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Criticality Safety Evaluation of the LLNL Inherently Safe Subcritical Assembly (ISSA)

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Disclaimer

1.0 INTRODUCTION

The LLNL Nuclear Criticality Safety Division has developed a training center to illustrate criticality safety and reactor physics concepts through hands-on experimental training. The experimental assembly, the Inherently Safe Subcritical Assembly (ISSA), uses surplus highly enriched research reactor fuel configured in a water tank. The training activities will be conducted by LLNL following the requirements of an Integration Work Sheet (IWS) and associated Safety Plan. Students will be allowed to handle the fissile material under the supervision of LLNL instructors.

This report provides the technical criticality safety basis for instructional operations with the ISSA experimental assembly.

2.0 DESCRIPTION

2.1 Description of Fuel Assemblies

The fuel assemblies used for ISSA were originally fabricated for the Los Alamos Omega West Reactor (OWR). The Omega West fuel fits into the broader category of Materials Test Reactor (MTR)-type fuel. The curved fuel plates are constructed of U_3O_8 powder mixed with high purity aluminum powder sandwiched and roll-bonded between two aluminum plates. A discussion of MTR fuel fabrication is given in *Nuclear Reactor Fuel Elements: Metallurgy and Fabrication*, pages 578-584.

The Omega West fuel was fabricated at Babcock and Wilcox (B&W) in Lynchburg, VA. Drawings and fuel specifications from B&W are provided as Appendix A. Pictures of the fuel assemblies are provided in Figure 2.1. A total of 26 surplus, un-irradiated OWR fuel assemblies were shipped from the Y-12 National Security Complex to LLNL. All assemblies contain 19 curved plates that are 27.125" long and are bundled together by two aluminum side plates into a 3.303" by 3.017" box. The side of the fuel was etched with a serial number (L-###) by B&W during fabrication.

Figure 2.1: Photograph Showing Cross Section (right) and Full-Length View (left) of 19-Plate ISSA Fuel Assembly

According to the inventory records from Y-12, some of the assemblies contain 220 grams of ^{235}U and some contain 232 grams of ^{235}U. Technical specifications LLNL received from Babcock and Wilcox indicate that a change was made to the fissile loading of the fuel plates in 1988 (included in Appendix A). Before 1988, each fuel plate contained 11.579 ± 0.250 grams of ^{235}U, with the entire assembly of 19 plates containing 220.0 ± 2.0 grams. The new specification increased the ^{235}U to 12.210 ± 0.250, with a 19 plate fuel assembly containing 232.0 ± 2.0 grams.

As shown by Table 2-1, LLNL currently has 9 assemblies with the lower fuel loading (L-69 through L-78) and 15 assemblies with the higher fuel loading (L-110 through L-139). B&W's electronic records indicate that 39 of the higher massed assemblies were fabricated and shipped in 1988, although electronic records do not exist for prior assemblies.

Table 2-1: Uranium Mass by Fuel Element Number

Fuel Element Serial Number	Uranium Mass (g)	^{235}U Mass (g)
L69	236	220
L70	236	220
L71	236	220
L72	236	220
L73	236	220
L74	236	220
L76	236	220
L77	236	220
L78	236	220
L110	249	232
L112	249	232
L114	249	232
L115	249	232
L120	249	232
L124	249	232
L125	249	232
L126	249	232
L129	249	232
L131	249	232
L132	249	232
L133	249	232
L134	249	232
L135	249	232
L136	249	232
L138	249	232
L139	249	232

As shown by Figure 2.1, the assemblies are designed to have a small gap (0.104”-0.117”) between each fuel plate. When placed in the ISSA tank, this gap will be filled with water, allowing for neutron moderation. LLNL modified the original fuel assemblies by removing the aluminum end pieces (“nozzles” used in the Omega West reactor for fuel positioning and handling), leaving a 3/8” end cap on each end of the fuel assembly (shown in the cross-sectional view of Figure 2.1). LLNL fabricated new aluminum positioning fixtures to be located at the top and bottom of the fuel elements to aid in placement of the fuel assemblies into the array. Figure 2.2 shows these aluminum positioning fixtures on one of the nine mock fuel (all aluminum) assemblies fabricated at LLNL based on the original fabrication drawings from B&W. The mock assemblies will be labeled to differentiate them from the uranium-bearing assemblies.

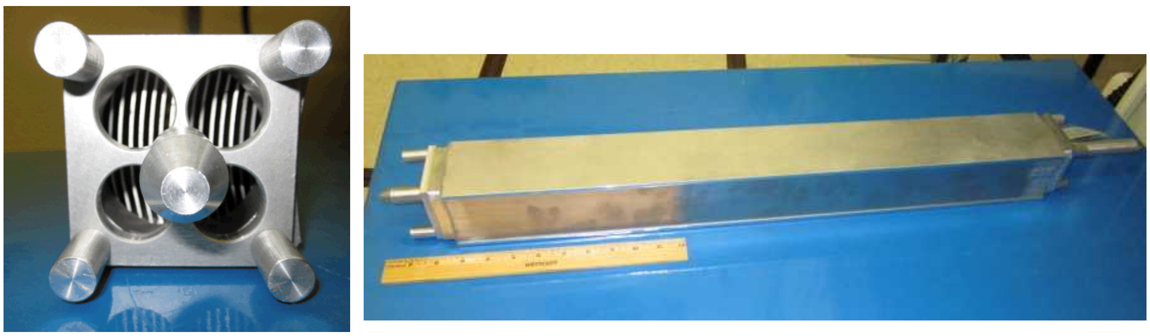

Figure 2.2: Photograph Showing Cross Section (right) and Full-Length View (left) of an Aluminum Mock Assembly with Positioning Fixtures on the Top and Bottom.

2.2 Description of ISSA Tank and Assembly

The ISSA consists of a large cylindrical steel tank that is large enough to provide at least 4” of water (infinite water reflection) on all sides of the fuel array. The tank will be filled with water and nine of the fuel assemblies will be placed into a 3×3 array in the water. In the bottom of the tank, there are alignment plates (either Lucite or aluminum) with multiple holes that match up with the fuel assembly alignment pins. The plates allow for the varied spacing between assemblies in the array. Once an array is built, a second alignment plate can be placed on top to ensure the proper spacing between the elements. Helium 3 (^{3}He) neutron detectors may be used in the water to measure neutron fluence. These neutron detectors will be placed within a polyethylene sleeve that will moderate the neutrons to increase the ^{3}He capture cross section, allowing measurement when the water height is varied.

2.3 Description of Operations

The ISSA fuel assemblies are currently stored in DOT-6M/2R containers (110 gallon drums with an inner pipe centered by a Celotex inner lining) laid on their sides on a large rack along the southern wall of Room 129A in B255. Figure 2.3 shows a fuel element in a DOT-6M/2R drum as part of the storage array. Storage and inspection operations are covered by CSM 1619 and a separate IWS.

Figure 2.3 Fuel Element Inside of a DOT-6M/2R Drum in the Storage Array. The element sits in a central pipe, with spacing provided by Celotex, a low-density fiber material.

ISSA course operations will begin by opening the DOT-6M/2R drums containing 9 of the 26 elements. The rest of the drums will remain closed and locked. The nine fuel assemblies will be taken out of the DOT-6M/2R drums and brought over to the ISSA tank. The assemblies may be hand-carried or placed on a cart to move them to the other side of the room.

The tank will be accessed by students and instructors via a raised platform structure. Initially, the tank may be dry or full of water, depending on the desired experiment. The ISSA assembly will be used to demonstrate various criticality, reactor physics, and neutron kinetics concepts. A short description of some of the experiments is given below.

Criticality and Multiplication Experiments

- **Approach to Critical by Mass**- a series of multiplication measurements will be taken as fuel elements are added to the assembly, up to 9 elements.
- **Approach to Critical by Spacing**- the array will be split into two halves and brought together.

- **Approach to Critical by Water Height**- the fuel elements will be put into a dry tank and a series of multiplication measurements will be taken as water is added to the tank.
- **Effect of Temperature**- the effect of water temperature on multiplication will be measured by heating the water in the tank.
- **Effect of Moderation**- the pitch (spacing between elements) will be varied to examine the effect of water moderation on the assembly.

Reactor Physics Experiments

- **Subcritical Safety Rod Calibration**- one of the 9 assemblies or a neutron absorber plate will be slowly pulled out of the core and its effect on multiplication will be measured.
- **Void Coefficient**- bubbles will be injected into the tank via an air hose and the effect on multiplication will be measured.

Neutron Kinetics Experiments

- **Source-Jerk Reactivity Measurements-** The neutron source will be removed quickly from the assembly and the resulting detector response will be monitored.
- **Multiplicity Counting-** Using the ^{3}He tubes in list-mode will allow for examination of the multiple neutrons from fission that simultaneously hit the detectors.
- **Kinetics of a Step Reactivity Insertion-** Time-dependent neutron counts during positive reactivity increases to the assembly (addition of fuel, moderator, etc.) will be monitored.

After any number of experiments are completed, the nine fuel assemblies will be removed from the water tank and placed on a table or cart to dry. The fuel assemblies will then be taken back to the DOT-6M/2R drum storage rack and repackaged.

3.0 REQUIREMENTS

This document satisfies the format and content requirements of DOE-STD-3007-2007, *Guidelines for Preparing Criticality Safety Evaluations at Department of Energy Non-Reactor Nuclear Facilities*. The document also satisfies additional LLNL content requirements specified in CS-P-004, Rev. 6, *Criticality Safety Evaluations.*

4.0 METHODOLOGY

The LLNL-developed Monte-Carlo code COG[1] (version 10) was used to make all calculations of the effective neutron multiplication constant (k_{eff}). The COG10 code has been installed and verified[2] on the Nuclear Criticality Safety Division's *Auk* unclassified server for criticality safety applications. All calculations utilized the ENDF/B-VI (Release 7) pointwise (continuous) cross-sections and ENDF/B-VI (Release 2) $S(\alpha,\beta)$ data.

This methodology has been validated against very closely-related critical experiments with highly enriched uranium (HEU) MTR-type fuel (HEU-MET-THERM-006, SPERT-D Experiments) using the benchmark specifications from the International Handbook of Evaluated Criticality Safety Benchmark Experiments (ICSBEP)[3]. Additionally, since the SPERT-D experiments had HEU-aluminum alloy fuel meat instead of HEU oxide-aluminum fuel meat and did not investigate polyethylene as a material of interest, cases from HEU-COMP-MIXED-001 and HEU-MET-THERM-031 were also used as benchmarks.

Details of the methodology used to determine the Upper Safety Limit (USL), including details on the evaluated cases and their results, are given in Appendix B. An overview of the COG10 benchmark results are presented graphically in Figure 4.1 below. The ordinate is labeled Normalized Calculated k_{eff}, with error bars added for the combined uncertainty in the benchmark experiment and computational model. The abscissa is labeled MFE, which is the median energy of those neutrons producing fission events. The USL was determined to be 0.9654.

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[1] *COG: A Multiparticle Monte Carlo Transport Code, Version 10*, **CCC-724**, contributed by the Lawrence Livermore National Laboratory to the Radiation Safety Information Computational Center at the Oak Ridge National Laboratory, released February 2006.

[2] C. Lee and P. Chou, *Verification of the Installation of COG10 on Auk,* CSAM10-144, Lawrence Livermore National Laboratory, November 18, 2010

[3] NEA/NSC/DOC(95)03, *International Handbook of Evaluated Criticality Safety Benchmark Experiments*, September 2005 Edition, Nuclear Energy Agency, Organisation for Economic Cooperation and Development.

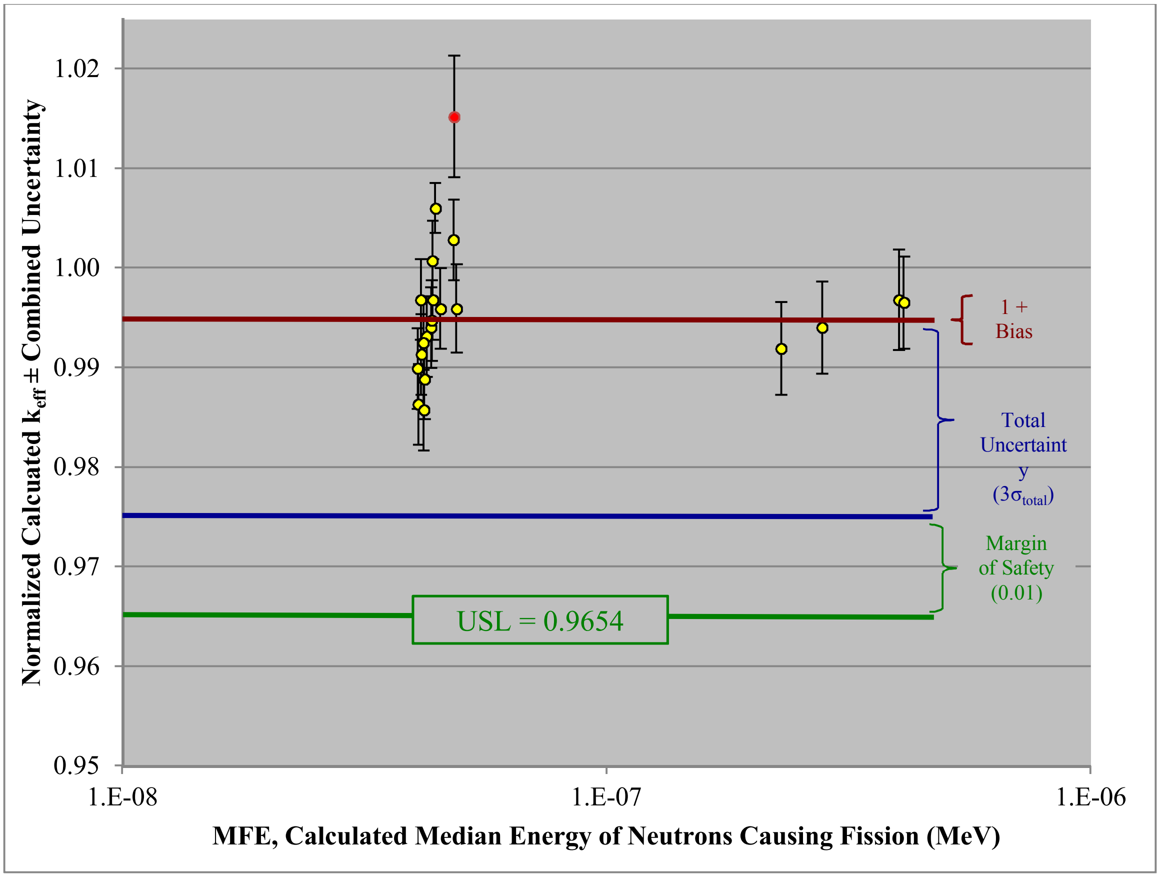


Figure 4.1: Thermal HEU Benchmark Results on the Auk Workstation with COG 10 and the ENDFB6R7 Neutron Cross Section Library. As discussed in more detail in Appendix B, the point shown in red (Benchmark HMT-006-013) was not used to calculate the USL as there are known problems with the benchmark specification that lead to large over-prediction of k_{eff}.

5.0 DISCUSSION OF CONTINGENCIES

Table 5-1 lists the contingencies (or events) together with the physical (design features) or administrative controls that are sufficient to preclude any credible criticality accident risk. A synopsis of the technical basis is provided in the far-right column. The details are provided in Section 6.

Table 5-1. **Contingency Table**

Contingency	Design Features	Controls and Barriers	Technical Basis
Normal Conditions			
Normal operations		IWS approves nine fuel assemblies and all configurations as part of an approved laboratory notebook	$k_{eff} = 0.9582$ < USL
Dry Fuel	Limited fissile loading, fuel assembly geometry	Criticality is incredible without moderating fuel	ANS 8.1 $M_{ISSA} = 2.09$ kg << 20.1 kg
Effect of Spacing	Optimal fuel spacing (moderation) was found to be 0.35"	Nine assemblies are subcritical at optimal spacing and fully water reflected	$k_{eff} = 0.9582$ < USL
Effect of Detectors and Sources	Most detectors/sources are physically small and have no effect on reactivity with the potential exception of large amounts of polyethylene or Lucite used as sleeves around ^{3}He detectors	Polyethylene in detectors does not impact k_{eff} Lucite in detectors was found to challenge the USL, so it will not be allowed unless explicitly analyzed	$\Delta k_{eff} \sim 0$
Effect of Grid Plates	Lucite or Aluminum grid plates may be used to align ISSA fuel assemblies	Three 1" gridplates (either Lucite or Al) does not impact k_{eff}	$\Delta k_{eff} \sim 0$
Effect of Temperature	Low temperatures could increase density of water	Increasing density of water to 1.0 g/cc does not impact k_{eff}	$\Delta k_{eff} \sim 0$
Effect of Lower Fuel Loading	Less uranium mass per assembly (220 vs 232 grams) results in lower k_{eff} for arrays	No controls required	$k_{eff} < 0.9582$ < USL

Effect of Mock Assemblies	Mock assemblies replacing fuel assemblies (0 vs 232 grams of uranium) results in lower k_{eff} for arrays	No controls required	$k_{eff} < 0.9582 <$ USL
Abnormal Conditions			
Over-mass	An additional fuel assembly (10 total) placed in a flooded tank at optimal spacing challenges the USL	1. IWS only allows 9 fuel assemblies to be outside of storage array at a time 2. All other assemblies are required to be secured by a lock	Beyond Extremely Unlikely
Small Fire	Credible fire is a small electrical fire of the smoke and stink type that does not involve fissile materials	1. Tank is usually flooded, making fire difficult 2. Automatic wet-pipe, fusable-link sprinklers 3. Hand extinguishers 4. Fire would deform (melt) fuel into a form less conducive to criticality	$k_{eff} <$ USL
Earthquake	Ground movement could reconfigure ISSA fuel assemblies in tank or DOT-6M/2R storage rack	1. Rearrangement of fuel in tank would result in less reactive configuration (sub-optimal) 2. Assemblies in storage array will remain in locked DOT-6M/2R drums, which provide spacing and effective isolation	$k_{eff} <$ USL

6.0 EVALUATION AND RESULTS

In order to calculate k_{eff} for various ISSA configurations using COG, a model of the fuel assemblies was developed based on Babcock and Wilcox Fuel Fabrication Facility drawings for the Omega West Reactor fuel. A cross-sectional view of the COG10 19 fuel plate arrangement is shown in Figure 6.1. Figure 6.2 shows a side-on length view of the fuel assembly and the 3/8" end cap geometry at the top and bottom of the fuel assembly. The curved surfaces of the end caps are the same as the outside fuel plates. Additional detail is provided in the COG10 input files included as Appendix C. To bound the calculations, only the higher fuel loading (12.2 grams per plate) assemblies were modeled. A high-resolution volume calculation was done in COG10 and each fuel assembly was found to contain 237.35 grams of ^{235}U, slightly more than the reference 232 grams per assembly. This will result in conservative k_{eff} criticality safety calculations.

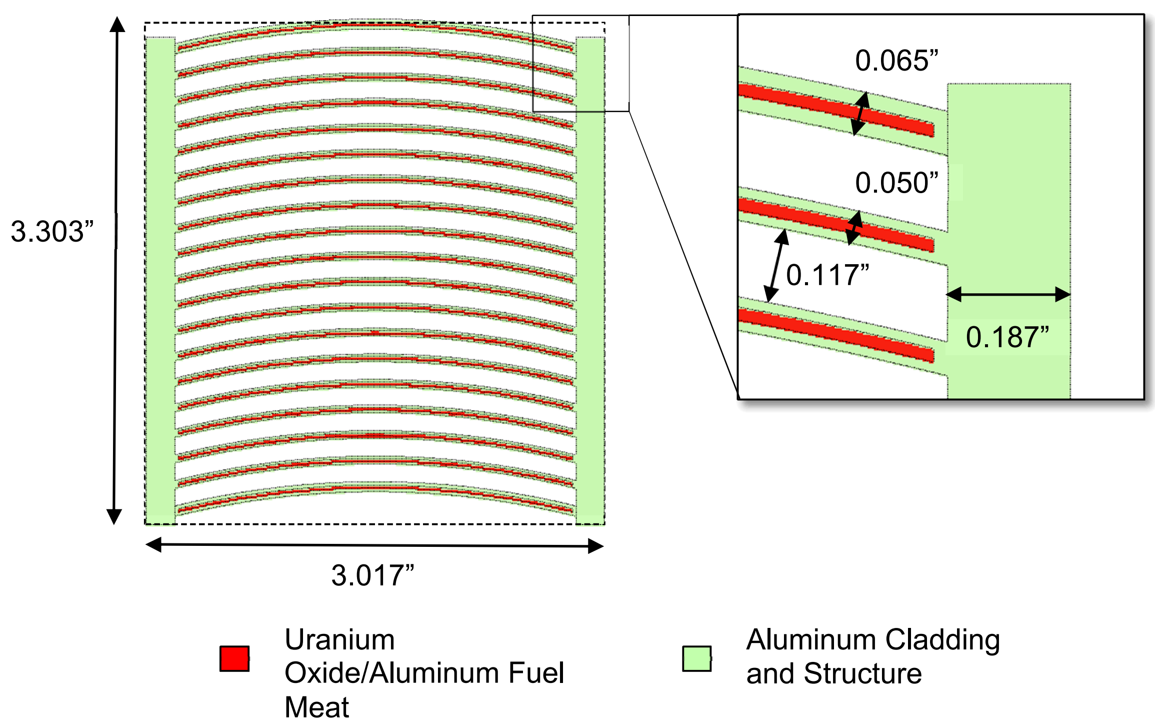


Figure 6.1: COG10 Model of the 19-Plate ISSA Fuel Assembly. The fuel meat (red) in all plates is 0.02" thick, but the two outermost fuel plates have slightly thicker aluminum cladding because they provide structural support to the assembly. The reference inner radius for all fuel plates is 5.5".

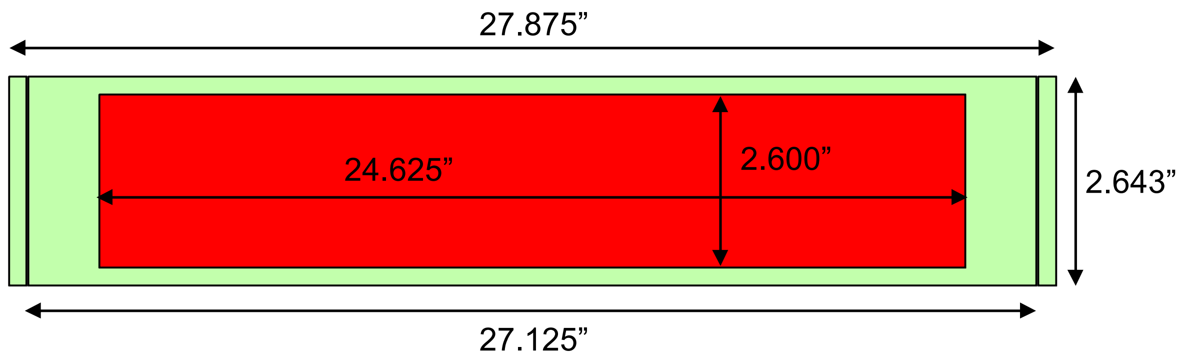
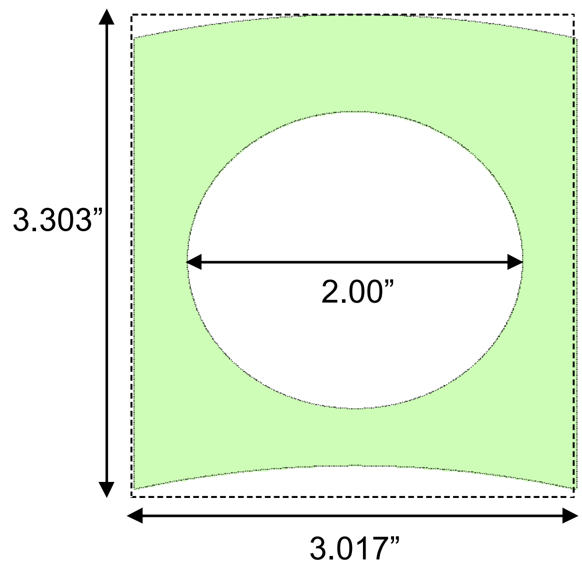


Figure 6.2: COG10 Model of the Fuel Assembly Showing Extent of Fuel Meat. The fuel meat (red) does not extend the entire length of the fuel plate, as shown in the above figure. The plates are 27.125” long, but there are 3/8” thick aluminum end caps on either side of the fuel assembly. A cross-sectional view of the end cap is shown at right.



6.1 NORMAL CONDITIONS

6.1.1 Dry Fuel

Fuel will be transported (by hand or on a cart) from the storage array to the experimental tank by students or instructors. Before the fuel is placed into the water tank, there is much less fuel than would be required for criticality. The total mass present in all 26 assemblies is approximately 6 kg of ^{235}U. Nine assemblies include 2.09 kg of ^{235}U. The water-reflected subcritical mass for ^{235}U in spherical, full-density metal form, as reported by American Nuclear Society (ANS) Standard 8.1 is 20.1 kg. The fuel meat in the assemblies is made of a U(93) oxide and aluminum powder mixture with a much lower density than that of uranium metal (3.4 g/cc versus 18.8 g/cc). Therefore, under dry conditions, criticality is not possible.

6.1.2 Effect of Spacing on the Experimental Array

The fuel elements are designed to be near optimum moderation when submerged in water. A series of calculations were completed to determine the optimal spacing for the array, beginning with the nine fuel assemblies closely packed in water and then increasing the spacing between them. The distance, d, between assemblies is defined as shown in Figure 6.3. Full water reflection was modeled around the fuel assemblies.

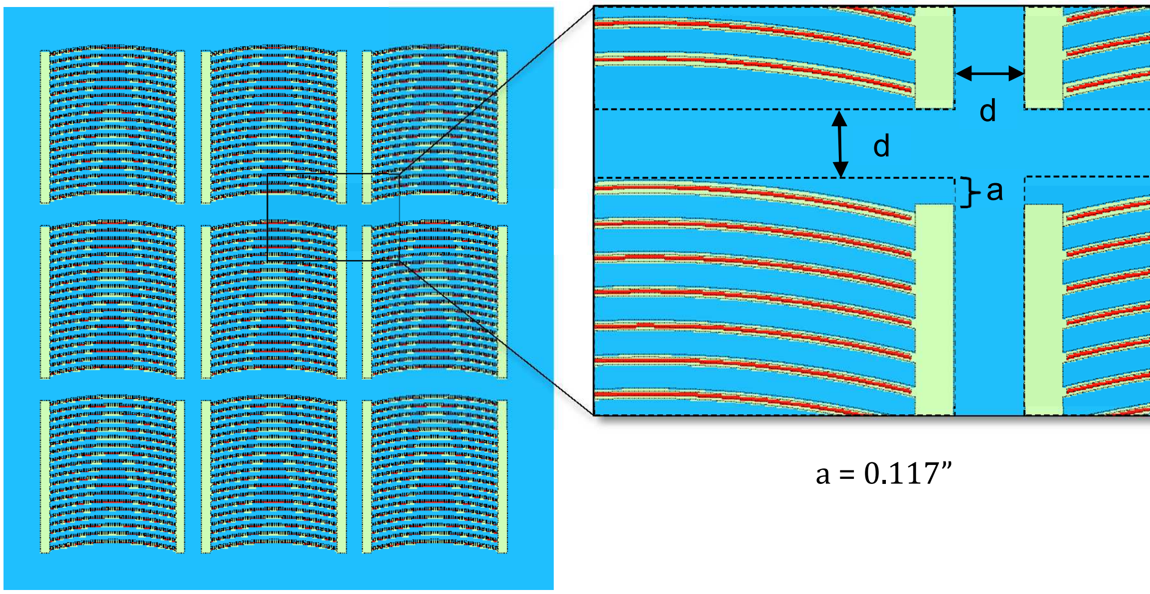


Figure 6.3: COG10 Model of the 9 Fuel Assembly ISSA Experimental Array. The nine fuel assemblies were modeled in water with full water reflection (blue). The distance between the assemblies was varied to find the optimal spacing, d.

The results of the COG10 spacing calculations are shown in Figure 6.4. When the fuel assemblies are closely packed (spacing of zero inches), the system is slightly under-moderated as the k_{eff} of the system initially increases as the spacing is increased. The optimal spacing was found to be 0.35” between the assemblies, with a maximum subcritical k_{eff} of 0.9582(13). Full isolation between assemblies was seen at approximately 10” spacing. All cases remained under the USL of 0.9654.

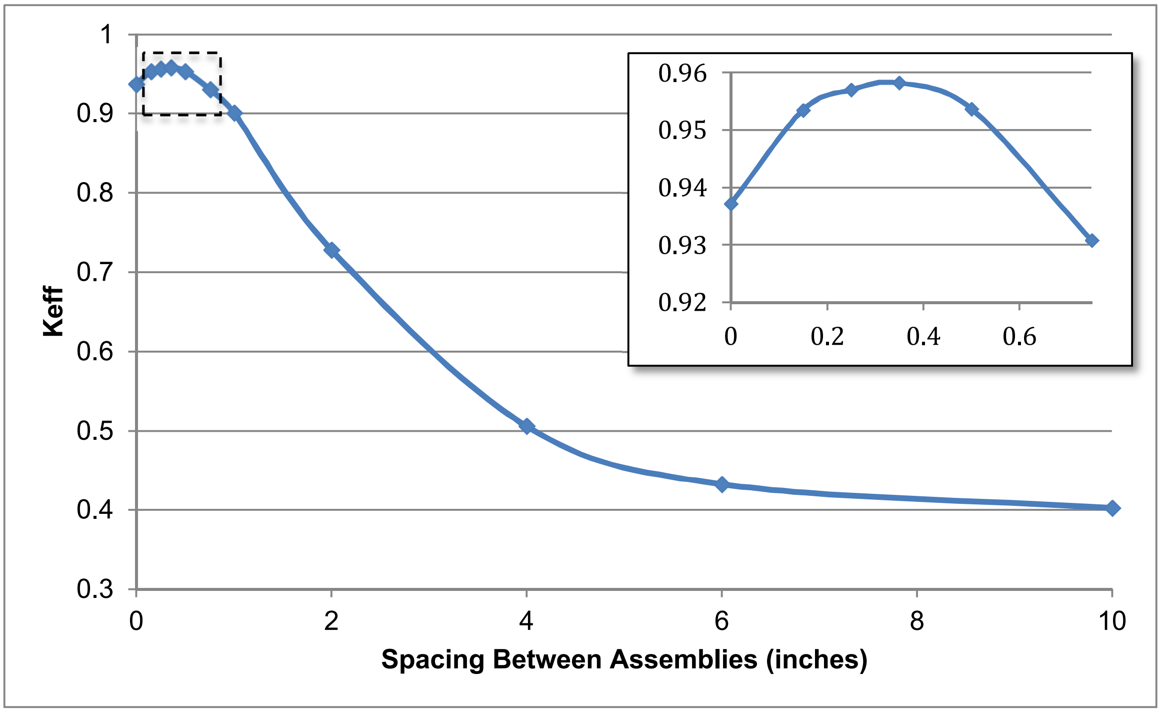
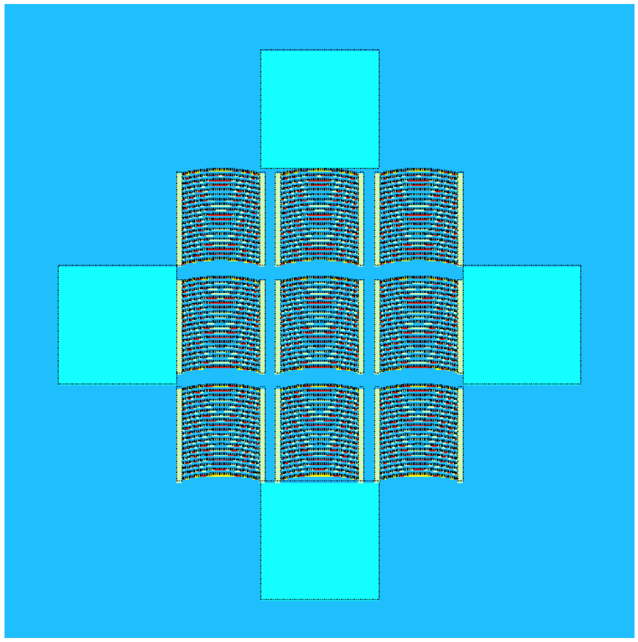


Figure 6.4: Effect of Spacing Distance Between Assemblies on k_{eff}. The nine fuel assemblies were modeled in water with full water reflection. The optimal spacing was found to be 0.35". Full isolation between assemblies was seen at approximately 10" spacing. The smaller inset graph shows the peak detail.

6.1.3 Effect of Detectors

A number of different detectors and detection methods will be used to quantify the observable quantities of the ISSA assembly. Many of the detectors, such as activation wires or foils and a flux-traversing probe, are physically very small and will thus not impact the multiplication of the system. However, ^{3}He tubes embedded in large amounts of polyethylene (used to ensure adequate neutron moderation) will be used to measure the neutron flux from the assembly. These detectors will be placed in the tank surrounding the assembly. A bounding calculation was completed to examine the effect of the neutron detectors on the ISSA array. As shown in Figure 6.5, four 4" × 4" x 30" polyethylene boxes were modeled as touching the flooded 0.35" spacing array of nine assemblies. The boxes extend the entire length of the assemblies and the polyethylene was modeled as high density (ρ = 0.967 g/cm^3) CH_2. This arrangement was shown to have a negligible effect on k_{eff}, as the result (CaseID: 4spoly, k_{eff} = 0.9592(13)) was comparable to the flooded 0.35" spacing case without detectors (k_{eff} = 0.9582(13)).



CaseID: 4spoly, k_{eff} = 0.9592(13)

Figure 6.5: COG10 Model of the ISSA Experimental Array with Polyethylene Boxes. The nine fuel assemblies were modeled in water with full water reflection and optimal 0.35” spacing. Four 4” × 4” x 30” polyethylene rectangular boxes were modeled touching the array on four sides (shown in light green).

Lucite ($C_5H_8O_2$, $\rho = 1.2$ g/cm^3) was also investigated as a detector material. A similar model as the polyethylene was employed, although this time Lucite was substituted for the 4” × 4” x 30” polyethylene rectangular boxes. K_{eff} for this case did challenge the safety limit (k_{eff} = 0.9714(13), CaseID: 4sluc). Therefore, if Lucite detectors are to be used, they must be specifically analyzed for their effect on multiplication before they are allowed in the ISSA tank.

6.1.4 Effect of Grid Plates

Grid plates will be used in the tank to keep the desired spacing between fuel assemblies. Two calculations were run to determine the effect of the grid plates on the system multiplication. In the first case, three 1” thick, 14” square Lucite ($C_5H_8O_2$, $\rho = 1.2$ g/cm^3) grid plates were modeled, one at the bottom of the fuel assemblies, one at the top of the assemblies, and one at the mid-plane of the assemblies. In the second case, three 1” aluminum ($\rho = 2.7$ g/cm^3) grid plates were modeled. Figure 6.6 shows a cross-sectional view of the mid-plane grid plate and a side-on view of all three grid plates and their locations relative to the fuel length. For both calculations, the fuel was modeled at 0.35” spacing with full water reflection.

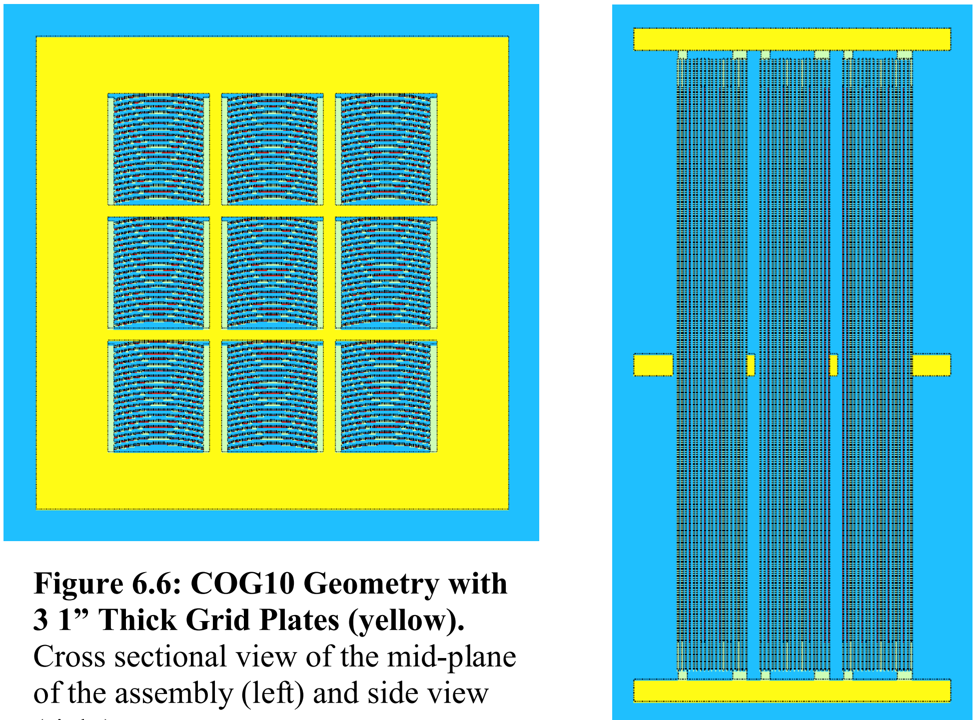


Figure 6.6: COG10 Geometry with 3 1" Thick Grid Plates (yellow). Cross sectional view of the mid-plane of the assembly (left) and side view (right).

For the aluminum grid plates, the model returned a keff of 0.9525(13), CaseID: agrid. This is slightly reduced from the 0.35" spacing model without the grid plates and is likely due to the fact that water (moderator) is being displaced by the aluminum grid plates. With Lucite grid plates, the result is not statistically different from the 0.35" spacing case (CaseID: lgrid, $k_{eff} = 0.9577(13)$), which is not surprising as Lucite has similar moderating properties as water.

Therefore, whether the grid plates are made of Lucite or aluminum, there is negligible effect on multiplication for plates under 1" of thickness.

6.1.5 Effect of Temperature

For the previous cases, water was modeled with a density of 0.9982 g/cm^3, which is water at 20°C. With lower temperatures, water density approaches 1.0 g/cm^3, so an additional set of calculations were run to determine the effect of lower temperatures. Figure 6.7 shows the results of spacing versus k_{eff} for the two different water densities.

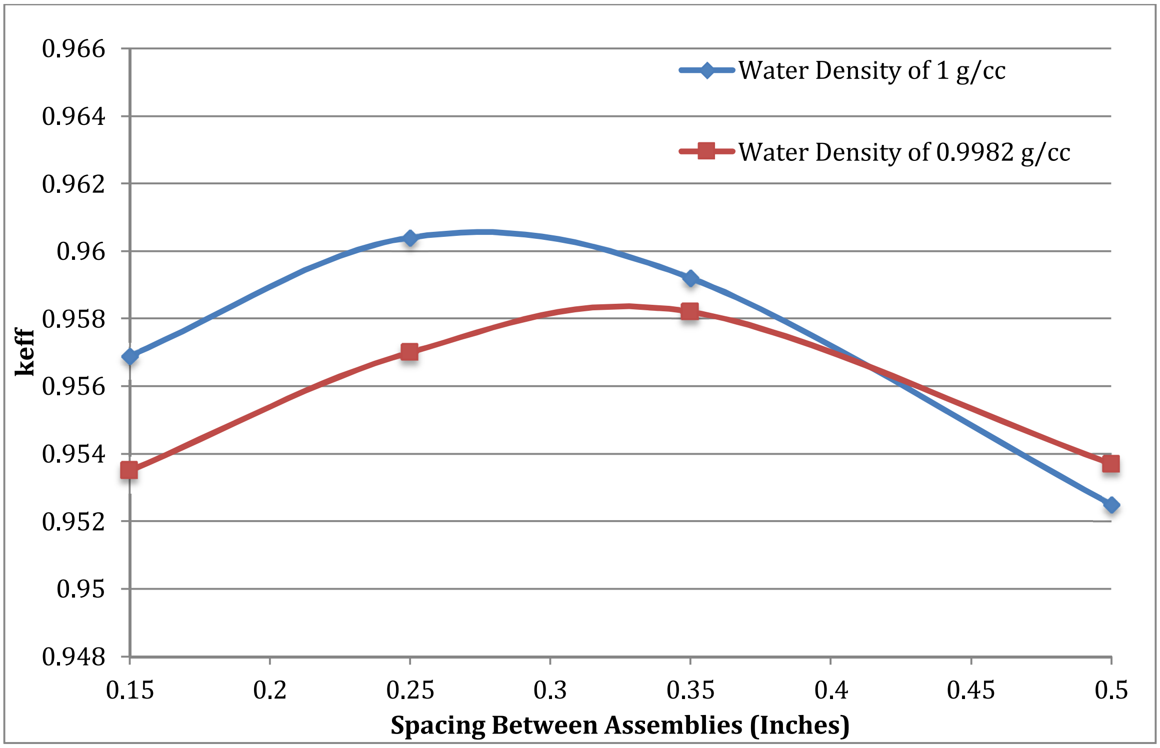


Figure 6.7: Effect of Water Density (Difference in Temperature) on Multiplication of Nine ISSA Fuel Assemblies at Varied Spacing. The nine fuel assemblies were modeled in water with full water reflection. The optimal spacing peak was found to shift to a lower spacing at the higher water density. The difference between the two curves was not statistically significant.

As shown by Figure 6.7, the curve at higher water density (blue) peaks at a lower spacing (0.25") than the lower water density curve (peaks at 0.35"). This is expected as it takes less water at higher density to achieve the same moderating effect. Despite the difference in appearance of the curves, the difference in multiplication factor between water at 1.0 g/cc (4°C) and the water at 0.9982 (20°C) was not statistically significant. The peak for the blue curve occurs at a spacing of 0.25" and a keff of 0.9604(13), while the peak for the red curve occurs at a spacing of 0.35" and has a keff of 0.9582(13), which have overlapping uncertainties.

Increases in temperature over 20°C will serve to reduce the water density and thus reduce k_{eff}. Therefore, no controls are necessary for heating the water in the ISSA tank.

6.1.6 Effect of Lower Fuel Loading

As mentioned in Section 2, Y-12's inventory records indicate that nine of the ISSA fuel assemblies have a lower fissile loading of 220 grams of ^{235}U instead of 232 grams. The class might want to use either kind of assembly for the ISSA array. Using the 220 gram fuel assemblies will result in a decrease in multiplication as fissile mass will be reduced. Therefore, no controls are needed to ensure only 232 gram fuel assemblies are used.

6.1.7 Effect of Mock Fuel Assemblies

During some of the experiments, the instructors will want to place mock fuel assemblies into the 9 element fuel array in the water tank. These mock assemblies are all aluminum (contain no uranium) and will be clearly labeled. Using the zero gram fuel assemblies in the array will result in a decrease in multiplication as fissile mass will be reduced. Therefore, no controls are needed for the mock fuel assemblies.

6.2 ABNORMAL CONDITIONS

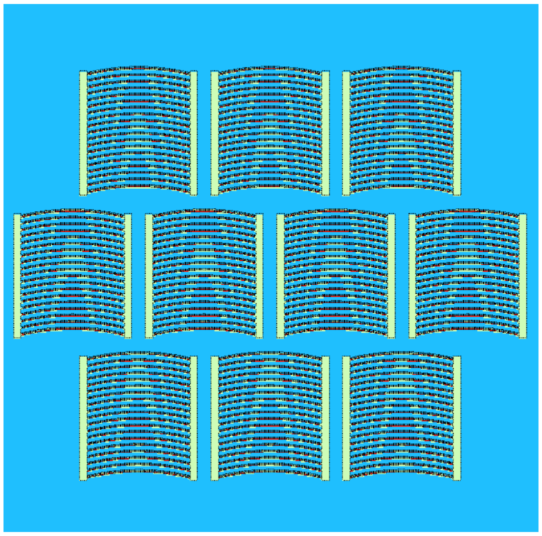
As shown from the above normal condition calculations, nine assemblies optimally moderated by water and fully water reflected are subcritical. Upset conditions with more effective moderators are considered incredible due to the configuration of the curved assemblies and the lack of large quantities of oils or other liquid moderators with a higher hydrogen density than water. Reflection upsets are likewise considered incredible as to be more effective than full water, additional reflectors would have to be placed in the water tank around a flooded assembly and would not be close-fitting except by deliberate design. A control is put in place to ensure all close-fitting reflectors are controlled.

CONTROL: The IWS shall specify all equipment authorized for placement within the ISSA tank.

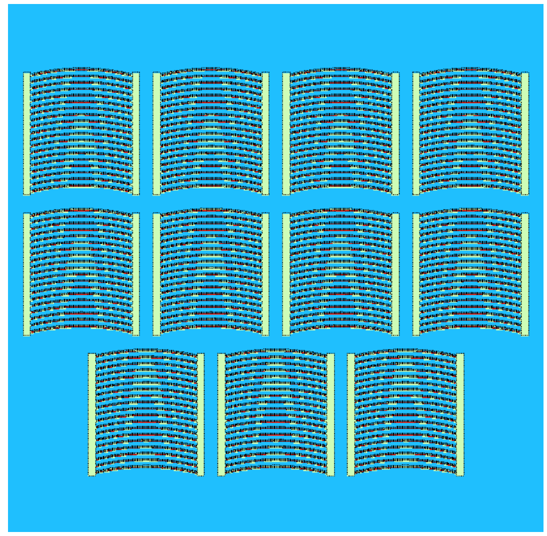
Abnormal conditions considered with the ISSA include unauthorized addition of more than nine assemblies into the tank array, earthquake, and fire.

6.2.1 Unauthorized Addition of Fissionable Material (Over-mass)

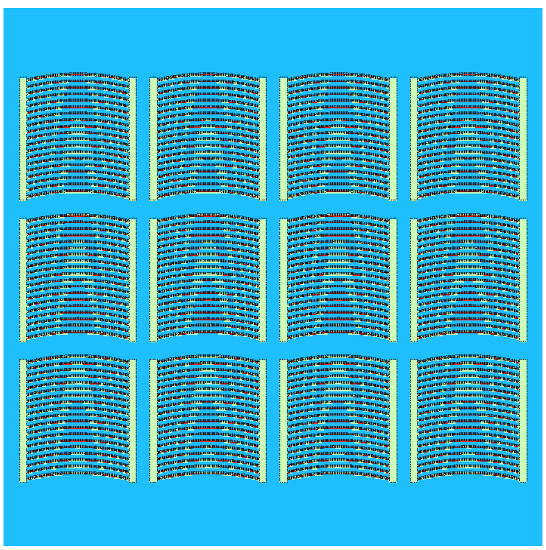
Addition of sufficient mass of other fissionable materials will achieve criticality *in any system*. COG10 calculations were run to determine the number of additional assemblies required to achieve criticality at the optimal 0.35” spacing. Geometries for these models are shown in Figure 6.8.



(a) One Additional Assembly
CaseID: omc1, k_{eff} = 0.9897(13)



(b) Two Additional Assemblies
CaseID: omc2, k_{eff} = 1.0090(13)



(c) Three Additional Assemblies
CaseID: omc3, k_{eff} = 1.0283(14)

Figure 6.8: COG10 Geometries for Over-mass Conditions with the ISSA Fuel. As seen in Figure 6.6a, one additional assembly added in the most reactive configuration (approximating a cylinder) results in a keff above the USL. Two additional assemblies is likely a critical configuration.

As shown by the COG10 calculations presented in Figure 6.8, only one additional assembly (10 total assemblies) in an approximately cylindrical configuration with 0.35" spacing and water reflection and moderation may be critical (above the USL). Two additional assemblies (11 total assemblies) is the predicted critical configuration.

When the fuel is dry, there is no criticality hazard. An overmass that would cause a potential for criticality would require removal of additional elements from the DOT-6M/2R storage drums and placement of the elements into unauthorized configurations within the ISSA tank. However, due to the fact that additional fuel assemblies do exist and are stored in the same room as the ISSA tank, a robust control on fissile mass is required.

CONTROL: Only nine fuel assemblies may be out of the DOT-6M/2R shipping package storage array at any time. All other shipping packages must be secured with a lock to prevent unauthorized access to the fuel.
Note: This control does not apply to the aluminum mock assemblies.

6.2.2 Fire

Equipment used to support the ISSA, including neutron detectors, water pumps, and other electrical equipment could pose a potential fire risk if poorly maintained or abused. This equipment is professionally maintained and checked for proper performance prior to use with fissile materials. Very few combustibles will be used within the ISSA workstation. The main source of combustibles would be the polyethylene used in the detectors. Additionally, the ISSA tank is full of water and the fuel will be submerged for almost all experiments (excepting the approach to critical on water height). The room has a fusable-link, wet pipe sprinkler system to respond to a fire.

The worst credible scenario is for the electrical equipment to overheat and possibly deform (or melt) some electrical or plastic components resulting in a small fire that would be terminated by either automatic activation of the sprinklers or hand fire extinguishers from the instructors. Hand-held fire extinguishers are available in the room for use by the RI, instructors, or other qualified personnel for putting out these types of fires.

Good Practice: Instructors and responsible individuals should be trained in the use of fire extinguishers by completing fire extinguisher training.

The ISSA fuel is designed to be near optimal moderation in its current configuration when immersed in water. Even if a fire were large enough to melt the aluminum cladding on the fuel (requiring a large fire of at least 660°C, the melting temperature of aluminum), the fuel would deform into a shape much less conducive to criticality, eliminating the moderating channels between the fuel and coalescing into a solid lump. As mentioned in Section 6.1.1, the quantities of ^{235}U in the fuel cannot support criticality without moderation.

6.2.3 Earthquake

Section 6.1 (Normal Conditions) analyzed the ISSA fuel under optimal spacing and fully water reflected. In an earthquake, it is conceivable that the nine fuel assemblies could re-orient themselves in the tank. However, this rearrangement would be sub-optimal and thus less reactive. The optimal spacing and fully water reflected case would similarly bound the nine fuel elements outside of the tank (during transit or while they are drying off) if they were to be rearranged due to earthquake.

An earthquake could also impact the storage array, but the assemblies are stored in closed and locked DOT-6M/2R drums that will maintain the spacing of the units in the storage array. Therefore, criticality caused by an earthquake is not considered credible.

7.0 CONTROLS

There are two controls resulting from the evaluation of the ISSA operations.

CONTROL: The IWS shall specify all equipment authorized for placement within the ISSA tank.

CONTROL: Only nine fuel assemblies may be out of the DOT-6M/2R shipping package storage array at any time. All other shipping packages must be secured with a lock to prevent unauthorized access to the fuel.
Note: This control does not apply to the aluminum mock assemblies.

8.0 CRITICALITY HAZARD TYPE

The Criticality Hazard Type is Type 1. Water may be used as required to suppress a fire. Treat as any other radioactive material fire.

9.0 SUMMARY AND CONCLUSIONS

This document satisfies the DOE O 420.1B, CS-P-004, and DOE-STD-3007-2007 requirements for a criticality safety evaluation. No credible criticality accident scenarios were identified. Only nine fuel assemblies will be allowed outside of the DOT-6M-2R storage array at a time, ensuring segmentation of the fissile material, and the nature of the process, shown by this evaluation, does not pose a criticality potential with only nine fuel assemblies, even under optimally moderated and fully water reflected conditions.

Appendix A

Fuel Specification and Drawings from Babcock and Wilcox

Appendix B
COG10 Validation Details

B.1 Benchmark Experiments

COG10 computational models for 19 experimental critical benchmarks were developed based on details found in *Volume II, Highly Enriched Uranium Systems* of the ICSBEP Handbook. Only thermal benchmarks were chosen, as the ISSA fuel will be optimally moderated during the experiments. Details of the cases are provided in Table B-1.

Table B-1: Selected Benchmarks from Volume II of the ICSBEP

Evaluation ID	Title	Number of Cases Selected
HEU-MET-THERM-006	SPERT-D Aluminum-Clad Plate-Type Fuel in Water, Dilute Uranyl Nitrate, or Borated Uranyl Nitrate	15[a]
HEU-MET-THERM-031	2x2 Array of Highly Enriched Uranium, Moderated and Reflected by Polyethylene	1
HEU-COMP-MIXED-001	Arrays of Highly Enriched Uranium Dioxide Reflected by Polyethylene	4[b]

[a] Only water moderated arrays that did not include poisons were evaluated and HMT-006-013 was not used to validate COG10
[b] Only thermal critical configurations were evaluated

B.2 Selected Code Options

Numerous code options are available to the user and default values are employed more often than not with a few notable exceptions that are relevant to validation and use. The total number of neutron histories simulated for each benchmark is specified in the basic data block as follows:

```
npart=5000
nbatch=1100
sdt=0.0001
nfirst=100
```

Also, the ENDFB6R7 neutron cross section library is employed for all benchmarks as is the available $S(\alpha,\beta)$ treatment for selected elements where appropriate. The only exception is the use of the RED2002 neutron cross section library for Zn and Pb. To this end, neutron cross section data is specified in the mix data block as follows:

```
nlib=ENDFB6R7
sablib=COGSAB (as necessary)
nlib2=RED2002 (as necessary)
```

B.3 Validation Methodology

Each benchmark result is normalized to the delayed critical condition ($k_{effective}$ = 1) as follows:

$$k_{normalized} = (k_{calculated} - k_{expected}) + 1$$

The associated uncertainty ($\sigma_{combined}$) for each benchmark result becomes:

$$\sigma_{combined} = \sqrt{(\sigma_{calculated})^2 + (\sigma_{expected})^2}$$

The determination of an Upper Subcritical Limit (USL) to differentiate subcritical and critical conditions to a high probability by computation requires an assessment of the bias, the total uncertainty, and a margin of safety as follows:

$$\text{USL} = \{1 + \text{bias}\} - \{\text{total uncertainty}\} - \{\text{margin of safety}\}$$

Thus, a conservative criterion for general application is:

$$k_{calculated} + 3\sigma_{calculated} \le \text{USL} = \{1 + \text{bias}\} - \{3\sigma_{total}\} - \{0.01\}$$

This criterion ensures better than 99.8% confidence that the USL lays below the selected benchmark results with an additional 0.01 margin of safety. This margin of safety was selected because of the highly relevant benchmark set employed.

In practice, a simple estimate of {1+ bias} is the un-weighted average ($k_{average}$) of the calculated $k_{normalized}$ benchmark results:

$$k_{average} = \frac{\sum_{i=1}^{n} (k_{i,\ normalized})}{n}$$

The total uncertainty {$3\sigma_{total}$} is determined from the combination of the uncertainty of the bias estimate (σ_{bias}) and the average of the combined uncertainties of the individual benchmark results ($\sigma_{average}$) according to the following relations:

$$\sigma_{total} = \sqrt{(\sigma_{bias})^2 + (\sigma_{average})^2}$$

$$\sigma_{bias} = \sqrt{\frac{\sum_{i=1}^{n} (k_{i,\ normalized} - k_{average})^2}{n}}$$

$$\sigma_{average} = \sqrt{\frac{n}{\sum_{i=1}^{n} \frac{1}{(\sigma_{i,\ combined})^2}}}$$

The 20 HEU benchmark results are provided in Table B-2 and illustrated in Figure B.1 (same as Figure 4.1). From this data, $k_{average}$ = 0.9945 {1 + bias} where σ_{bias} = 0.0049 and $\sigma_{average}$ = 0.0040 are combined to yield $3\sigma_{total}$ = 0.0191 {total uncertainty}. Where a {margin of safety} of 0.01 is desired, the corresponding USL becomes 0.9654.

The result from HMT-006-013 was not used to in the calculation to determine the USL. As reported in the ICSBEP benchmark evaluation, both SCALE and MCNP5 codes produce a similar result as COG10, in which k_{eff} is highly over-predicted. In discussions with personnel familiar with the SPERT-D experiments, it was clear that this bias is likely due to uncertainly in the water height measurement of the tank for this case. While the benchmark models this array as being fully water reflected on all sides, the experimental notes indicate that the water height did not provide full water reflection on the top side of this particular experiment. Thus, when modeled with full water reflection on all sides, the multiplication of Case 13 is over-predicted.

Table B.2: HEU Benchmark Results on the Auk Workstation with COG10 and the ENDFB6R7 Neutron Cross Section Library

Benchmark ID	Experimental Benchmark k-effective ($k_{expected}$)	Experimental Benchmark Uncertainty ($\sigma_{expected}$)	Calculated k-effective ($k_{calculated}$)	Calculational Uncertainty ($\sigma_{calculated}$)	Calculated Median Energy of the Neutrons Causing Fission (MeV)	Normalized Calculated k-effective ($k_{normalized}$)	Combined Uncertainty ($\sigma_{combined}$)
hcm001-15	1.0083	0.0050	1.0051	0.0006	4.02E-07	0.9968	0.0050
hcm001-16	1.0001	0.0046	0.9966	0.0006	4.12E-07	0.9965	0.0046
hcm001-17	0.9997	0.0046	0.9937	0.0006	2.79E-07	0.9940	0.0046
hcm001-18	1.0075	0.0046	0.9994	0.0006	2.30E-07	0.9919	0.0046
hmt031-01	1.0037	0.0024	1.0097	0.0006	4.43E-08	1.0060	0.0025
hmt006-01	1.0000	0.0044	0.9959	0.0006	4.90E-08	0.9959	0.0044
hmt006-02	1.0000	0.0040	0.9959	0.0006	4.54E-08	0.9959	0.0040
hmt006-03	1.0000	0.0040	1.0007	0.0006	4.37E-08	1.0007	0.0040
hmt006-04	1.0000	0.0040	0.994	0.0006	4.34E-08	0.9940	0.0040
hmt006-05	1.0000	0.0040	0.9931	0.0006	4.26E-08	0.9931	0.0040
hmt006-06	1.0000	0.0040	0.9925	0.0005	4.19E-08	0.9925	0.0040
hmt006-07	1.0000	0.0040	0.9913	0.0005	4.14E-08	0.9913	0.0040
hmt006-08	1.0000	0.0040	0.9863	0.0006	4.09E-08	0.9863	0.0040
hmt006-09	1.0000	0.0040	0.9899	0.0006	4.08E-08	0.9899	0.0040
hmt006-10	1.0000	0.0040	1.0028	0.0006	4.84E-08	1.0028	0.0040
hmt006-11	1.0000	0.0040	0.9947	0.0006	4.36E-08	0.9947	0.0040
hmt006-12	1.0000	0.0040	0.9968	0.0006	4.14E-08	0.9968	0.0040
hmt006-13*	1.0000	0.0061	1.0152	0.0006	4.85E-08	1.0152	0.0061
hmt006-14	1.0000	0.0040	0.9888	0.0005	4.21E-08	0.9888	0.0040
hmt006-15	1.0000	0.0040	0.9857	0.0006	4.19E-08	0.0000	0.0040
hmt006-16	1.0000	0.0040	0.9968	0.0006	4.38E-08	0.9968	0.0040

* Results from HMT-006-13 were not used to calculate the USL as there are known problems with the experimental benchmark that cause over-prediction of k_{eff}.

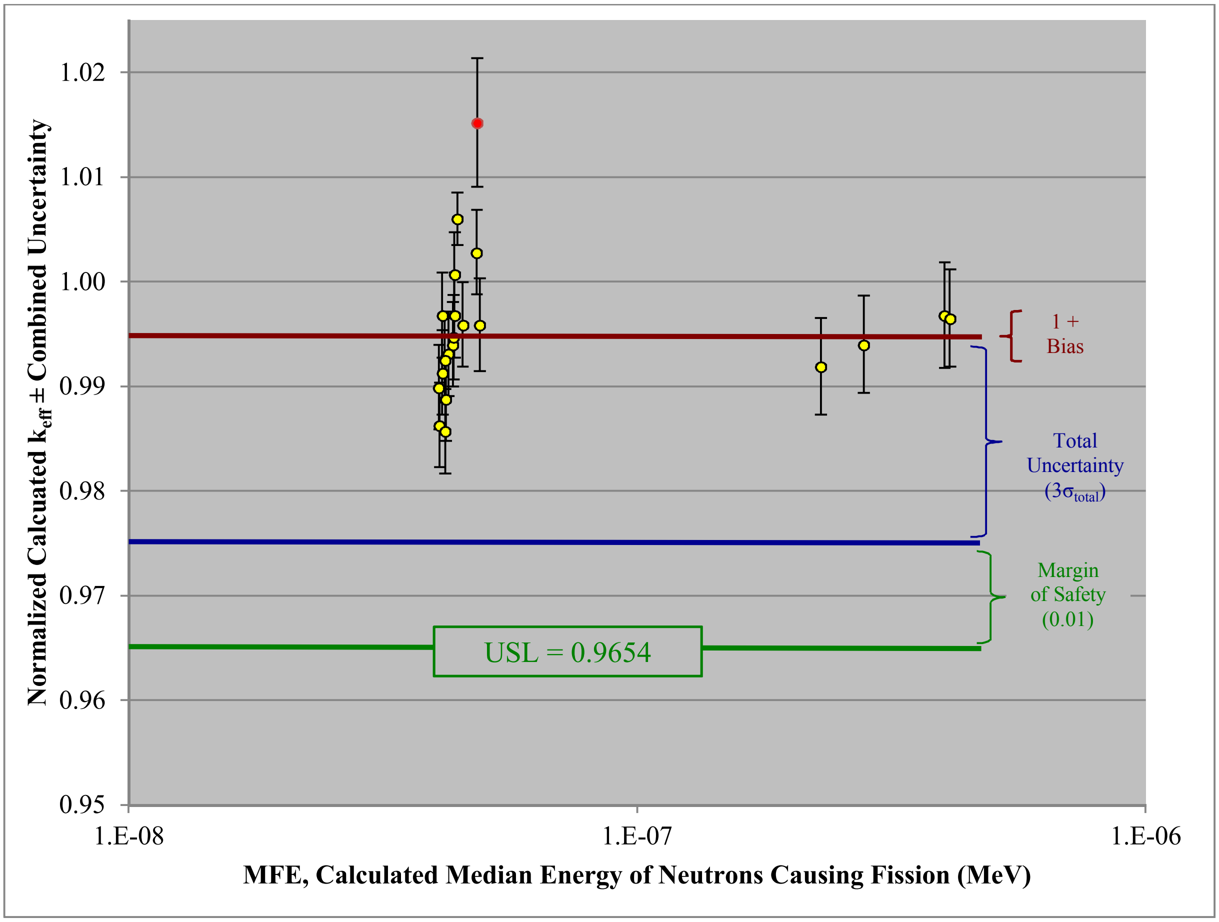


Figure B.1: Thermal HEU Benchmark Results on the Auk Workstation with COG 10 and the ENDFB6R7 Neutron Cross Section Library. The point shown in red (HMT-006-013) was not included in the USL determination, as there are known problems with the experimental benchmark.

Appendix C
Sample COG10 Input Files

CaseID: spp35, Inherently Safety Subcritical Assembly Model
$ 3x3 Array of Fuel Assemblies Water Tank - 0.35" Spacing

```
Basic

  neutron delayedn INCHES

Criticality

  npart=1000 nbatch=1000 sdt=0.0001 nfirst=100 norm=1. nsource=2 0 0 0  3 0 0

Assign-mc

  1 red 2 lime 3 lime 4 sky 5 gray


Mix

nlib=ENDFB6R7

mat=1 W-P 3.2748 u234 0.0020 u235 0.1837 u236 0.0010 u238 0.0104 o16 0.0358 al 0.7671 $
12.22g U-235 per plate
mat=2 al   2.7
mat=3 al   2.7
mat=4 a-f  0.9982 (h.h2o) 2 o16 1
mat=5 fe 7.78


Geometry


  use unit 5 asy1  -301 tr 0  3.653 -3.367  $ Assembly 1
  use unit 5 asy2  -302 tr 0  3.653  0      $ Assembly 2
  use unit 5 asy3  -303 tr 0  3.653  3.367  $ Assembly 3
  use unit 5 asy4  -304 tr 0  0     -3.367  $ Assembly 4
  use unit 5 asy5  -305 tr 0  0      0      $ Assembly 5
  use unit 5 asy6  -306 tr 0  0      3.367  $ Assembly 6
  use unit 5 asy7  -307 tr 0 -3.653 -3.367  $ Assembly 7
  use unit 5 asy8  -308 tr 0 -3.653  0      $ Assembly 8
  use unit 5 asy9  -309 tr 0 -3.653  3.367  $ Assembly 9

  fill 4
  boundary vacuum 500

$ ---------------------------------------------------------------------------------
  define unit 5 $ One fuel assembly in water
$ ---------------------------------------------------------------------------------
  unit 4 plt19 119 -219 5 -8 tr 0 -3.9135 0
  unit 3 plt18 118 -218 5 -8 tr 0 -4.0805 0
  unit 3 plt17 117 -217 5 -8 tr 0 -4.2475 0
```

```
  unit 3 plt16 116 -216 5 -8 tr 0 -4.4145 0
  unit 3 plt15 115 -215 5 -8 tr 0 -4.5815 0
  unit 3 plt14 114 -214 5 -8 tr 0 -4.7485 0
  unit 3 plt13 113 -213 5 -8 tr 0 -4.9155 0
  unit 3 plt12 112 -212 5 -8 tr 0 -5.0825 0
  unit 3 plt11 111 -211 5 -8 tr 0 -5.2495 0
  unit 3 plt10 110 -210 5 -8 tr 0 -5.4165 0
  unit 3 plt9  109 -209 5 -8 tr 0 -5.5835 0
  unit 3 plt8  108 -208 5 -8 tr 0 -5.7505 0
  unit 3 plt7  107 -207 5 -8 tr 0 -5.9175 0
  unit 3 plt6  106 -206 5 -8 tr 0 -6.0845 0
  unit 3 plt5  105 -205 5 -8 tr 0 -6.2515 0
  unit 3 plt4  104 -204 5 -8 tr 0 -6.4185 0
  unit 3 plt3  103 -203 5 -8 tr 0 -6.5855 0
  unit 3 plt2  102 -202 5 -8 tr 0 -6.7525 0
  unit 4 plt1  101 -201 5 -8 tr 0 -6.9345 0
  sector 2 leftwal -41
  sector 2 rghtwal -42
  sector 2 albot   -51 55 -53 54 5 -8
  sector 2 altop    52 55 -53 54 5 -8
  fill   4

$ ------------------------------------------------------------------------------
  define unit 4 $ OUTER fuel plate
$ ------------------------------------------------------------------------------
  sector 1 fuelo    2 -3 6 -7
  sector 3 clado    1 -4 5 -8 -2 3 -6 7
  fill   3

$ ------------------------------------------------------------------------------
  define unit 3 $ INNER fuel plate
$ ------------------------------------------------------------------------------
  sector 1 fueli   12 -13 6 -7
  sector 2 clado   11  -14   5  -8 -12 13 -6 7
  fill   2

  picture cs material color  0 7  -7   0 -7 -7   0 -7 7  title="plane view"
  picture cs material color  0 2.5 -0.25  0 0.5 -0.25  0 0.5 2.5 title="plate edge detail"
  picture cs material color -13.7 2 -2   -13.7 -2 -2   -13.7 -2 2 title="al bottom"


Surfaces $ All dimensions are in INCHES

$ --- OUTER Fuel Plate Surfaces (0.065 Thickness)
  1 cylinder x 5.5000 -13.5625 13.5625  $ Plate/inner
  2 cylinder x 5.5225 -12.3125 12.3125  $ Alloy/inner
  3 cylinder x 5.5425 -12.3125 12.3125  $ Alloy/outer
  4 cylinder x 5.5650 -13.5625 13.5625  $ Plate/outer
  5 plane z -1.3215                      $ Plate/LHS
  6 plane z -1.3                         $ Alloy/LHS
  7 plane z  1.3                         $ Alloy/RHS
  8 plane z  1.3215                      $ Plate/RHS

$ --- INNER Fuel Plate Surfaces (0.50 Thickness)
  11 cylinder x 5.500 -13.5625 13.5625  $ Plate/inner
  12 cylinder x 5.515 -12.3125 12.3125  $ Alloy/inner
```

```
  13 cylinder x 5.535 -12.3125 12.3125  $ Alloy/outer
  14 cylinder x 5.550 -13.5625 13.5625  $ Plate/outer

$ --- Fuel Plates Surfaces Translated In y-Direction
  219 cylinder x 5.565 -13.5625 13.5625 tr 0 -3.9135 0  $  19 Out
  119 cylinder x 5.500 -13.5625 13.5625 tr 0 -3.9135 0  $  19 In
  218 cylinder x 5.550 -13.5625 13.5625 tr 0 -4.0805 0  $  18 Out
  118 cylinder x 5.500 -13.5625 13.5625 tr 0 -4.0805 0  $  18 In
  217 cylinder x 5.550 -13.5625 13.5625 tr 0 -4.2475 0  $  17 Out
  117 cylinder x 5.500 -13.5625 13.5625 tr 0 -4.2475 0  $  17 In
  216 cylinder x 5.550 -13.5625 13.5625 tr 0 -4.4145 0  $  16 Out
  116 cylinder x 5.500 -13.5625 13.5625 tr 0 -4.4145 0  $  16 In
  215 cylinder x 5.550 -13.5625 13.5625 tr 0 -4.5815 0  $  15 Out
  115 cylinder x 5.500 -13.5625 13.5625 tr 0 -4.5815 0  $  15 In
  214 cylinder x 5.550 -13.5625 13.5625 tr 0 -4.7485 0  $  14 Out
  114 cylinder x 5.500 -13.5625 13.5625 tr 0 -4.7485 0  $  14 In
  213 cylinder x 5.550 -13.5625 13.5625 tr 0 -4.9155 0  $  13 Out
  113 cylinder x 5.500 -13.5625 13.5625 tr 0 -4.9155 0  $  13 In
  212 cylinder x 5.550 -13.5625 13.5625 tr 0 -5.0825 0  $  12 Out
  112 cylinder x 5.500 -13.5625 13.5625 tr 0 -5.0825 0  $  12 In
  211 cylinder x 5.550 -13.5625 13.5625 tr 0 -5.2495 0  $  11 Out
  111 cylinder x 5.500 -13.5625 13.5625 tr 0 -5.2495 0  $  11 In
  210 cylinder x 5.550 -13.5625 13.5625 tr 0 -5.4165 0  $  10 Out
  110 cylinder x 5.500 -13.5625 13.5625 tr 0 -5.4165 0  $  10 In
  209 cylinder x 5.550 -13.5625 13.5625 tr 0 -5.5835 0  $   9 Out
  109 cylinder x 5.500 -13.5625 13.5625 tr 0 -5.5835 0  $   9 In
  208 cylinder x 5.550 -13.5625 13.5625 tr 0 -5.7505 0  $   8 Out
  108 cylinder x 5.500 -13.5625 13.5625 tr 0 -5.7505 0  $   8 In
  207 cylinder x 5.550 -13.5625 13.5625 tr 0 -5.9175 0  $   7 Out
  107 cylinder x 5.500 -13.5625 13.5625 tr 0 -5.9175 0  $   7 In
  206 cylinder x 5.550 -13.5625 13.5625 tr 0 -6.0845 0  $   6 Out
  106 cylinder x 5.500 -13.5625 13.5625 tr 0 -6.0845 0  $   6 In
  205 cylinder x 5.550 -13.5625 13.5625 tr 0 -6.2515 0  $   5 Out
  105 cylinder x 5.500 -13.5625 13.5625 tr 0 -6.2515 0  $   5 In
  204 cylinder x 5.550 -13.5625 13.5625 tr 0 -6.4185 0  $   4 Out
  104 cylinder x 5.500 -13.5625 13.5625 tr 0 -6.4185 0  $   4 In
  203 cylinder x 5.550 -13.5625 13.5625 tr 0 -6.5855 0  $   3 Out
  103 cylinder x 5.500 -13.5625 13.5625 tr 0 -6.5855 0  $   3 In
  202 cylinder x 5.550 -13.5625 13.5625 tr 0 -6.7525 0  $   2 Out
  102 cylinder x 5.500 -13.5625 13.5625 tr 0 -6.7525 0  $   2 In
  201 cylinder x 5.565 -13.5625 13.5625 tr 0 -6.9345 0  $   1 Out
  101 cylinder x 5.500 -13.5625 13.5625 tr 0 -6.9345 0  $   1 In

$ --- Fuel Assembly Surfaces
  41 box 27.125 3.186 0.187 TR  0 -0.0585 -1.415       $ Left Side of Aluminum
  42 box 27.125 3.186 0.187 TR  0 -0.0585  1.415       $ Right Side of Aluminum

$ --- Fuel Assembly End Surfaces
  51 p x -13.5625                                      $ Aluminum Gap
  52 p x  13.5625                                      $ Aluminum Gap
  53 cylinder x 5.565 -13.9375 13.9375 tr 0 -3.9135 0  $ 19th plate/outer
  54 cylinder x 5.550 -13.9375 13.9375 tr 0 -6.9345 0  $ 1st plate/inner
  55 cylinder x 1.0 -13.9375 13.9375                   $ Cylindrical Bore

$ --- Array Boxes (Spacing of 0.35")
  301 box 28 3.303 3.017 tr 0  3.653 -3.367          $ Assembly 1
```

```
  302 box 28 3.303 3.017 tr 0  3.653  0                 $ Assembly 2
  303 box 28 3.303 3.017 tr 0  3.653  3.367             $ Assembly 3
  304 box 28 3.303 3.017 tr 0  0     -3.367             $ Assembly 4
  305 box 28 3.303 3.017 tr 0  0      0                 $ Assembly 5
  306 box 28 3.303 3.017 tr 0  0      3.367             $ Assembly 6
  307 box 28 3.303 3.017 tr 0 -3.653 -3.367             $ Assembly 7
  308 box 28 3.303 3.017 tr 0 -3.653  0                 $ Assembly 8
  309 box 28 3.303 3.017 tr 0 -3.653  3.367             $ Assembly 9


$ --- Water refl
  500 cylinder x 30    -30    30         $ Water refl

end
```

CaseID: omc, Inherently Safe Subcritical Assembly Model
$ 3x3 Array of Fuel Assemblies Water Tank - 0.35" Spacing, Overmass of one assembly, centered

```
Basic

  neutron delayedn INCHES

Criticality

  npart=1000 nbatch=1000 sdt=0.0001 nfirst=100 norm=1. nsource=2 0 0 0  3 0 0

Assign-mc

  1 red 2 lime 3 lime 4 sky 5 gray

Mix

nlib=ENDFB6R7

mat=1 W-P 3.2748 u234 0.0020 u235 0.1837 u236 0.0010 u238 0.0104 o16 0.0358 al 0.7671 $
12.22g U-235 per plate
mat=2 al   2.7
mat=3 al   2.7
mat=4 a-f  0.9982 (h.h2o) 2 o16 1
mat=5 fe 7.78

Geometry


  use unit 5 asy1  -301 tr 0  3.653 -3.367   $ Assembly 1
  use unit 5 asy2  -302 tr 0  3.653  0        $ Assembly 2
  use unit 5 asy3  -303 tr 0  3.653  3.367   $ Assembly 3
  use unit 5 asy4  -304 tr 0  0      -5.0505 $ Assembly 4
  use unit 5 asy5  -305 tr 0  0      -1.6835 $ Assembly 5
  use unit 5 asy6  -306 tr 0  0       1.6835 $ Assembly 6
```

```
  use unit 5 asy10 -310 tr 0  0        5.0505 $ Assembly 10
  use unit 5 asy7  -307 tr 0 -3.653 -3.367  $ Assembly 7
  use unit 5 asy8  -308 tr 0 -3.653  0        $ Assembly 8
  use unit 5 asy9  -309 tr 0 -3.653  3.367  $ Assembly 9

  fill 4
  boundary vacuum 500



$ ---------------------------------------------------------------------------------
  define unit 5 $ One fuel assembly in water
$ ---------------------------------------------------------------------------------
  unit 4 plt19 119 -219 5 -8 tr 0 -3.9135 0
  unit 3 plt18 118 -218 5 -8 tr 0 -4.0805 0
  unit 3 plt17 117 -217 5 -8 tr 0 -4.2475 0
  unit 3 plt16 116 -216 5 -8 tr 0 -4.4145 0
  unit 3 plt15 115 -215 5 -8 tr 0 -4.5815 0
  unit 3 plt14 114 -214 5 -8 tr 0 -4.7485 0
  unit 3 plt13 113 -213 5 -8 tr 0 -4.9155 0
  unit 3 plt12 112 -212 5 -8 tr 0 -5.0825 0
  unit 3 plt11 111 -211 5 -8 tr 0 -5.2495 0
  unit 3 plt10 110 -210 5 -8 tr 0 -5.4165 0
  unit 3 plt9  109 -209 5 -8 tr 0 -5.5835 0
  unit 3 plt8  108 -208 5 -8 tr 0 -5.7505 0
  unit 3 plt7  107 -207 5 -8 tr 0 -5.9175 0
  unit 3 plt6  106 -206 5 -8 tr 0 -6.0845 0
  unit 3 plt5  105 -205 5 -8 tr 0 -6.2515 0
  unit 3 plt4  104 -204 5 -8 tr 0 -6.4185 0
  unit 3 plt3  103 -203 5 -8 tr 0 -6.5855 0
  unit 3 plt2  102 -202 5 -8 tr 0 -6.7525 0
  unit 4 plt1  101 -201 5 -8 tr 0 -6.9345 0
  sector 2 leftwal -41
  sector 2 rghtwal -42
  sector 2 albot   -51 55 -53 54 5 -8
  sector 2 altop    52 55 -53 54 5 -8
  fill   4

$ ---------------------------------------------------------------------------------
  define unit 4 $ OUTER fuel plate
$ ---------------------------------------------------------------------------------
  sector 1 fuelo    2 -3 6 -7
  sector 3 clado    1 -4 5 -8 -2 3 -6 7
  fill   3

$ ---------------------------------------------------------------------------------
  define unit 3 $ INNER fuel plate
$ ---------------------------------------------------------------------------------
  sector 1 fueli   12 -13 6 -7
  sector 2 clado   11  -14   5  -8 -12 13 -6 7
  fill   2

  picture cs material color  0 7  -7   0 -7 -7   0 -7 7  title="plane view"
  picture cs material color  0 2.5 -0.25  0 0.5 -0.25  0 0.5 2.5 title="plate edge detail"
  picture cs material color -13.7 2 -2   -13.7 -2 -2   -13.7 -2 2 title="al bottom"
Surfaces $ All dimensions are in INCHES
```

```
$ --- OUTER Fuel Plate Surfaces (0.065 Thickness)
  1 cylinder x 5.5000 -13.5625 13.5625 $ Plate/inner
  2 cylinder x 5.5225 -12.3125 12.3125 $ Alloy/inner
  3 cylinder x 5.5425 -12.3125 12.3125 $ Alloy/outer
  4 cylinder x 5.5650 -13.5625 13.5625 $ Plate/outer
  5 plane z -1.3215                     $ Plate/LHS
  6 plane z -1.3                        $ Alloy/LHS
  7 plane z  1.3                        $ Alloy/RHS
  8 plane z  1.3215                     $ Plate/RHS

$ --- INNER Fuel Plate Surfaces (0.50 Thickness)
  11 cylinder x 5.500 -13.5625 13.5625 $ Plate/inner
  12 cylinder x 5.515 -12.3125 12.3125 $ Alloy/inner
  13 cylinder x 5.535 -12.3125 12.3125 $ Alloy/outer
  14 cylinder x 5.550 -13.5625 13.5625 $ Plate/outer

$ --- Fuel Plates Surfaces Translated In y-Direction
  219 cylinder x 5.565 -13.5625 13.5625 tr 0 -3.9135 0 $  19 Out
  119 cylinder x 5.500 -13.5625 13.5625 tr 0 -3.9135 0 $  19 In
  218 cylinder x 5.550 -13.5625 13.5625 tr 0 -4.0805 0 $  18 Out
  118 cylinder x 5.500 -13.5625 13.5625 tr 0 -4.0805 0 $  18 In
  217 cylinder x 5.550 -13.5625 13.5625 tr 0 -4.2475 0 $  17 Out
  117 cylinder x 5.500 -13.5625 13.5625 tr 0 -4.2475 0 $  17 In
  216 cylinder x 5.550 -13.5625 13.5625 tr 0 -4.4145 0 $  16 Out
  116 cylinder x 5.500 -13.5625 13.5625 tr 0 -4.4145 0 $  16 In
  215 cylinder x 5.550 -13.5625 13.5625 tr 0 -4.5815 0 $  15 Out
  115 cylinder x 5.500 -13.5625 13.5625 tr 0 -4.5815 0 $  15 In
  214 cylinder x 5.550 -13.5625 13.5625 tr 0 -4.7485 0 $  14 Out
  114 cylinder x 5.500 -13.5625 13.5625 tr 0 -4.7485 0 $  14 In
  213 cylinder x 5.550 -13.5625 13.5625 tr 0 -4.9155 0 $  13 Out
  113 cylinder x 5.500 -13.5625 13.5625 tr 0 -4.9155 0 $  13 In
  212 cylinder x 5.550 -13.5625 13.5625 tr 0 -5.0825 0 $  12 Out
  112 cylinder x 5.500 -13.5625 13.5625 tr 0 -5.0825 0 $  12 In
  211 cylinder x 5.550 -13.5625 13.5625 tr 0 -5.2495 0 $  11 Out
  111 cylinder x 5.500 -13.5625 13.5625 tr 0 -5.2495 0 $  11 In
  210 cylinder x 5.550 -13.5625 13.5625 tr 0 -5.4165 0 $  10 Out
  110 cylinder x 5.500 -13.5625 13.5625 tr 0 -5.4165 0 $  10 In
  209 cylinder x 5.550 -13.5625 13.5625 tr 0 -5.5835 0 $   9 Out
  109 cylinder x 5.500 -13.5625 13.5625 tr 0 -5.5835 0 $   9 In
  208 cylinder x 5.550 -13.5625 13.5625 tr 0 -5.7505 0 $   8 Out
  108 cylinder x 5.500 -13.5625 13.5625 tr 0 -5.7505 0 $   8 In
  207 cylinder x 5.550 -13.5625 13.5625 tr 0 -5.9175 0 $   7 Out
  107 cylinder x 5.500 -13.5625 13.5625 tr 0 -5.9175 0 $   7 In
  206 cylinder x 5.550 -13.5625 13.5625 tr 0 -6.0845 0 $   6 Out
  106 cylinder x 5.500 -13.5625 13.5625 tr 0 -6.0845 0 $   6 In
  205 cylinder x 5.550 -13.5625 13.5625 tr 0 -6.2515 0 $   5 Out
  105 cylinder x 5.500 -13.5625 13.5625 tr 0 -6.2515 0 $   5 In
  204 cylinder x 5.550 -13.5625 13.5625 tr 0 -6.4185 0 $   4 Out
  104 cylinder x 5.500 -13.5625 13.5625 tr 0 -6.4185 0 $   4 In
  203 cylinder x 5.550 -13.5625 13.5625 tr 0 -6.5855 0 $   3 Out
  103 cylinder x 5.500 -13.5625 13.5625 tr 0 -6.5855 0 $   3 In
  202 cylinder x 5.550 -13.5625 13.5625 tr 0 -6.7525 0 $   2 Out
  102 cylinder x 5.500 -13.5625 13.5625 tr 0 -6.7525 0 $   2 In
  201 cylinder x 5.565 -13.5625 13.5625 tr 0 -6.9345 0 $   1 Out
  101 cylinder x 5.500 -13.5625 13.5625 tr 0 -6.9345 0 $   1 In
```

```
$ --- Fuel Assembly Surfaces
  41 box 27.125 3.186 0.187 TR  0 -0.0585 -1.415        $ Left Side of Aluminum
  42 box 27.125 3.186 0.187 TR  0 -0.0585  1.415        $ Right Side of Aluminum

$ --- Fuel Assembly End Surfaces
  51 p x -13.5625                                        $ Aluminum Gap
  52 p x  13.5625                                        $ Aluminum Gap
  53 cylinder x 5.565 -13.9375 13.9375 tr 0 -3.9135 0  $ 19th plate/outer
  54 cylinder x 5.550 -13.9375 13.9375 tr 0 -6.9345 0  $ 1st plate/inner
  55 cylinder x 1.0 -13.9375 13.9375                   $ Cylindrical Bore

$ --- Array Boxes (Spacing of 0.25")
  301 box 28 3.303 3.017 tr 0  3.653 -3.367           $ Assembly 1
  302 box 28 3.303 3.017 tr 0  3.653  0               $ Assembly 2
  303 box 28 3.303 3.017 tr 0  3.653  3.367           $ Assembly 3
  304 box 28 3.303 3.017 tr 0  0     -5.0505          $ Assembly 4
  305 box 28 3.303 3.017 tr 0  0     -1.6835          $ Assembly 5
  306 box 28 3.303 3.017 tr 0  0      1.6835          $ Assembly 6
  310 box 28 3.303 3.017 tr 0  0      5.0505          $ Assembly 10
  307 box 28 3.303 3.017 tr 0 -3.653 -3.367           $ Assembly 7
  308 box 28 3.303 3.017 tr 0 -3.653  0               $ Assembly 8
  309 box 28 3.303 3.017 tr 0 -3.653  3.367           $ Assembly 9


$ --- Water refl
  500 cylinder x 30    -30    30         $ Water refl

end
```