0.0006	0.8143
leub_4e_0.8	Case leub_4e, but spacing between elements is 0.8cm	0.8132 ± 0.0006	0.8144
leub_4e_1.0	Case leub_4e, but spacing between elements is 1.0 cm	0.8123 ± 0.0007	0.8136
leub_4e_1.2	Case leub_4e, but spacing between elements is 1.2 cm	0.8103 ± 0.0006	0.8115
leub_4e_1.4	Case leub_4e, but spacing between elements is 1.4 cm	0.8070 ± 0.0006	0.8082
leub_4e_1.6	Case leub_4e, but spacing between elements is 1.6 cm	0.8028 ± 0.0006	0.8041
leub_4e_1.8	Case leub_4e, but spacing between elements is 1.8 cm	0.7974 ± 0.0006	0.7986
Infinite length Mod 0.1 elements; Configuration E shown in Figure 22			
leub_4e_0.4I	Spacing between elements is 0.4 cm	0.8246 ± 0.0006	0.8258
leub_4e_0.6I	Case leub_4e_0.4I, but spacing between elements is 0.6 cm	0.8270 ± 0.0006	0.8281
leub_4e_0.8I	Case leub_4e_0.4I, but spacing between elements is 0.6 cm	0.8261 ± 0.0007	0.8274
leub_4e_1.0I	Case leub_4e_0.4I, but spacing between elements is 1.0 cm	0.8259 ± 0.0006	0.8272
leub_4e_1.2I	Case leub_4e_0.4I, but spacing between elements is 1.2 cm	0.8229 ± 0.0006	0.8242
leub_4e_1.4I	Case leub_4e_0.4I, but spacing between elements is 1.4 cm	0.8187 ± 0.0006	0.8199
leub_4e_1.6I	Case leub_4e_0.4I, but spacing between elements is 1.6 cm	0.8138 ± 0.0006	0.8150
leub_4e_1.8I	Case leub_4e_0.4I, but spacing between elements is 1.8 cm	0.8093 ± 0.0006	0.8104
Infinite length Mod 0.1 elements in FSA Port			
leub_4b_1.2P	Spacing between elements is 1.2 cm	0.8316 ± 0.0007	0.8329
leub_4b_1.4P	Case leub_4b_1.2P, but spacing between elements is 1.4 cm	0.8338 ± 0.0006	0.8350
leub_4b_1.6P	Case leub_4b_1.6P, but spacing between elements is 1.6 cm	0.8357 ± 0.0007	0.8371
leub_4b_1.8P	Case leub_4b_1.8P, but spacing between elements is 1.8 cm	0.8355 ± 0.0006	0.8367
leub_4b_2.0P	Case leub_4b_2.0P, but spacing between elements is 2.0 cm	0.8348 ± 0.0007	0.8362
Finite length Mod 0.1 elements; Configuration E shown in Figure 22; thicker fuel meats			
leubT_4e	Adjacent elements are essentially touching	0.8122 ± 0.0006	0.8135
leubT_4e_0.2	Case leubT_4e, but spacing between elements is 0.2 cm	0.8166 ± 0.0006	0.8179
leubT_4e_0.4	Case leubT_4e, but spacing between elements is 0.4 cm	0.8199 ± 0.0007	0.8213
leubT_4e_0.6	Case leubT_4e, but spacing between elements is 0.6 cm	0.8214 ± 0.0007	0.8227
leubT_4e_0.8	Case leubT_4e, but spacing between elements is 0.8 cm	0.8216 ± 0.0007	0.8229
leubT_4e_1.0	Case leubT_4e, but spacing between elements is 1.0 cm	0.8201 ± 0.0006	0.8213
leubT_4e_1.2	Case leubT_4e, but spacing between elements is 1.2 cm	0.8193 ± 0.0007	0.8206
leubT_4e_1.4	Case leubT_4e, but spacing between elements is 1.4 cm	0.8162 ± 0.0006	0.8174
leubT_4e_1.6	Case leubT_4e, but spacing between elements is 1.6 cm	0.8119 ± 0.0006	0.8132
leubT_4e_1.8	Case leubT_4e, but spacing between elements is 1.8 cm	0.8057 ± 0.0006	0.8070
Infinite length Mod 0.1 elements; "Configuration ELF" shown in Figure 22; thicker fuel meats			
leubT_4b_1.0I	Spacing between elements is 1.0 cm	0.8262 ± 0.0007	0.8275
leubT_4b_1.2I	Case leubT_4b_1.0I, but spacing between elements is 1.2 cm	0.8306 ± 0.0006	0.8318
leubT_4b_1.4I	Case leubT_4b_1.0I, but spacing between elements is 1.4 cm	0.8331 ± 0.0006	0.8343
leubT_4b_1.6I	Case leubT_4b_1.0I, but spacing between elements is 1.6 cm	0.8335 ± 0.0006	0.8348
leubT_4b_1.8I	Case leubT_4b_1.0I, but spacing between elements is 1.8 cm	0.8341 ± 0.0007	0.8354
leubT_4b_2.0I	Case leubT_4b_1.0I, but spacing between elements is 2.0 cm	0.8333 ± 0.0007	0.8347
leubT_4b_2.2I	Case leubT_4b_1.0I, but spacing between elements is 2.2 cm	0.8307 ± 0.0007	0.8320
leubT_4b_2.4I	Case leubT_4b_1.0I, but spacing between elements is 2.4 cm	0.8271 ± 0.0007	0.8284
Infinite length Mod 0.1 elements in FSA Port; thicker fuel meats			
leubT_4b_1.2P	Spacing between elements is 1.2 cm	0.8393 ± 0.0006	0.8404

Case (MCNP Input File)	Description	$k_{eff} \pm \sigma$	$k_{eff} + 2\sigma$
leubT_4b_1.4P	Case leubT_4b_1.2P, but spacing between elements is 1.4 cm	0.8425 ± 0.0007	0.8438
leubT_4b_1.6P	Case leubT_4b_1.2P, but spacing between elements is 1.6 cm	0.8443 ± 0.0006	0.8456
leubT_4b_1.8P	Case leubT_4b_1.2P, but spacing between elements is 1.8 cm	0.8438 ± 0.0006	0.8449
leubT_4b_2.0P	Case leubT_4b_1.2P, but spacing between elements is 2.0 cm	0.8429 ± 0.0007	0.8442
Mk1B ELF thicker fuel meat elements results			
l11bT_4b_1.8I	Infinite length with spacing between elements of 1.8 cm	0.8426 ± 0.0006	0.8439
l11bT_4b_1.6P	Infinite length elements spaced 1.6 cm apart in FSA Port	0.8516 ± 0.0006	0.8528