

**PARTIALLY-REFLECTED WATER-MODERATED SQUARE-PITCHED
U(6.90)O₂ FUEL ROD LATTICES WITH 0.52 FUEL TO WATER VOLUME
RATIO (0.855 CM PITCH)**

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PARTIALLY-REFLECTED WATER-MODERATED SQUARE-PITCHED U(6.90)O₂ FUEL ROD LATTICES WITH 0.52 FUEL-TO-WATER RATIO (0.855 CM PITCH)

IDENTIFICATION NUMBER: LEU-COMP-THERM-101

[SPECTRA](#)

KEY WORDS: acceptable, array, critical experiment, fuel rods, low enriched, square pitch, undermoderated, uranium, uranium dioxide, water-reflected, water-moderated

1.0 DETAILED DESCRIPTION

1.1 Overview of Experiment

The US Department of Energy (DOE) Nuclear Energy Research Initiative funded the design and construction of the Seven Percent Critical Experiment (7uPCX) at Sandia National Laboratories. The start-up of the experiment facility and the execution of the experiments described here were funded by the DOE Nuclear Criticality Safety Program. The 7uPCX is designed to investigate critical systems with fuel for light water reactors in the enrichment range above 5 % ²³⁵U. The 7uPCX assembly is a water-moderated and -reflected array of aluminum-clad square-pitched U(6.90 %)O₂ fuel rods. Other critical experiments performed in the 7uPCX assembly are documented in [LEU-COMP-THERM-078](#), [LEU-COMP-THERM-080](#), [LEU-COMP-THERM-096](#), and [LEU-COMP-THERM-097](#).

The fuel used in these experiments was fabricated using unirradiated 6.90 % enriched UO₂ fuel pellets from fuel elements designed to be used in the internal nuclear superheater section of the Pathfinder boiling water reactor operated in South Dakota by the Northern States Power Company in the 1960s. The fuel elements were obtained from The Pennsylvania State University where they had been stored for many years. The fuel pellets in those fuel elements were removed from the original Incoloy cladding and reclad in 3003 aluminum tubes and end caps for use in the experiments reported here.

The nominal outside diameter of the fuel pellets is 0.207 in (0.52578 cm). The nominal outside diameter of the fuel rod cladding is 0.250 in (0.635 cm). The distance between the fuel rods in the square-pitched array is 0.3366 in (0.854964 cm). This geometry gives a fuel-to-water volume ratio of 0.52 in a fuel rod cell in the array. In the configurations examined, the arrays are significantly undermoderated in that an increased amount of moderator in the array, such as might be caused by an increased pitch of the array or an increased density of the moderator, results in an increase in the reactivity of the system.

The twenty-two critical experiments in this series were performed in 2019 in the Sandia Critical Experiments at the Sandia Pulsed Reactor Facility.

The first of the experiments had the critical assembly core fully loaded with a 45×45 array of 2025 fuel rods with no water holes and was intended to provide a baseline against which the remaining experiments could be compared. The remaining twenty-one critical experiments contained various configurations of the fuel in the assembly. The purpose of these experiments was to measure the critical water height in the assembly for the twenty-two experiment configurations. The case-to-case variations involved 1) the number of fuel rods in the array (Cases 1 through 11); and 2) the width of water-filled gaps between two or four identical fuel rod subarrays (Cases 10 [base case with no gap] and 12 through 22).

All twenty-two critical experiments are judged to be acceptable as benchmark experiments.

1.2 **Description of Experimental Configuration**

1.2.1 Design of the Critical Assembly – A schematic of the critical assembly as it was configured for the experiments evaluated in [LEU-COMP-THERM-079](#) is shown in Figure 1. The same assembly tank was used for the experiments evaluated here though the assembly core was modified. Figure 2 shows a view of the critical assembly configured for the current experiments. The assembly core resides in an elevated assembly core tank that is connected to a moderator dump tank at a lower elevation. When the assembly is not being operated, the moderator resides in the dump tank. When the assembly is being brought to delayed critical, the moderator is pumped from the dump tank into the core tank. The moderator can be released by gravity to the dump tank through two large-diameter normally-open pneumatically operated dump valves. A heater is included in the dump tank to keep the moderator at a constant temperature set by a controller at the assembly control system. During operation, the moderator is continually circulated between the dump tank and the assembly tank. During initial filling of the core tank, the moderator/reflector water is pumped from the dump tank through the “fast fill” system that fills the core tank in about 15 minutes. The fast fill system operates until a float switch in the core tank is actuated. Actuation of the float switch prohibits the operation of the fast fill system. Further filling of the core tank is done using the “slow fill” system. The slow fill system is designed to provide moderator/reflector to the core tank in a controlled manner to limit the maximum reactivity addition rate during this part of the operation. During experiments in which the reactivity of the critical assembly is controlled by the level of moderator/reflector in the core tank, the float switch is typically set at the level that causes it to actuate when the k_{eff} of the system is about 0.9.

Figure 3 shows a cut-away view of the critical assembly core tank with the moderator drained from the core tank. The inset shows the core tank with the moderator at the critical level as it was during one of the experiments. The assembly fuel rods are described in detail in a subsequent section. The assembly is driven by a small ^{252}Cf source that is located in the assembly grid or immediately adjacent to the assembly fuel array. The assembly fuel is supported in the assembly tank by two 1 in (2.54 cm) thick aluminum grid plates. A guide plate, used to align the fuel rods in the assembly during insertion, is located above the upper grid plate. The grid and guide plates are separated by aluminum support posts. The assembly core is situated in the tank to provide a 6.5 in (16.51 cm) thick water reflector below the lower grid plate. The diameter of the tank provides a radial water reflector around the assembly greater than 6 in (15.24 cm).

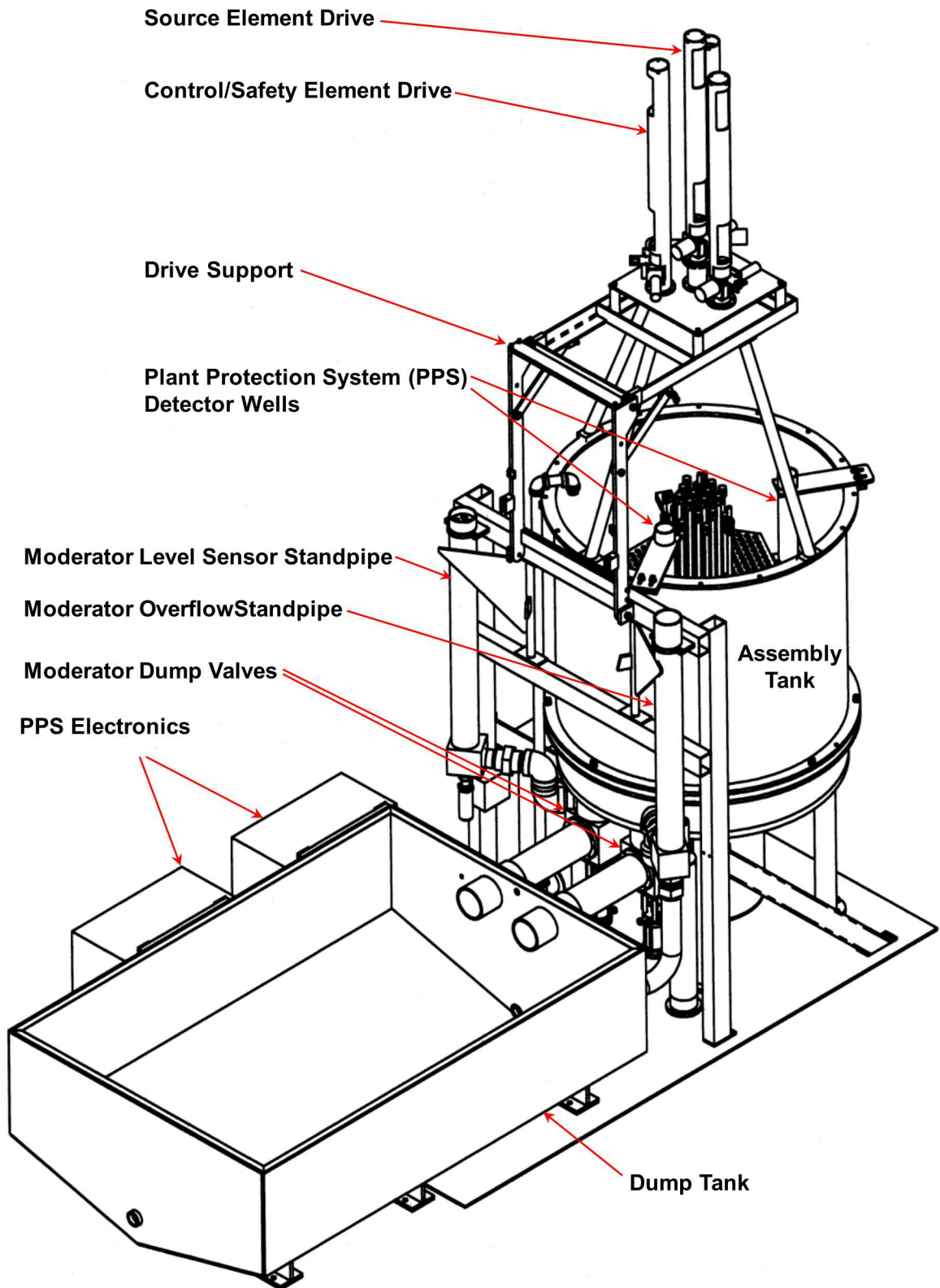


Figure 1. A Schematic of the Critical Assembly.

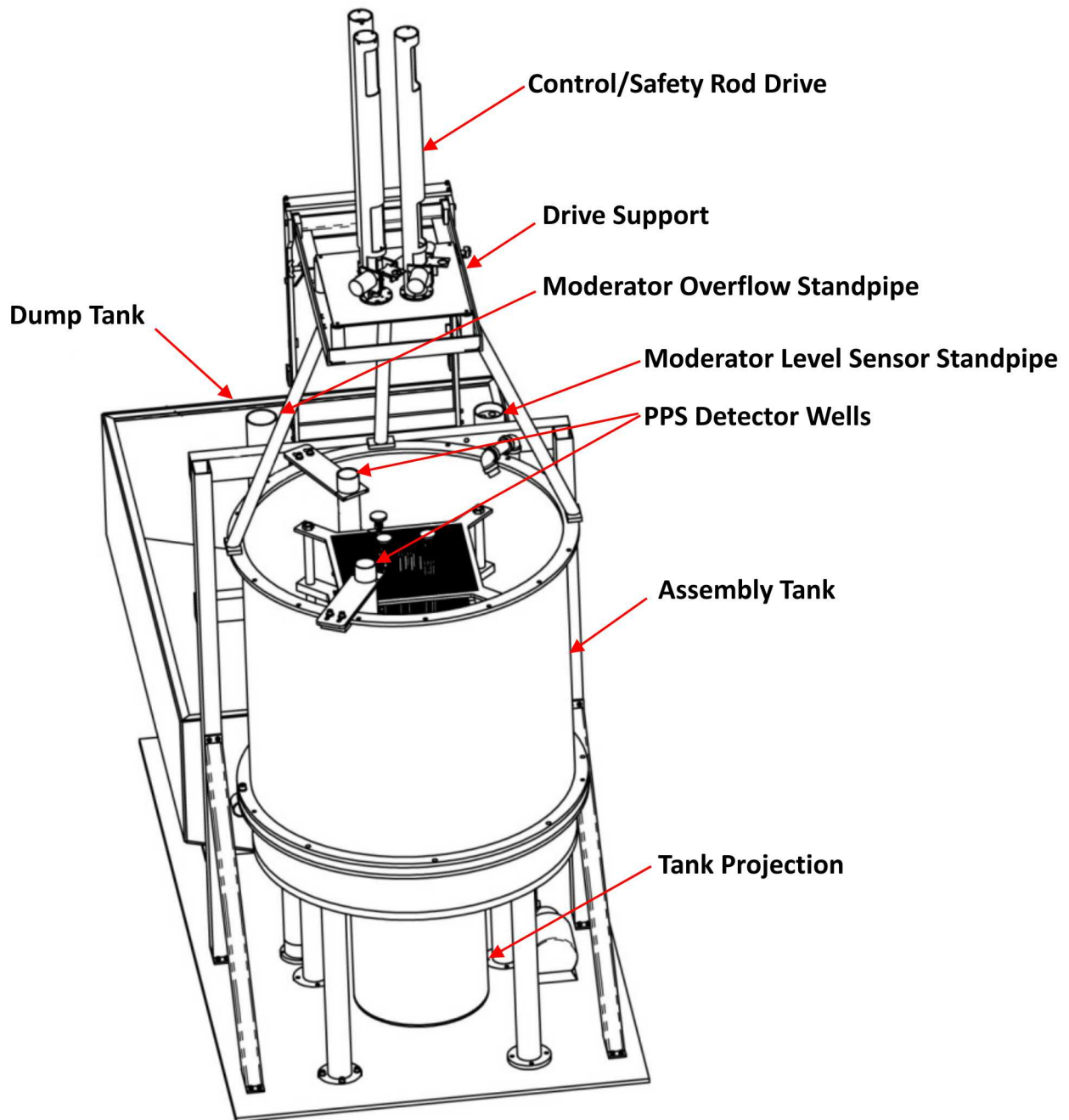


Figure 2. View of the Critical Assembly.

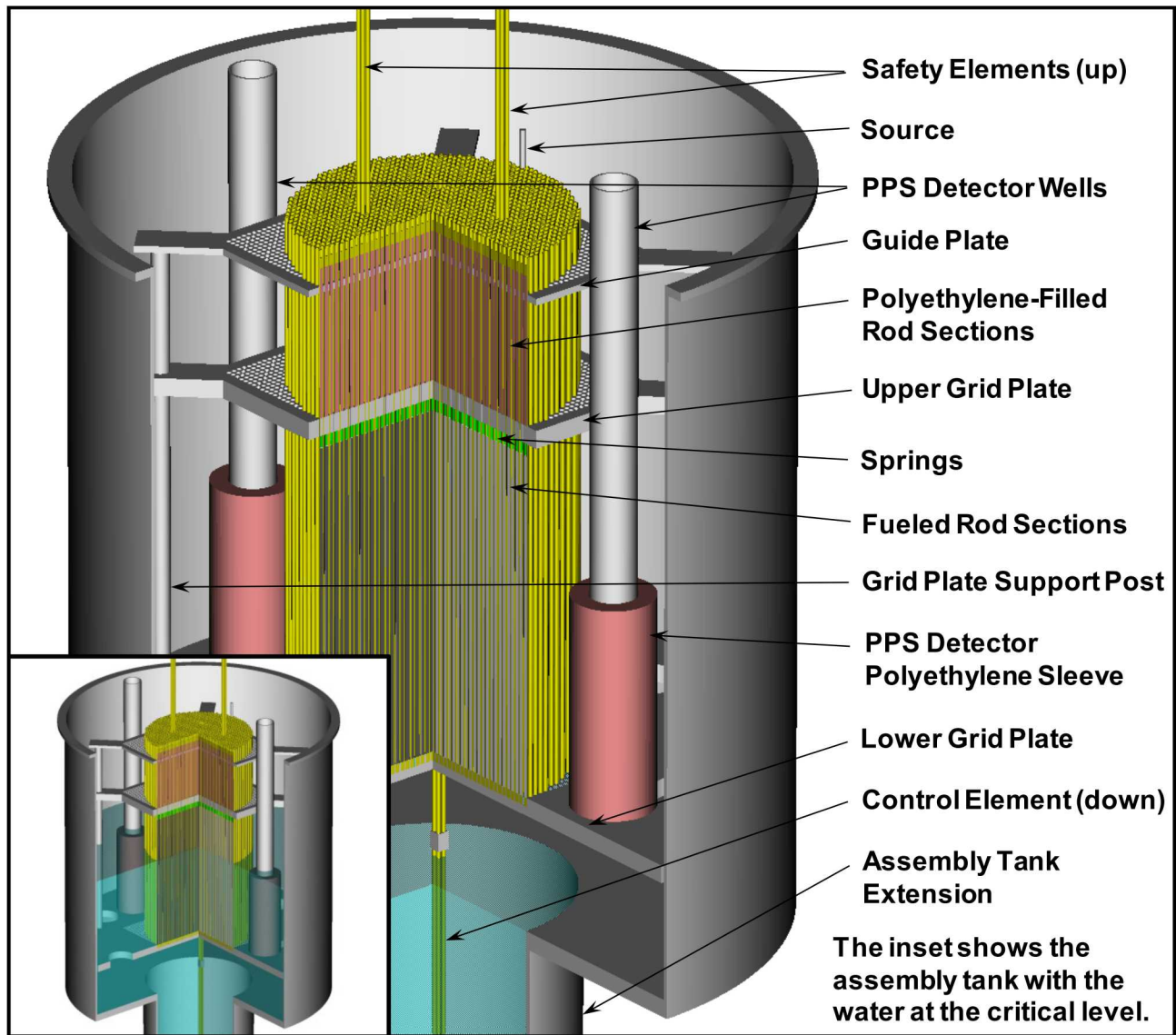


Figure 3. Cut-Away View of the Critical Assembly Core Tank (Case 4).

The assembly has one control and two safety elements of identical design. Each consists of a ganged four-rod assembly that passes through the grid and guide plates. Each of the rods in these elements has a B_4C -filled absorber section separated from a fuel follower by a polyethylene-filled decoupler section. When each of the elements is fully withdrawn, the fuel follower is in the assembly and the absorber is above the surface of the assembly moderator. The two types of elements are differentiated by the way in which they are used. During operations, the two safety elements are held in the most reactive position and provide a redundant shutdown mechanism that can be rapidly inserted by gravity drop. The control element is used to make fine adjustments to the reactivity of the assembly during operations. During the measurements reported here, all three elements were fully withdrawn to their most reactive positions. The three control/safety elements are attached to the control/safety element drives through electromagnets. The control/safety element drives are supported above the assembly tank by the drive support.

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During operation of the critical assembly, water is continuously pumped from the dump tank to the core tank. The level of the moderator in the assembly tank is maintained by overflow into one of two overflow standpipes. One overflow standpipe (the fixed standpipe) is set at a level that allows the core tank to fill until the fuel in the critical assembly is fully reflected, a level about 6 inches above the upper grid plate. A second overflow standpipe (the remotely adjustable standpipe or RASP) is, as the name implies, adjustable from the control console of the critical assembly. The RASP limits the reactivity available in the assembly during an approach-to-critical experiment with the level of the moderator/reflector in the core tank as the approach variable. Figure 4 shows the two overflow standpipes on the critical assembly.

The level of the moderator/reflector in the core tank is monitored by an uncalibrated linear level measurement system located in a standpipe outside the core tank and by a calibrated system that uses four ultrasonic distance measurement devices in still tubes around the periphery of the core tank. The ultrasonic sensors operate by emitting a pulse of ultrasound and measuring the time required to receive an echo from a surface. The still tubes restrict the field of view of the ultrasonic sensors to an area in which surface disturbances of the moderator are limited by the presence of the tube. Each still tube has a hinged door on the side that allows placement of the length standards used to calibrate the system. The air temperature in each still tube was monitored by a high-precision platinum resistance temperature detector (RTD) to allow corrections to be made for the temperature-dependent velocity of sound in the tubes. The ultrasonic sensors are operated in sets of two with the still tubes for the two sensors in a set positioned in diametrically-opposed locations across the critical assembly core from one another. The moderator/reflector level in the center of the assembly core is obtained by averaging the measured levels of the two sensors in a set. Two measurements of the level of the moderator/reflector at the center of the core are thus provided by the two sets of two ultrasonic level sensors.

Figures 5 and 6 show photographs of two of the cores in the assembly. At the time that both photographs were taken, the moderator had been drained from the core tank. Figure 5 shows an overall view of the critical assembly core in the assembly tank. In this view, the control and safety elements are down. The upper grid plate is visible. The guide plate is visible above the upper grid plate. The upper grid plate and the guide plate have checkerboard markings to aid in the placement of the fuel rods in the assembly grid. The guide plate has each column and row in the grid pattern identified. Two dry wells that house the fission chambers for the assembly instrumentation are visible in the picture as are the four still tubes for the ultrasonic level sensors.

Figure 6 shows a view of the top of the core for a different configuration. In this view, the control and safety elements are also down. The lower and upper grid plates and the guide plate are visible in the figure. The handle of the neutron source, which stands above the tops of the fuel rods, is visible on the far side of the fuel array. Three still tubes for the ultrasonic sensors and two of the detector drywells are visible in the figure.

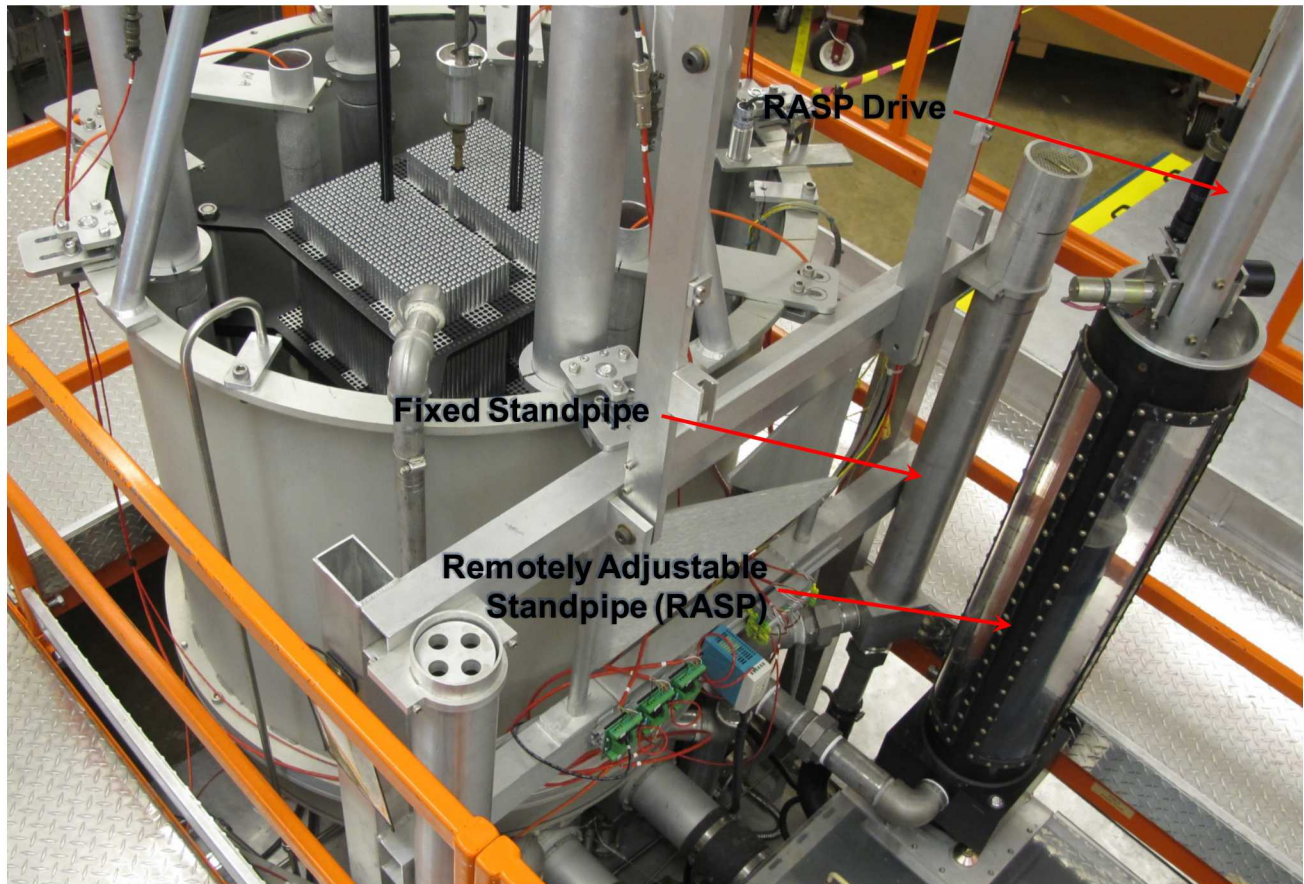


Figure 4. View of the Critical Assembly showing the Overflow Standpipes (Case 17).

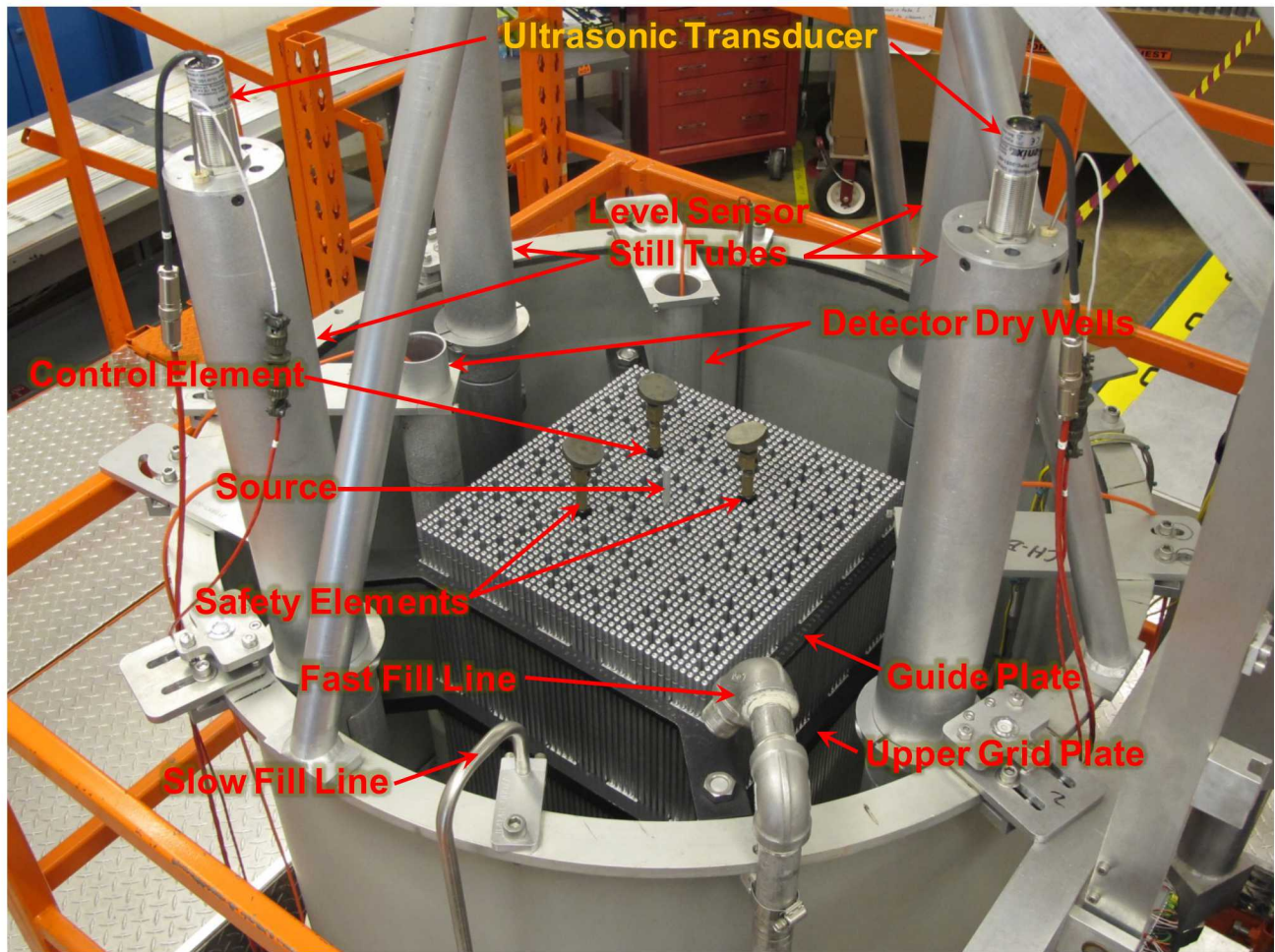


Figure 5. View of One of the Critical Configurations (Case 2).

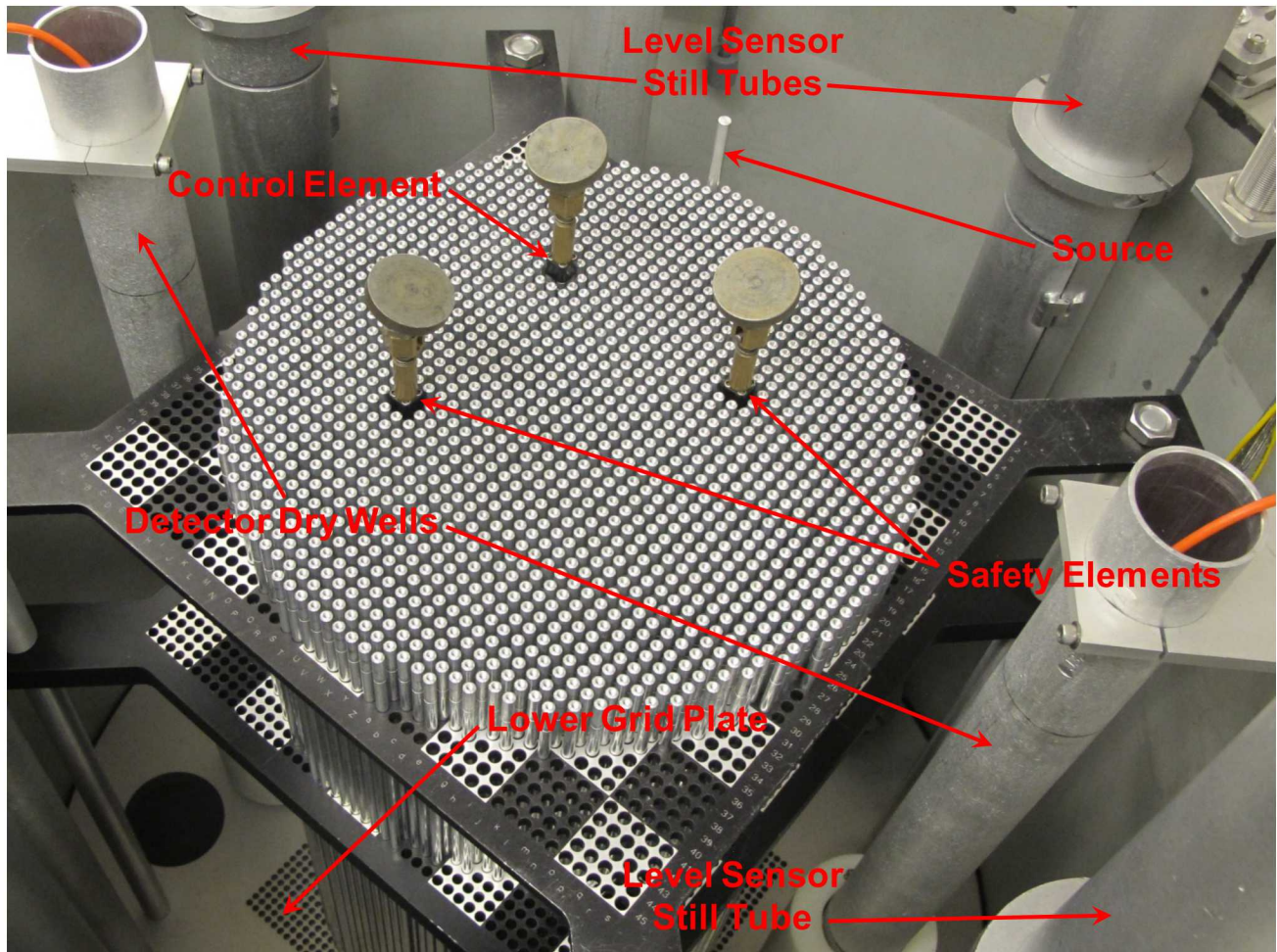


Figure 6. View of One of the Critical Configurations (Case 4).

1.2.2 Reactor Room – The critical experiments were performed in the reactor building at the Sandia Pulsed Reactor Facility. The reactor building is a large thick-walled, steel-reinforced concrete structure with a base in the shape of a cylinder having an inside diameter of approximately 30 ft (9.1 m) and capped with a hemispherical shell. A large steel and concrete door is present in the wall. Inside the building, the reactor room is lined on the walls and the dropped ceiling by 8 in (20.32 cm) of gypsum. The 4 in (10.16 cm) of gypsum that is nearest the concrete walls is borated. The floor is an 8 in (20.32 cm) thick concrete slab, the upper 4 in (10.16 cm) of which is borated. The ceiling is about 12 ft 5 in (378.46 cm) above the floor. A view of the critical assembly in the reactor room is shown in Figure 7.



Figure 7. View of the Critical Assembly in the Reactor Room.

1.2.3 Assembly Tank - The assembly tank supports the assembly and contains the moderator during approach-to-critical experiments. The tank is cylindrical with a coaxial cylindrical projection out the bottom to accommodate the motion of the fuel-followed control/safety elements. The assembly tank consists of two welded flanged sections joined through a ring that supports the lower grid plate of the assembly. All parts of the tank were fabricated from 6061 aluminum.

The upper tank section is essentially a flanged tube. The inside dimensions of the upper tank are 40 in (101.6 cm) tall by 36.88 in (93.6752 cm) diameter. The upper tank is 6061 aluminum. It has a radial wall thickness of 0.25 in (0.635 cm). The lower flange is drilled to match the flange on the lower tank section and

the grid plate support ring. The upper flange is drilled to connect to the support structure for the control/safety and source element drives.

The lower tank section has the same inner diameter and wall thickness as the upper tank section and has a 1 in (2.54 cm) thick floor that provides support for the assembly tank. The floor is drilled and tapped to accommodate the tank supports and has holes to connect to the two moderator dump valves. The floor also has a large central hole for the projection. The inside dimensions of the projection are 21.75 in (55.25 cm) tall by 15 in (38.1 cm) diameter. The radial wall thickness and floor thickness of the projection are both 0.25 in (0.635 cm). The lower tank section has a flange at the top with an O-ring groove used for connection to the grid plate support ring. The flange is drilled and tapped to match the lower flange in the upper tank section and the grid plate support ring.

The grid plate support ring fits between the upper and lower tank sections and has an O-ring groove in the surface that mates with the lower flange on the upper tank section. The lower grid plate attaches to the grid plate support ring.

The assembly tank is connected to three different standpipes. One standpipe contains a linear moderator level sensor and is shown in Figures 1 and 2. The second contains a fixed overflow pipe that determines the moderator level when the assembly is fully reflected. The third standpipe is the RASP used to set the moderator/reflector level during approach-to-critical experiments with moderator/reflector level as the approach variable. The assembly tank also has a float switch used to indicate the moderator/reflector level at a fixed point.

1.2.4 Grid Plates – The two 6061 aluminum grid plates support and maintain the spacing of the fuel rods in the critical assembly. A third grid plate, similar to but thinner than the upper grid plate, is located above the upper grid plate to guide the fuel rods as they are being inserted into the assembly. The guide plate was fabricated from cast aluminum tooling plate, a standard aluminum product known for its dimensional stability. The upper and lower grid plates are 1 in (2.54 cm) thick while the guide plate is 0.375 in (0.9525 cm) thick. The lower grid plate is circular, 36.5 in (92.71 cm) in diameter, and is supported by the grid plate support ring that is part of the assembly tank. The lower grid plate has six 4.00 in (10.16 cm) diameter holes in it equally spaced on a 28 in (71.12 cm) diameter circle to allow passage of the moderator when the dump valves are opened. The upper grid plate is a 16.50 in $\pm$ 0.06 in (41.91 cm $\pm$ 0.1524 cm) square with four support bosses at the corners. The support bosses are rectangular projections of the grid plates and are visible in Figures 5 and 6. The upper grid plate is supported above the lower grid plate by four 1 in (2.54 cm) diameter threaded aluminum standoffs that attach to the bosses. The standoffs maintain a spacing of 19.88 in $\pm$ 0.02 in (50.4952 cm $\pm$ 0.0508 cm) between the top of the lower grid plate and the bottom of the upper grid plate. The standoffs are placed on a 28 in (71.12 cm) diameter circle centered on the center of the grid plates. Similar standoffs maintain a 7.00 in $\pm$ 0.02 in (17.78 cm $\pm$ 0.0508 cm) spacing between the top of the upper grid plate and the bottom of the guide plate.

A set of three grid plates – lower, upper, and guide – was fabricated for the experiments. These plates have provisions for 2025 fuel rods in the 45 $\times$ 45 square-pitched critical array. The array has a pitch of 0.3366 in (0.854964 cm). The tolerance on the absolute location of each fuel rod position in the grid is 0.005 in (0.0127 cm). The lower grid plate has 2013 0.5 in (1.27 cm) deep holes bored in it to support and locate the bottom of the fuel rods. The upper grid plate and guide plate have matching through holes in them to locate the top of the fuel rods. The diameter of the grid plate holes is 0.260 +0.005/–0.000 in (0.6604 + 0.0127/–0.0000 cm). All three plates have three through holes – square in shape with rounded corners – machined in them to allow for passage of the four-rod control/safety elements. An excerpt from the design drawing for the upper grid plate is shown in Figure 8.

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The rows and columns of holes in the guide plate are marked for identification. The guide plate and the upper grid plate are anodized in a checkerboard pattern to assist in identifying the grid locations.

Table 1 shows the axial locations of the grid/guide plates under the assumption that the origin is at the top of the lower grid plate.

Table 1. Axial Locations of the Grid and Guide Plate Surfaces as Installed in the Critical Assembly.

Part	Location	Axial Position Relative to the Top of the Lower Grid Plate	
		Position (in)	Position (cm)
Lower Grid Plate	Bottom of the lower grid plate	-1	-2.5400
	Bottom of the fuel rod support holes	-0.5	-1.2700
	Top of the lower grid plate	0	0.0000
Upper Grid Plate	Bottom of the upper grid plate	19.88	50.4952
	Top of the upper grid plate	20.88	53.0352
Guide Plate	Bottom of the guide plate	27.88	70.8152
	Top of the guide plate	28.255	71.7677

1.2.5 Radiation Detectors – Two cylindrical fission chambers that are part of the facility plant protection system were used to obtain count-rate data during the experiments. The active material in the fission chambers was uranium enriched to about 93 % ^{235}U . The fission chambers have a 9.75 in (24.765 cm) length and 2 in (5.04 cm) OD. They are constructed of aluminum with an overall mass of 793.79 g. The detectors were placed in dry wells outside the fuel array. The dry wells were fabricated from aluminum 6061-T6511 tubing 2.50 in (6.35 cm) OD with 0.125 in (0.3175 cm) wall. The bottom of the tube was closed with a 0.250 in (0.635 cm) thick welded aluminum 6061-T6 or –T651 plate. The bottom of the tube was in contact with the top of the lower grid plate. The detector tubes were surrounded by an annulus of polyethylene 11.82 in (30.0228 cm) tall with an inner diameter of 2.603 in (6.61162 cm) and an outer diameter of 4.535 in (11.5189 cm). The bottom of the polyethylene was 0.3 in (0.762 cm) above the top surface of the lower grid plate. The mass of each of the polyethylene annuli was measured on a balance with the following specifications given by the manufacturer: repeatability 0.01 g, linearity 0.02 g, readability 0.01 g. The average mass of the two annuli was 2017.28 g. The vertical axis of one detector tube, using the orientation of the upper grid plate shown in Figure 8, was 28.94 cm to the right of and 6.4122 cm above the center of the grid plate. The second detector was 28.94 cm to the left of and 6.4122 cm below the center of the grid plate, as the grid plate is shown in the figure. The detectors were placed axially at the bottom of the dry wells with the axes of the detectors parallel to the axis of the tank. A third fission chamber, located below and immediately adjacent to the bottom of the core tank, was used in some of the experiments.

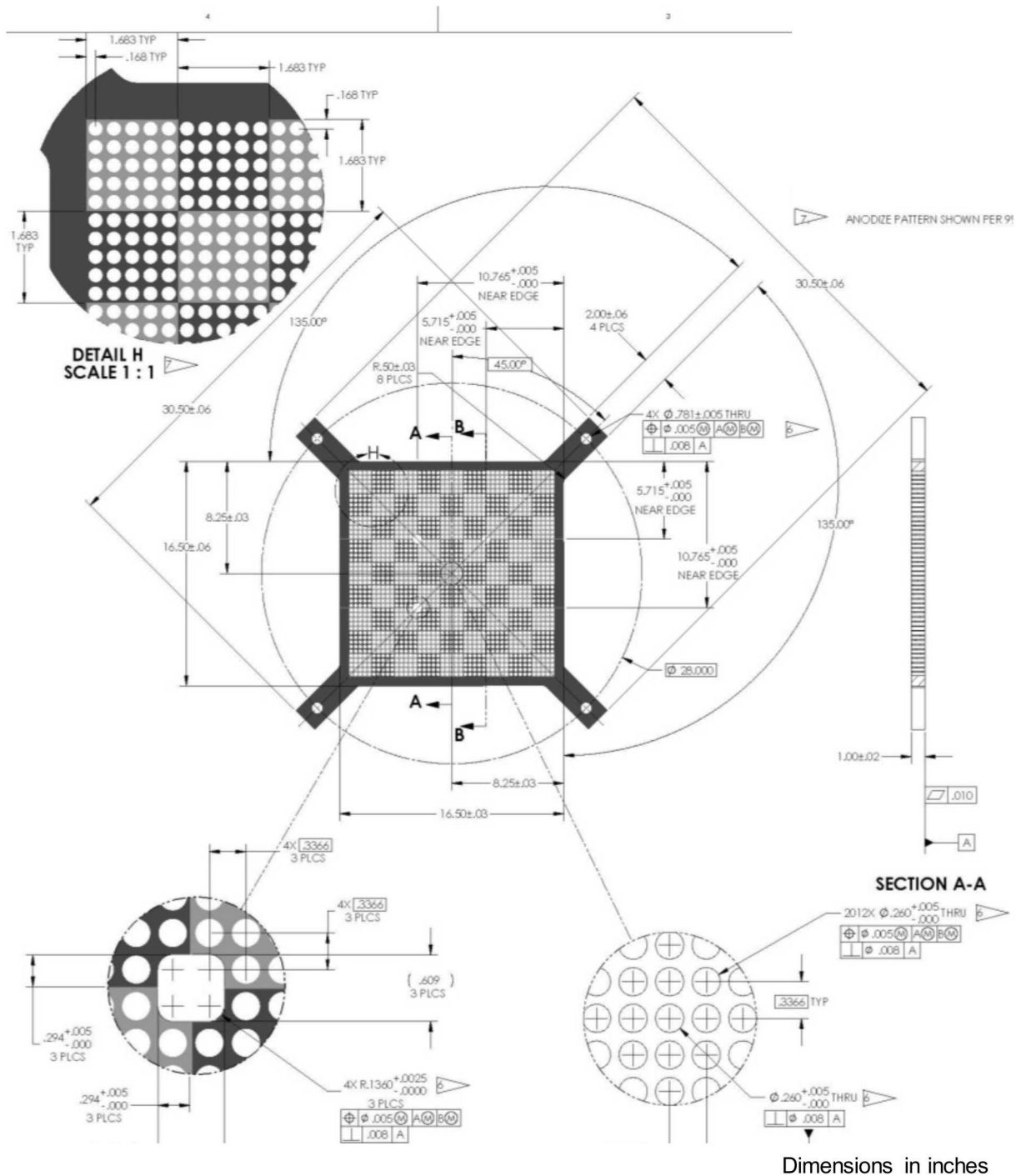


Figure 8. Excerpt From the Design Drawing for the Upper Grid Plate.

1.2.6 Water Moderator and Reflector – As noted above, the lower grid plate was supported in the core tank so that the core was reflected on the bottom by a 6.5 in (16.51 cm) thick layer of water. The bottom surface of the water in the core tank is 7.5 in (19.05 cm) below the upper surface of the lower grid plate. The

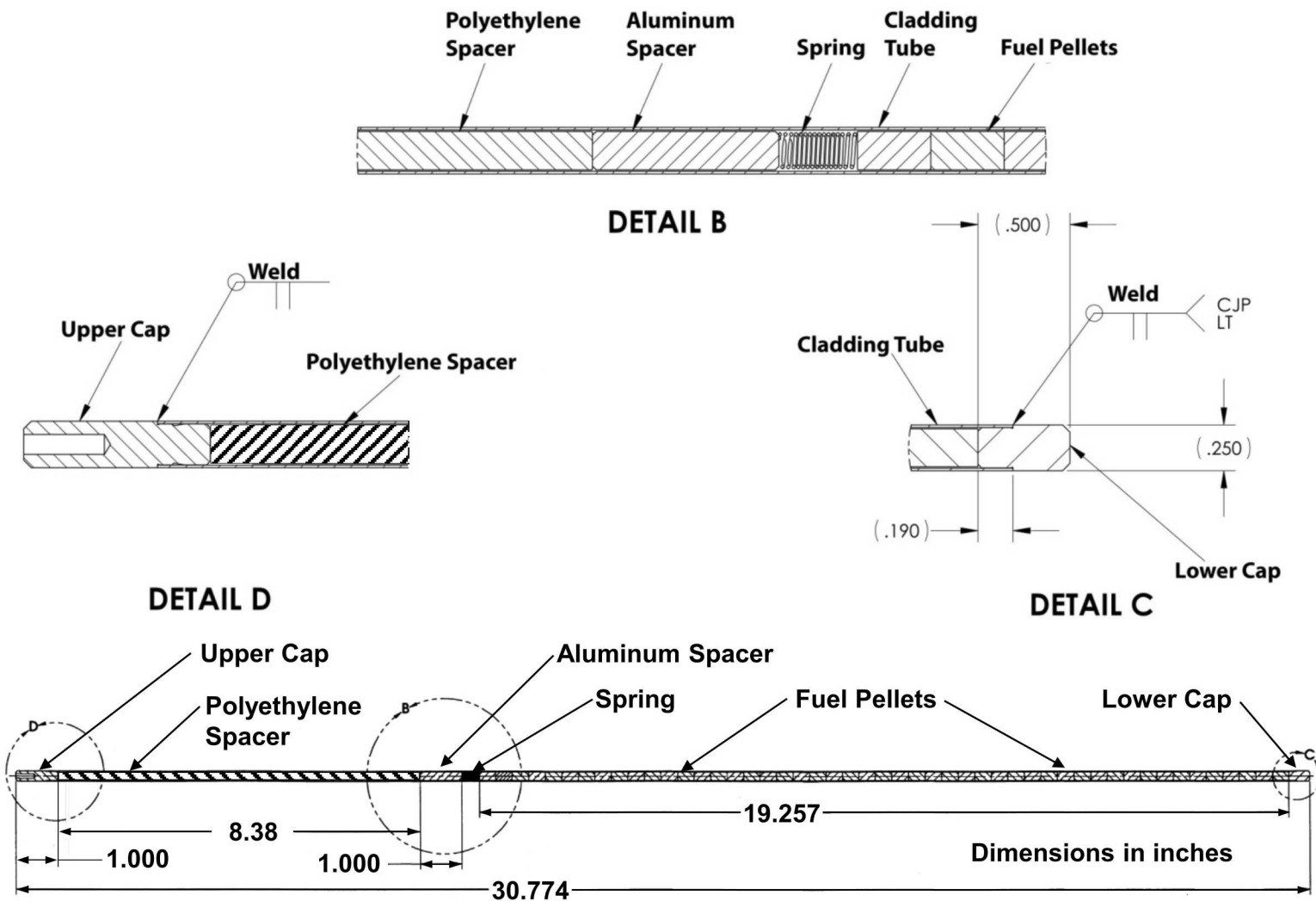
diameter of the core tank was sufficient that the core was reflected radially by more than 6 in (15.24 cm) of water for all cores. There was nothing that is not described above within 6 in (15.24 cm) of the fuel rods.

During the experiments, water was continuously pumped from the dump tank to the core tank. The level of the moderator/reflector in the core tank was controlled by the remotely adjustable standpipe. The level was monitored by four ultrasonic distance measurement instruments operated as two pairs of diametrically-opposed instruments. Averaging the measured level from a pair of detectors gives the level at the center of the core. Each instrument was calibrated using a set of length standards with known lengths.

1.2.7 Fuel Rods – With the exception of the fueled sections of the control and safety elements, the fuel rods in the critical assembly were all of the same design. The design of the fuel rods is shown in Figure 9. The fuel rods were fabricated in 2004 at Sandia National Laboratories from existing UO_2 fuel pellets removed from “Pathfinder” fuel assemblies obtained from The Pennsylvania State University. The fuel rods in the Pathfinder fuel assemblies were separated from the assemblies and the fuel pellets were removed from the original cladding tubes and fabricated into new fuel rods using 3003 aluminum tubing welded to end plugs of the same aluminum alloy.

The cladding tubes are welded to the lower caps. During fabrication, each weld was subjected to and certified to have passed a helium leak test. Passing the helium leak test assured that the water moderator would not enter the fuel rods. The material stack in the fuel rods, starting at the bottom, is as follows: a 0.500 in (1.270 cm) aluminum 3003 lower cap; a nominal 19.257 in (48.91278 cm) stack of fuel pellets; a corrosion-resistant steel compression spring 0.180 in (0.4572 cm) outside diameter, 0.138 in (0.35052 cm) inside diameter, 0.875 in (2.2225 cm) uncompressed length whose length adjusts according to the actual length of the fuel stack; a 1.000 in (2.540 cm) aluminum 6061 spacer 0.207 in $\pm$ 0.010 in (0.52578 cm $\pm$ 0.02540 cm) diameter, an 8.38 in $\pm$ 0.02 in (21.2852 cm $\pm$ 0.0508 cm) long high-density polyethylene spacer also 0.207 in $\pm$ 0.010 in (0.52578 cm $\pm$ 0.02540 cm) diameter, and a 1.000 inch (2.540 cm) aluminum 3003 top cap. Table 2 lists the axial locations of the interfaces between the fuel rod components when the fuel rods are installed in the critical assembly.

The cladding tubes used in the fuel rods have a nominal outer diameter of 0.250 in (0.635 cm) with a nominal 0.014 in (0.03556 cm) wall. The lower cap of the fuel rods is 0.500 in (1.270 cm) long.



Detail A of the original drawing has been omitted here.

Figure 9. Design of the Fuel Rod.

Table 2. Axial Locations of the Interfaces in the Fuel Rods as Installed in the Critical Assembly.

Location	Axial Position Relative to the Top of the Lower Grid Plate	
	Position (in)	Position (cm)
Bottom of the lower grid plate	-1.00	-2.54
Bottom of the fuel rod	-0.50	-1.27
Bottom of the fuel pellet stack	0.00	0.00
Top of the fuel pellet stack (measured)	19.2045	48.780 ^(a)
Bottom of the aluminum spacer	19.894	50.53076
Top of the aluminum spacer	20.894	53.07076
Top of the polyethylene spacer	29.274	74.35596
Top of the fuel rod	30.274	76.89596

(a) This is the mean measured fuel column length, different from the 19.257 in (48.91278 cm) nominal length. The measured length in inches is this value (48.780) divided by 2.54.

Before the fuel rods were fabricated, the masses of 100 of each non-fuel components of the fuel rods were measured. The mass measurements were made on a balance with the following specifications given by the manufacturer: repeatability 0.01 g, linearity 0.02 g, readability 0.01 g. The results of the mass measurements are summarized in Table 3. The sixth row in the table gives the results for 100 sets of all five parts. It can be seen that the variability in the mass sum is dominated by the variability in the mass of the polyethylene spacer. The variability is attributed to the manufacturing process used to fabricate the polyethylene spacers. The last (seventh) row in the table gives the results for 100 sets of parts without the polyethylene spacers.

Table 3. Measured Mass Data for the Fuel Rod Components.

Component	Average Mass (g)	Standard Deviation (g)
Cladding Tube/Lower Cap Assembly	13.824	0.027
Corrosion-Resistant Steel Springs	0.1923	0.0095
Aluminum Spacer	1.4368	0.0043
Polyethylene Spacer	4.524	0.094
Upper Cap	1.8350	0.0052
Sum of Five Parts for 100 Sets	21.813	0.094
Sum Without Polyethylene Spacer	17.289	0.027

During the fabrication of the 2199 fuel rods available for the experiments, the following quantities were measured for each fuel rod: total rod mass, polyethylene spacer mass, and fuel pellet column length. The mass measurements were made on a balance with the following specifications given by the manufacturer: repeatability 0.01 g, linearity 0.02 g, readability 0.01 g. The length measurements were made to the nearest 0.1 cm. The values of the measured masses and lengths were preserved for each fuel rod. The mass of the fuel pellets in each rod was obtained by subtracting the measured mass of the polyethylene spacer plus the 17.289 g average mass of the remaining hardware given in Table 3 from the total mass of the fuel rod. Table 4 lists average values of UO_2 fuel mass and fuel pellet stack length for the entire population of 2199 fuel rods. The linear fuel mass in each fuel rod was obtained from the UO_2 mass and the fuel pellet stack length for each fuel rod. The average value of the linear fuel mass is also listed in the table as is the average polyethylene spacer mass.

Table 4. Population Averages for the 2199 Fuel Rods.

Characteristic	Average Value	Standard Deviation
UO ₂ Mass (g)	108.7165	0.323
Fuel Pellet Stack Length (cm)	48.780	0.125
Linear Fuel Mass (g/cm)	2.2287	0.0050
Polyethylene Spacer Mass (g)	4.454	0.102

After the fuel rods were fabricated, the outer diameter of each fuel rod was measured using a high-precision laser micrometer system. The system consisted of three micrometer heads and the hardware required to position the fuel rods in the micrometer heads. The micrometer heads were located to measure the fuel rod outside diameter at 6.4 in (16.256 cm), 10.15 in (25.781 cm), and 13.9 in (35.306 cm) above the bottom end of the fuel rod. This gave a fuel rod outer diameter measurement at about the midplane of the fuel pellet stack and 3.75 in (9.525 cm) above and below the midplane. Each micrometer made two simultaneous orthogonal diameter measurements. For each fuel rod, a measurement was taken, the fuel rod was rotated by 45°, and another measurement was taken. Thus, the outer diameter of each fuel rod was measured at three axial locations in four azimuthal orientations. The manufacturer's specifications indicated that the laser micrometers had a resolution of 0.000001 in (0.00000254 cm) and a repeatability of 0.000005 in (0.0000127 cm). The bias in the micrometer measurements was established using a pin gage standard with a calibration traceable to the US National Institute of Standards and Technology. The diameter measurements had a systematic uncertainty of 0.000022 in (0.00005588 cm) which is the sum in quadrature of the 0.000015 in (0.0000381 cm) uncertainty in the pin gage standard with the maximum in the random variations in the measurement of the standard on any axis for the three micrometers. The fuel rod diameter measurements were made in a number of sessions over the course of several months. The stability of the measurement system was monitored by repeatedly measuring two 12 in (30.48 cm) long pin gages during each of the sessions. These measurements also showed that the diameter measurements had a random reproducibility uncertainty of about 0.000030 in (0.0000762 cm). Of the 2199 fuel rods fabricated for the experiment, five were removed from service and not used. The average measured fuel rod diameter for the remaining population of 2194 fuel rods is 0.249980 in (0.634948 cm as rounded from the original data) with a standard deviation of 0.000086 in (0.000218 cm).

The design documents for the fuel elements from which the fuel pellets were removed specified the diameter of the fuel pellets as 0.207 in (0.52578 cm). The outer diameter of a sample of 123 fuel pellets, drawn randomly from the fuel pellet stock used in the fuel rods, was measured using one of the laser micrometers described above. The average measured diameter was 0.20694 in (0.52563 cm) with a standard deviation of the 123 measurements of 0.00019 in (0.00048 cm).

The fuel rods were designed to be supported by the two 1 in (2.54 cm) thick grid plates. The lower cap fits in a 0.5 in (1.27 cm) deep blind hole in the lower grid plate. The top of the lower cap is then aligned with the top of the grid plate to make the combination appear as a solid sheet of metal. With the appropriate grid plate spacing, the top and bottom of the aluminum spacers in the fuel rods are nearly aligned with the top and bottom of the upper grid plate.

1.2.8 Control and Safety Elements - The critical assembly has three identical fuel-followed control/safety elements, two operated as safety elements and one operated as a control element. Each control/safety element occupies four adjacent fuel rod positions in the critical assembly. Each element consists of four B₄C-loaded absorber sections followed by four polyethylene-filled decoupler sections followed by four fueled rod sections. These sections are joined into four-rod bundles by 6061 aluminum bundle plates. The three sections use the same 3003 aluminum tubing as the fuel rods. Each section has 3003 aluminum end caps at the top and bottom of identical design. When a control/safety element is fully

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withdrawn from the assembly, the fueled rod sections are in the core and are nearly identical neutronically to the other fueled positions in the critical assembly. The design of the control and safety elements is shown in Figure 10. The design of the lower bundle plate is shown in Figure 11. The design of the middle bundle plate, of which there are two in each control or safety element, is shown in Figure 12. The design of the upper bundle plate is shown in Figure 13. All of the bundle plates were fabricated from 6061 aluminum.

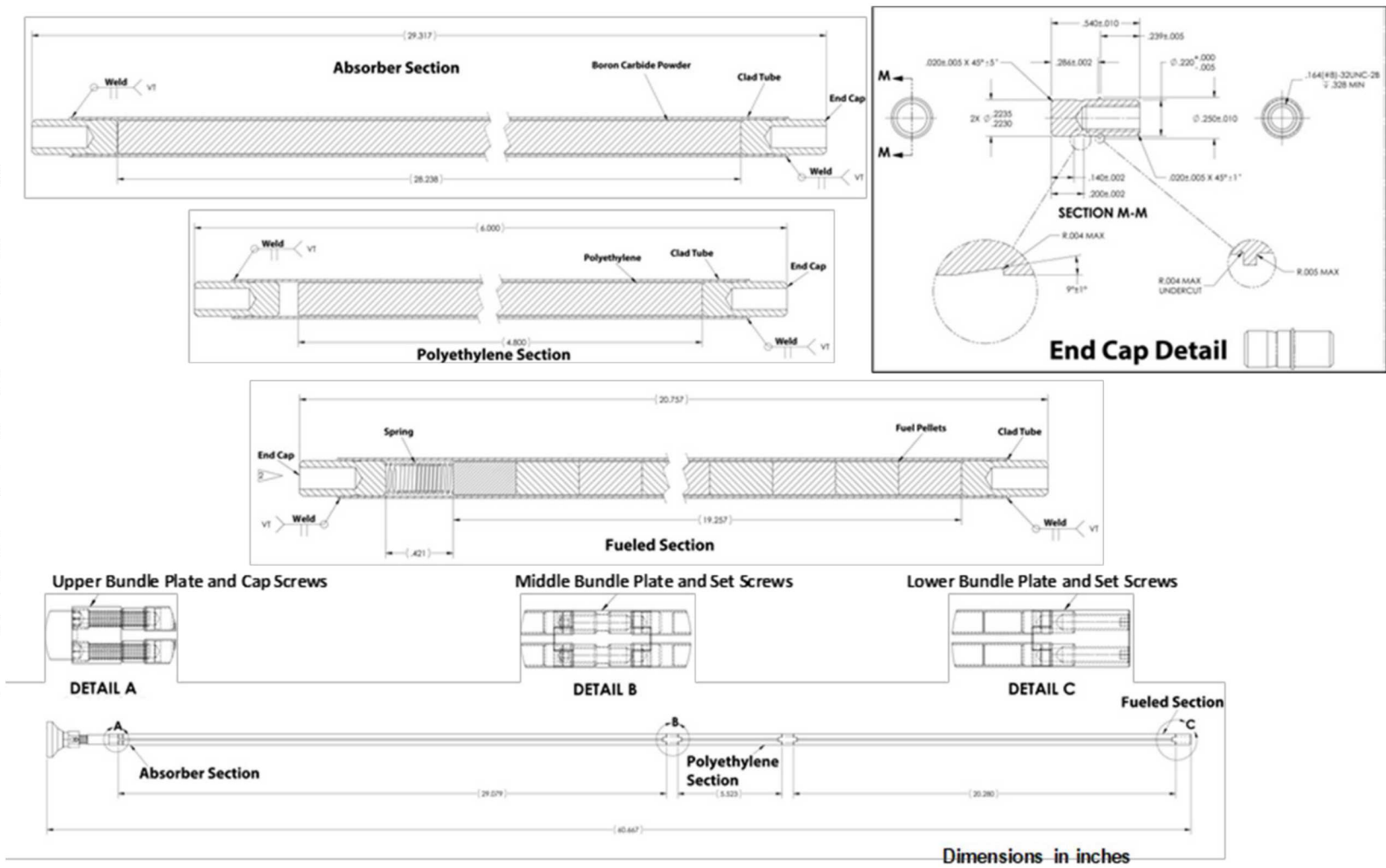


Figure 10. Design of the Control and Safety Elements.





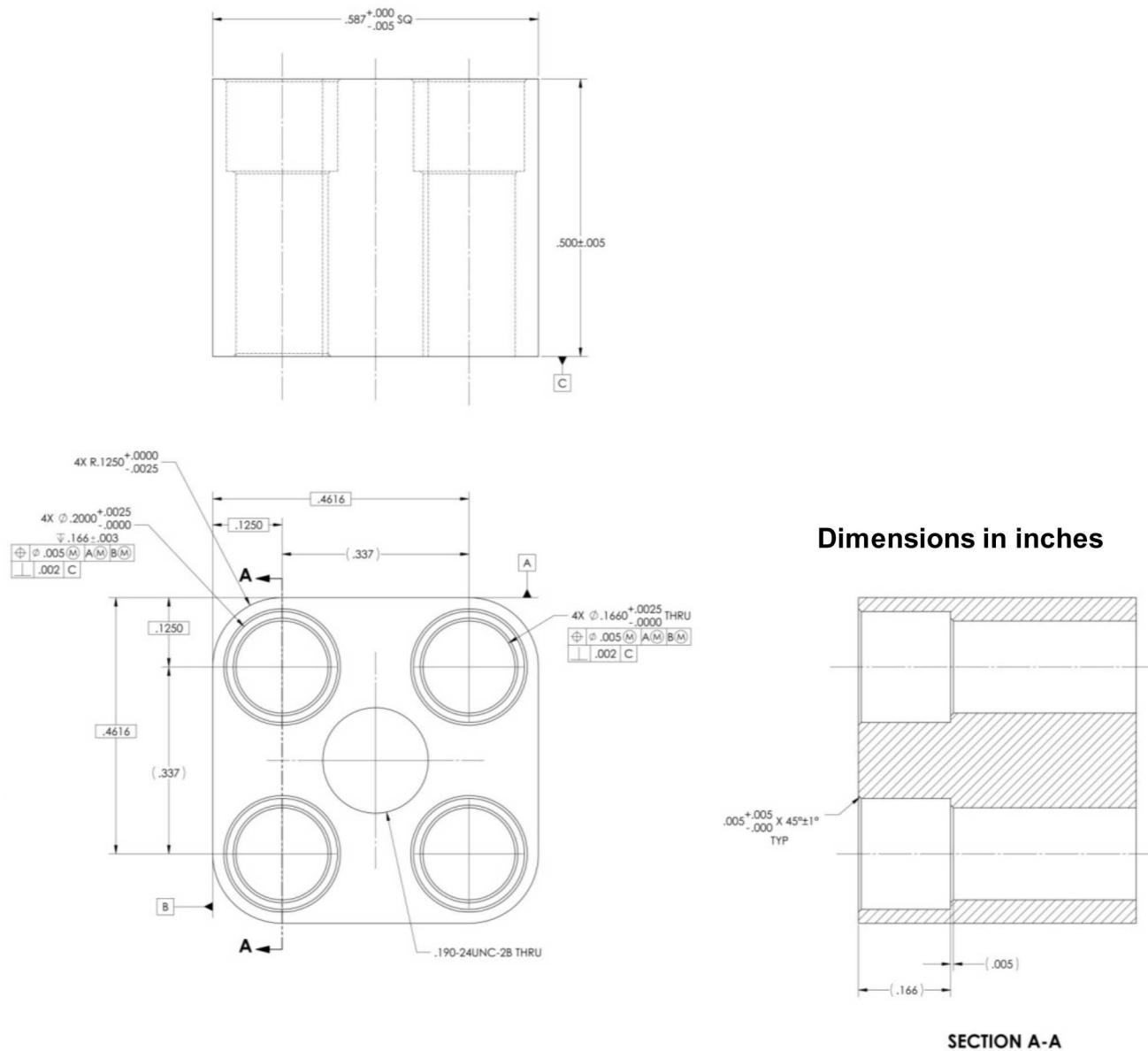


Figure 13. Excerpt From the Design Drawing for the Upper Bundle Plate.

The fueled section of the control/safety elements is similar to the fueled section of a fuel rod. The 3003 aluminum cladding tubes and end cap material are the same as were used in the fuel rods. In order to allow the elements to be lowered from the assembly, the lower grid plate has four-position through holes at the control/safety element positions as described above. The end caps on the fueled sections of the control/safety elements mate with a 6061 aluminum lower bundle plate that fills the hole in the lower grid plate. An 8-32 corrosion-resistant steel set screw 0.750 in (1.905 cm) long joins each fueled section to the bundle plate. Above the bottom end cap is a stack of fuel pellets and a spring similar to those in a fuel rod. The length and mass of the fuel pellet stack is known for each of the 23 fueled sections that were fabricated to the same precision as for the fuel rods. The relevant data on the fuel pellet stack for the population of 23 fueled sections is given in Table 5. The total mass of the UO₂ in the twelve fueled sections used in the experiments reported here is 1303.79 g and the total stack length is 584.7 cm.

Table 5. Population Averages for the 23 Control/Safety Element Fueled Sections.

Characteristic	Average Value	Standard Deviation
UO ₂ Mass (g)	108.62	0.13
Fuel Pellet Stack Length (cm)	48.717	0.049
Linear Fuel Mass (g/cm)	2.2295	0.0020

The top end caps of the fueled sections are joined to the bottom end caps of the polyethylene-filled decoupler sections through a middle bundle plate using the same set screws as in the lower bundle plates. The length of the fueled sections is set so that, when the lower bundle plate upper and lower surfaces are in line with the surfaces of the lower grid plate, the upper and lower surfaces of the middle bundle plate are nearly in line with the upper and lower surfaces of the upper grid plate.

The decoupler sections contain 4.800 in (12.192 cm) long 0.207 in (0.52578 cm) diameter polyethylene rods inside the same 3003 aluminum tubes used for the fuel rod cladding. The average polyethylene mass in the population of 24 decoupler sections is 2.531 g with a standard deviation of 0.037 g. The end caps on the decoupler sections are identical to those on the fueled section.

The bottoms of the absorber sections are joined to the tops of the decoupler sections through a middle bundle plate. The same corrosion-resistant set screws are used. The absorber sections are filled with boron carbide powder. Two lots of boron carbide powder, each with a different average particle size, were mixed in equal parts prior to loading into the absorber sections. During loading, the powder was compacted by vibrating the tubes. The loading procedure specified that the absorber sections be filled to within about 0.3 in of the top of the tube. The top caps of the sections extend 0.286 in into the tubes. Thus the gap between the bottom of the cap and the top of the powder was small. The average boron carbide mass in the population of 23 absorber sections that were fabricated is 26.37 g with a standard deviation of 0.22 g. After filling, the top caps were welded to the absorber section tubes.

The top of each absorber section is joined to the upper bundle plate by a modified 8-32 socket head cap screw 1.125 in (2.8575 cm) tall. Table 6 lists the axial positions of the interfaces in the control and safety elements when the elements are fully withdrawn from the assembly to the positions in which the measurements reported here were made.

Table 6. Axial Locations of the Interfaces in the Control and Safety Elements when the Elements are Fully Withdrawn from the Critical Assembly.

Part	Location	Axial Position Relative to the Top of the Lower Grid Plate	
		Position (in)	Position (cm)
Lower Bundle Plate	Bottom of the lower bundle plate	-1.000	-2.54000
	Bottom of the 0.222 in ID hole	-0.438	-1.11252
	Bottom of the 0.251 in ID hole	-0.199	-0.50546
	Top of the lower bundle plate	0.000	0.00000
Fueled Section	Bottom of the fueled section	-0.438	-1.11252
	Bottom of the full-diameter clad	-0.199	-0.50546
	Bottom of the fuel pellet stack	0.102	0.25908
	Top of the fuel pellet stack	19.282	48.97608
	Bottom of the top end cap	19.78	50.24120
	Top of the full-diameter clad	20.081	51.00574
	Top of the fueled section	20.320	51.61280
Middle Bundle Plate 1	Bottom of the middle bundle plate 1	19.882	50.50028
	Top of the lower 0.251 in ID hole	20.081	51.00574
	Top of the lower 0.222 in ID hole	20.320	51.61280
	Bottom of the upper 0.222 in ID hole	20.444	51.92776
	Bottom of the upper 0.251 in ID hole	20.683	52.53482
	Top of the middle bundle plate 1	20.882	53.04028
Polyethylene Decoupler Section	Bottom of the decoupler section	20.444	51.92776
	Bottom of the full-diameter clad	20.683	52.53482
	Bottom of the polyethylene	20.984	53.29936
	Top of the polyethylene	25.784	65.49136
	Bottom of the top end cap	25.905	65.79870
	Top of the full-diameter clad	26.206	66.56324
	Top of the decoupler section	26.445	67.17030
Middle Bundle Plate 2	Bottom of the middle bundle plate 2	26.007	66.05778
	Top of the lower 0.251 in ID hole	26.206	66.56324
	Top of the lower 0.222 in ID hole	26.445	67.17030
	Bottom of the upper 0.222 in ID hole	26.569	67.48526
	Bottom of the upper 0.251 in ID hole	26.808	68.09232
	Top of the middle bundle plate 2	27.007	68.59778
Absorber Section	Bottom of the absorber section	26.569	67.48526
	Bottom of the full-diameter clad	26.808	68.09232
	Bottom of the absorber	27.109	68.85686
	Bottom of the top end cap	55.347	140.58138
	Top of the full-diameter clad	55.648	141.34592
	Top of the absorber section	55.887	141.95298
Upper Bundle Plate	Bottom of the upper bundle plate	55.887	141.95298
	Bottom of the 0.200 in ID hole	56.221	142.80134
	Top of the upper bundle plate	56.387	143.22298

Whenever moderator is present in the core tank during the execution of a critical experiment, the safety elements are held at their most reactive position with the absorber above the surface of the water and the fueled sections in the assembly core. In this position, a large negative reactivity is available to quickly shut down the assembly should the need arise. The absorber section in the elements is also well away from the assembly core and does not significantly affect the reactivity of the system. The control element is used during critical assembly operations to make fine adjustments in the reactivity of the assembly. When data are taken during an approach-to-critical experiment, the control element is also fully withdrawn to its most reactive position so the absorber does not affect the system neutronically.

1.2.9 Neutron Source – The neutron source in the assembly is a small double-sealed 316L stainless steel capsule containing a ^{252}Cf spontaneous fission source. The source is attached to a fixture designed to be placed in a fuel rod location in the assembly grid structure or in a mounting location outside the grid plates. The source and fixture are shown in Figure 14. The bottom (source) end of the fixture is the bottom end cap, essentially a cylinder of aluminum 3003 0.540 in (1.3716 cm) long and 0.220 in (0.5588 cm) diameter that is drilled and tapped to accommodate a 3-48 steel set screw that is 0.313 in (0.79502 cm) long. The bottom of the source fixture and top of the source capsule are 5.099 in (12.95146 cm) above the top of the lower grid plate. An aluminum 3003 tube identical to the fuel rod cladding tubes (nominally 0.250 in outer diameter, 0.0014 in wall) covers the top 0.254 in (0.64516 cm) of the bottom end cap and extends above the moderator where it connects to a handle that rests on the guide plate. The tube is slotted at the ends so that it fills with moderator when the critical assembly is filled.

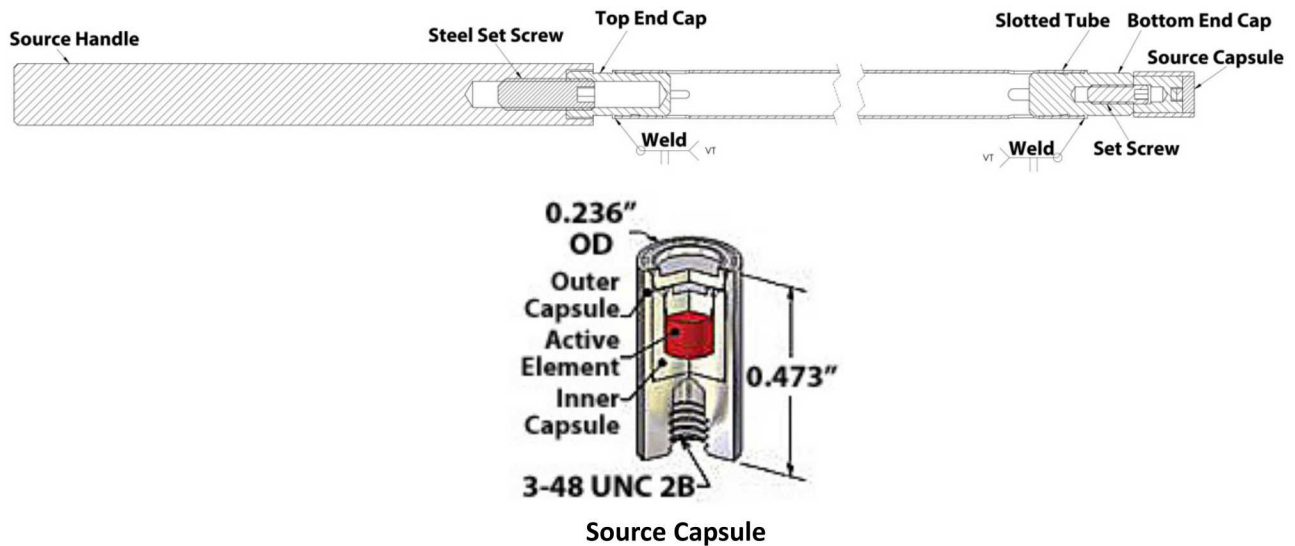


Figure 14. The Neutron Source and Supporting Fixture.

Table 7 shows the axial locations of the surfaces of the neutron source under the assumption that the origin is at the top of the lower grid plate.

Table 7. Axial Locations of the Interfaces in the Neutron Source as Installed in the Critical Assembly.

Part	Location	Axial Position Relative to the Top of the Lower Grid Plate	
		Position (in)	Position (cm)
Source Capsule	Bottom of the source capsule	4.626	11.75004
	Bottom of the set screw hole	5.016	12.74064
	Top of the source capsule	5.099	12.95146
Lower Set Screw	Bottom of the set screw	5.016	12.74064
	Top of the set screw	5.329	13.53566
Bottom End Cap	Bottom of the bottom end cap	5.099	12.95146
	Top of the set screw hole	5.586	14.18844
	Top of the bottom end cap	5.940	15.08760
Slotted Tube	Bottom of the slotted tube	5.382	13.67028
	Top of the slotted tube	28.156	71.51624
Top End Cap	Bottom of the top end cap	27.855	70.75170
	Bottom of the hole in the top end cap	27.908	70.88632
	Top of the top end cap	28.395	72.12330
Upper Set Screw	Bottom of the upper set screw	28.255	71.76770
	Top of the upper set screw	28.755	73.03770
Handle	Bottom of the handle	28.255	71.76770
	Top of the end cap hole in the handle	28.395	72.12330
	Top of the set screw hole in the handle	28.885	73.36790
	Top of the handle	32.255	81.92770

1.2.10 Experimental Method – The focus of these critical experiments was to explore partially reflected arrays.

The critical water height for each configuration was determined in an approach-to-critical experiment with the water height as a free parameter. During the experiments, water was continuously pumped from the dump tank to the core tank. The height of the water in the core tank was determined by the setting of the remotely adjustable overflow standpipe. The inverse count rate at successively higher water levels for two or three detectors as a function of the height of the water was linearly extrapolated to zero inverse count rate to obtain an estimate of the critical water height. During all measurements the control and safety elements were in their fully withdrawn or most reactive positions

The arrays addressed in the first two cases completely filled the 45×45 array of holes in the grid plates. The differences among these arrays were in the number of water holes inside the array – Case 1 had none and Case 2 had 189 holes distributed around the core. The arrays addressed in Cases 3 through 8 had decreasing numbers of fuel rods with no internal water holes. Cases 9 through 11 also had no internal water holes with a square overall shape of the fuel array.

Cases 10 and 12 through 22 all included the same 1296 fuel rods. Case 10 had a 36x36 array of fuel rods. In the arrays in Cases 12 through 17, the 1296-rod core was divided into two 18x36 halves with an internal water-filled linear slot between the two halves. The width of the slot varied from one to six fuel rod rows.

In Cases 18 through 22, the 1296-rod array was divided into 18x18 324-rod quarters with cruciform slots between the quarters. The width of the slot varied from one to five fuel rod rows.

Each of the configurations was addressed with an inverse-count-rate approach-to-critical experiment. The first two moderator levels in these configurations were known to be subcritical either by calculation or by comparison with similar configurations. The array sizes used in subsequent measurements were guided by the count rate results. Early in each approach, the water height increments were several millimeters. The water height increments decreased during the approach until the last few count rate measurements were made at increments of a small number of millimeters.

All of the final configurations had subcritical multiplications that significantly exceeded 100.

1.2.11 Experiment Arrays – During the approach-to-critical experiments, detailed records were kept of the location and identity of each fuel rod in each core. In Cases 1 through 11, a given fuel rod was placed in the same grid location in each core in which it was used. Each grid location in the array was identified with a single fuel rod. A particular grid location had the same fuel rod in it whenever that location was occupied. Whenever a grid location was unoccupied, the fuel rod assigned to that grid location was not in the fuel array. Each of the arrays for cases 12 through 22 included the same set of fuel rods as Case 10. The slots in the arrays of Cases 12 through 22 were created by moving whole fuel rod rows from the inside to the outside of the array.

The total number of fuel rod positions occupied, the mass of UO_2 in the core, and the total length of the fuel columns in all the fuel rods for the array measured in each of the twenty-two configurations are listed in Table 8. Also listed in the table is the extrapolated water height at delayed critical with uncertainty, the temperature at which the experimental measurements were made, and the last water level that was used in the extrapolation to delayed critical.

The uncertainties in the extrapolated critical water heights were estimated by propagating the random uncertainties in the count rate data and the random uncertainties in the level sensor readings through the linear extrapolation. That result was then added in quadrature to the estimated uncertainty in the level sensor calibration to obtain the uncertainty in the extrapolated critical water height. In all cases, the calibration uncertainty was significantly larger than the other components of the uncertainty. The difference between the extrapolated critical water height and the last water level used in the extrapolation ranged from a maximum of 0.39 cm (Case 7) to a minimum of 0.15 cm (Case 2).

Table 9 lists the average fuel rod diameter with standard deviation for the set of fuel rods used in each benchmark experiment. The fuel rod arrangement in the array measured for each of the twenty-two cores is shown in Figures 15 through 36.

In Cases 2 through 22, the source was in the fuel grid as shown in the figures. For Case 1, the source was located in a fixture outside the grid. In this case, the source was located 21.6205 cm to the left of the center of the array and centered vertically on the array oriented as shown in Figure 15.

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Table 8. Extrapolated Critical Water Height, Total UO₂ Mass and Column Length, and Assembly Temperature for the Twenty-Two Cases.

Case	Array Size (rods) ^(a)	UO ₂ Mass (g) ^(b)	Fuel Column Length (cm) ^(c)	Extrapolated Critical Water Height (cm) ^(d)		Temperature (°C)	Highest Water Level (cm) ^(f)
				Value	Uncertainty ^(e)		
1	2025	220166.31	98774.7	28.031	0.073	24.9	27.844
2	1836	199600.44	89543.2	25.763	0.051	25.3	25.616
3	1781	193661.13	86870.9	29.906	0.046	23.6	29.730
4	1573	171070.74	76724.8	32.773	0.067	25.0	32.564
5	1425	154999.05	69503.6	35.651	0.032	23.5	35.501
6	1281	139343.58	62483.3	39.729	0.032	24.3	39.535
7	1137	123686.83	55461.7	46.187	0.050	25.0	45.798
8	1109	120640.44	54095.9	48.138	0.030	23.5	47.945
9	1600	174000.93	78040.3	33.051	0.060	23.2	32.886
10	1296	140958.28	63213.0	40.340	0.029	23.5	40.176
11	1156	125744.61	56387.0	46.530	0.038	23.5	46.342
12	1296	140958.28	63213.0	37.321	0.049	24.3	37.139
13	1296	140958.28	63213.0	36.002	0.022	24.3	35.774
14	1296	140958.28	63213.0	36.313	0.029	25.1	36.079
15	1296	140958.28	63213.0	37.872	0.033	25.1	37.663
16	1296	140958.28	63213.0	40.904	0.035	25.2	40.733
17	1296	140958.28	63213.0	45.610	0.036	25.0	45.389
18	1296	140958.28	63213.0	35.023	0.053	24.5	34.818
19	1296	140958.28	63213.0	33.290	0.049	24.6	33.102
20	1296	140958.28	63213.0	34.283	0.026	24.4	34.078
21	1296	140958.28	63213.0	37.912	0.039	24.6	37.720
22	1296	140958.28	63213.0	45.212	0.029	25.1	44.990

- (a) Includes the twelve fueled sections in the control element and the two safety elements.
(b) Sum of the UO₂ masses in the rods included in the configuration.
(c) Sum of the fuel column lengths in the rods included in the configuration.
(d) The water depth is measured from the top of the lower grid plate.
(e) The method of obtaining the uncertainty in the extrapolated critical water height is described in the text.
(f) The highest water level in the approach-to-critical experiment that was used in the extrapolation to the critical water height.

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Table 9. Average Fuel Rod Diameter and Standard Deviation of the Distribution for the Fuel Rods in Each Case.

Case	Array Size (rods)	Average Fuel Rod Outside Diameter (cm)	Standard Deviation (cm)	Number of Fuel Rods ^(a)
1	2025	0.634954	0.000217	2013
2	1836	0.634955	0.000217	1824
3	1781	0.634963	0.000217	1769
4	1573	0.634974	0.000215	1561
5	1425	0.634983	0.000215	1413
6	1281	0.634989	0.000216	1269
7	1137	0.634996	0.000212	1125
8	1109	0.634994	0.000210	1097
9	1600	0.634972	0.000217	1588
10	1296	0.634979	0.000216	1284
11	1156	0.634985	0.000212	1144
12	1296	0.634979	0.000216	1284
13	1296	0.634979	0.000216	1284
14	1296	0.634979	0.000216	1284
15	1296	0.634979	0.000216	1284
16	1296	0.634979	0.000216	1284
17	1296	0.634979	0.000216	1284
18	1296	0.634979	0.000216	1284
19	1296	0.634979	0.000216	1284
20	1296	0.634979	0.000216	1284
21	1296	0.634979	0.000216	1284
22	1296	0.634979	0.000216	1284

(a) Each configuration also included 12 fueled sections in the control and safety elements.

During the course of the critical experiment series, data were taken to test the consistency of the measured critical water heights. For several of the configurations investigated, the approach-to-critical experiment was repeated using the same fuel rods and fuel rod layout. The critical water level was determined from the new approach data. The temporal separation between the original approach-to-critical experiment and the repeat of that experiment ranged from 1 day to about 6 months. The scatter in the extrapolated critical water level was consistent with a standard deviation of about 0.04 cm in the extrapolated critical water level.

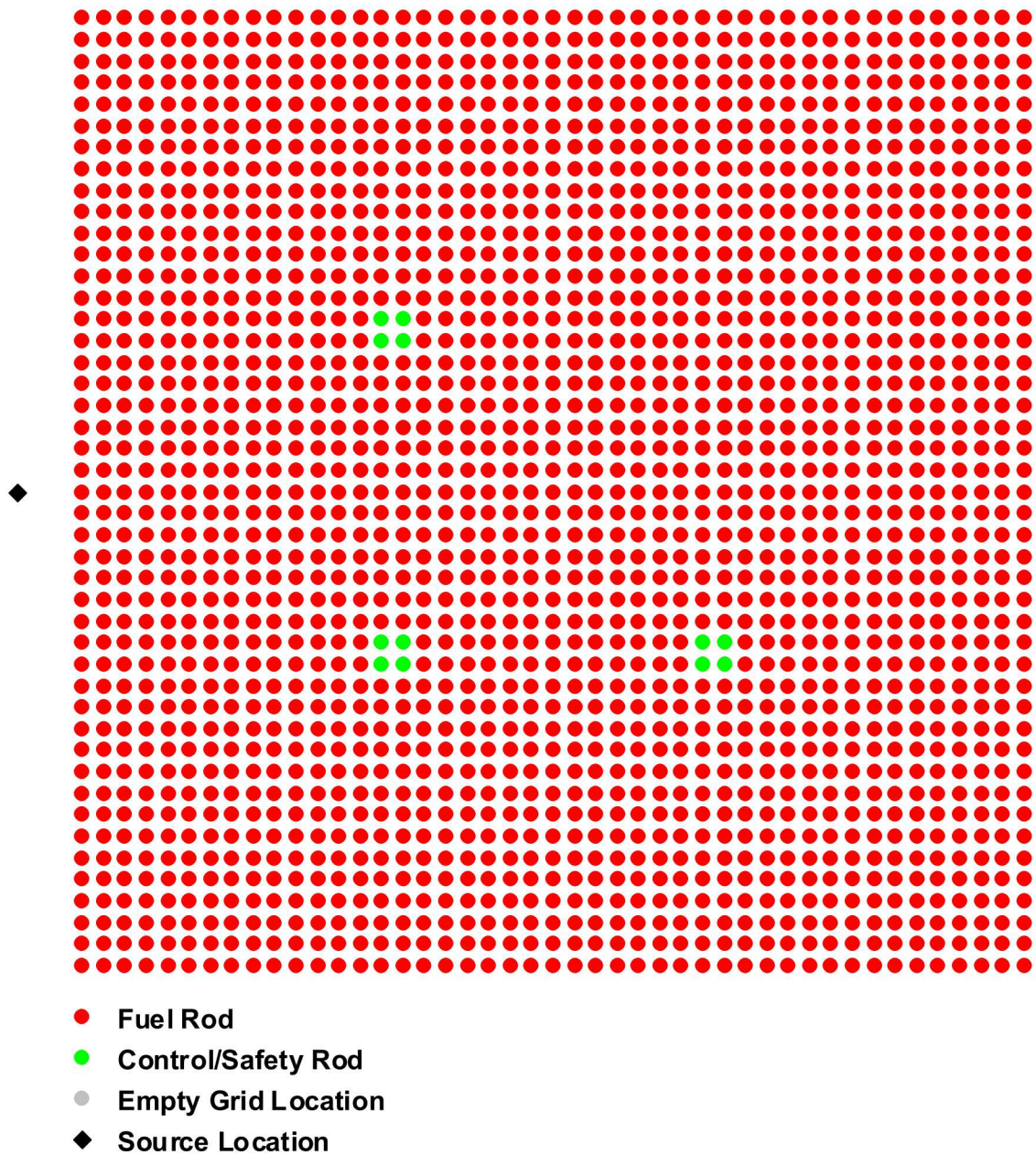


Figure 15. Fuel Rod Layout of the Array Measured for Case 1.

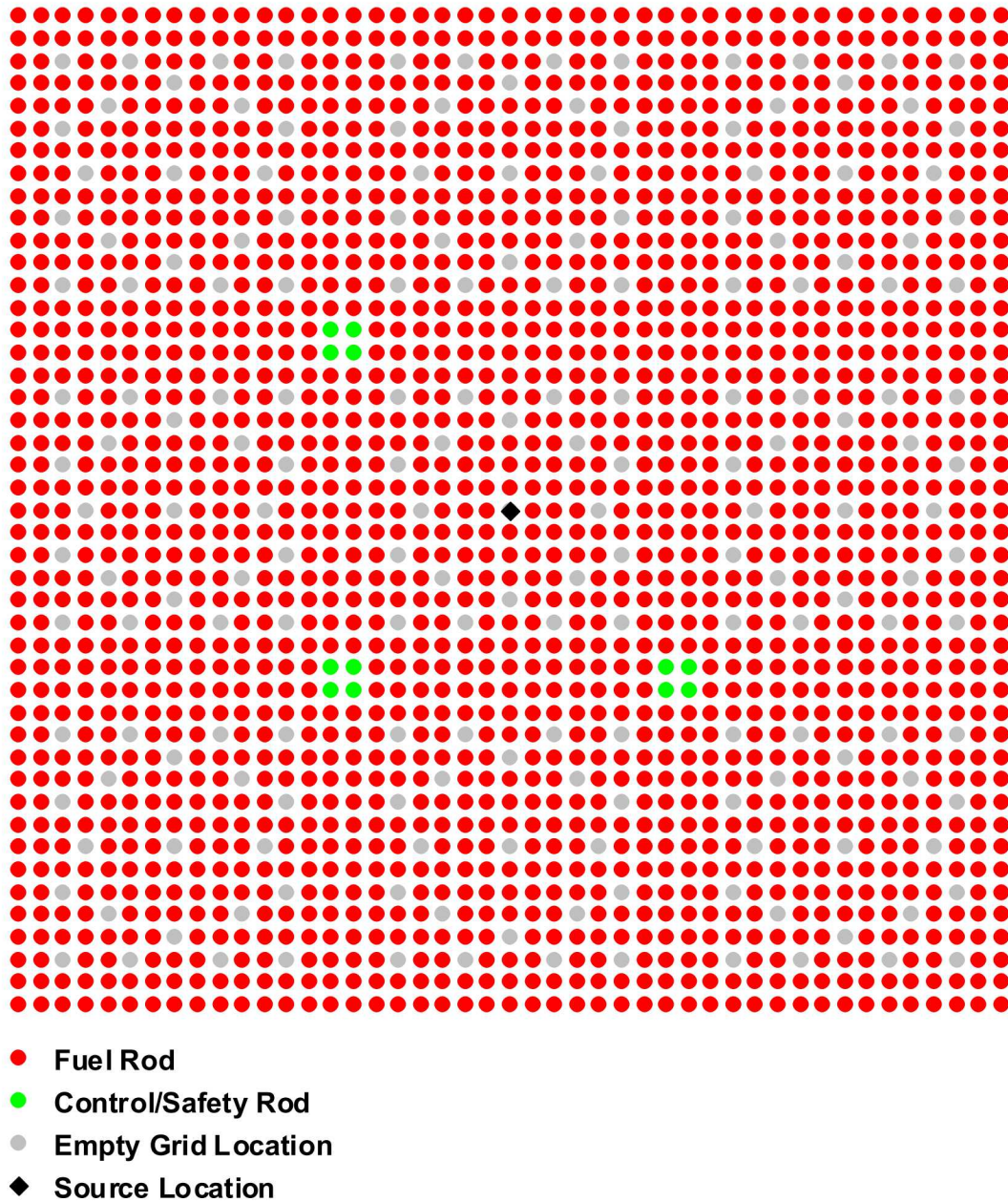


Figure 16. Fuel Rod Layout of the Array Measured for Case 2.

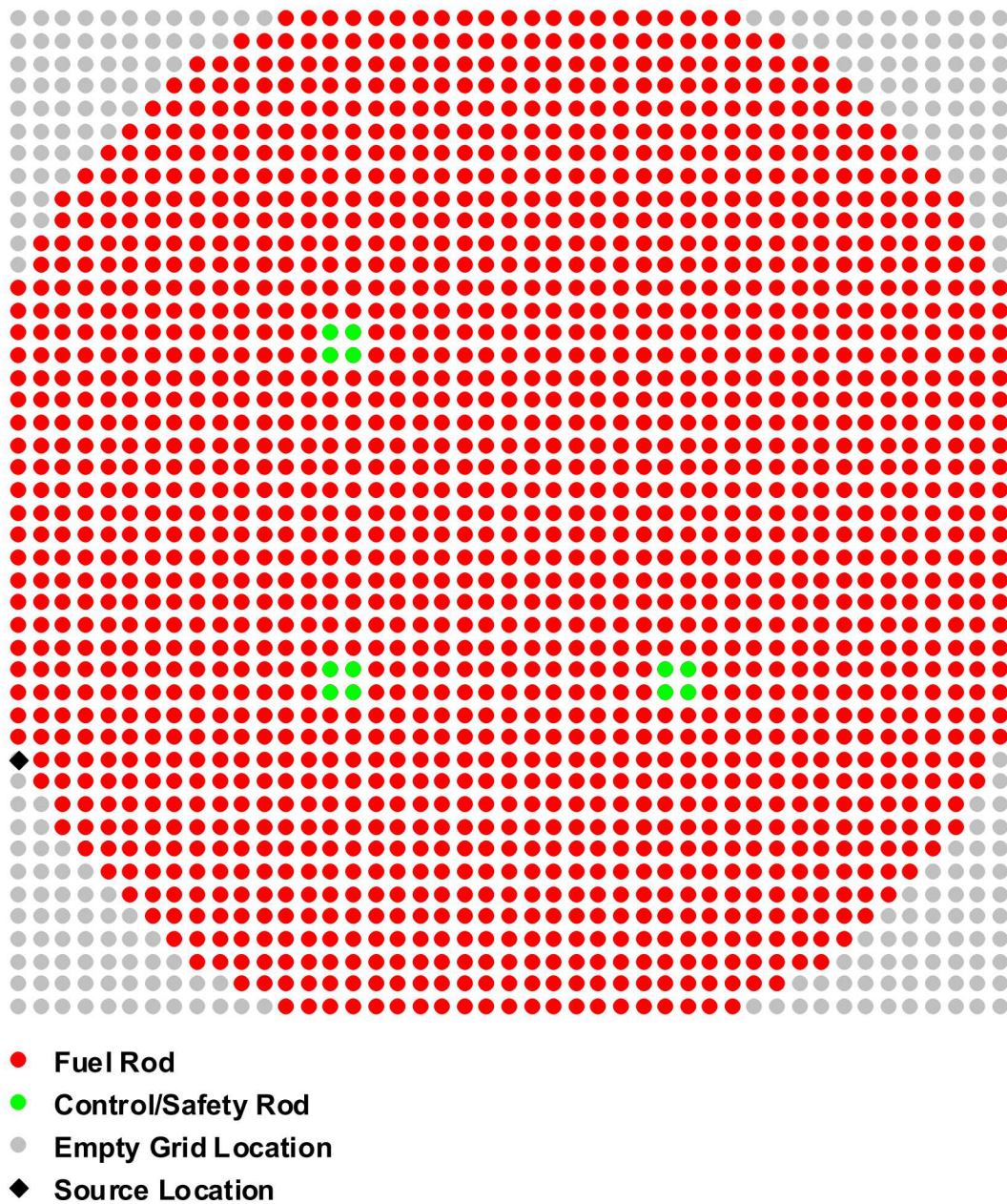


Figure 17. Fuel Rod Layout of the Array Measured for Case 3.

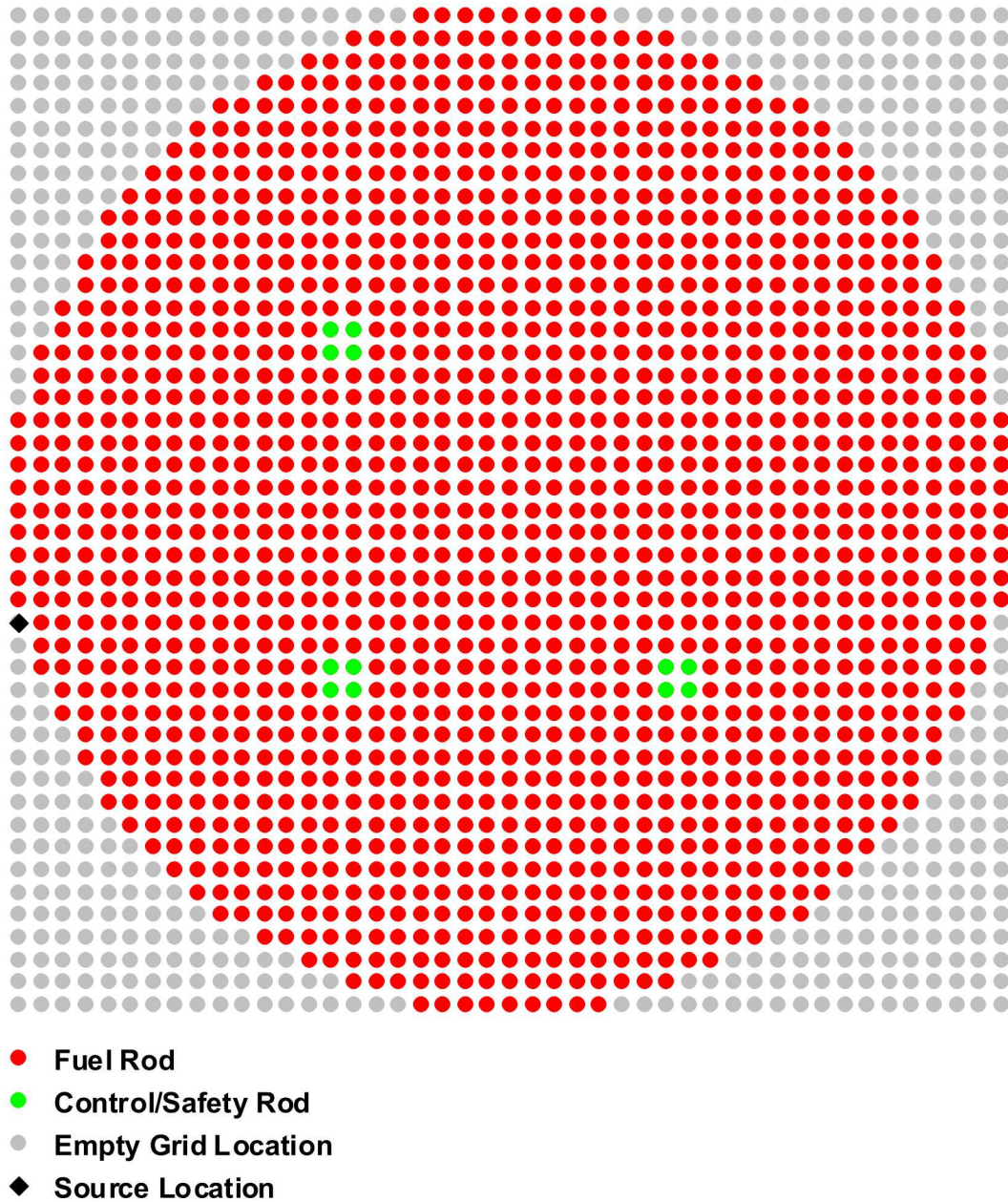


Figure 18. Fuel Rod Layout of the Array Measured for Case 4.

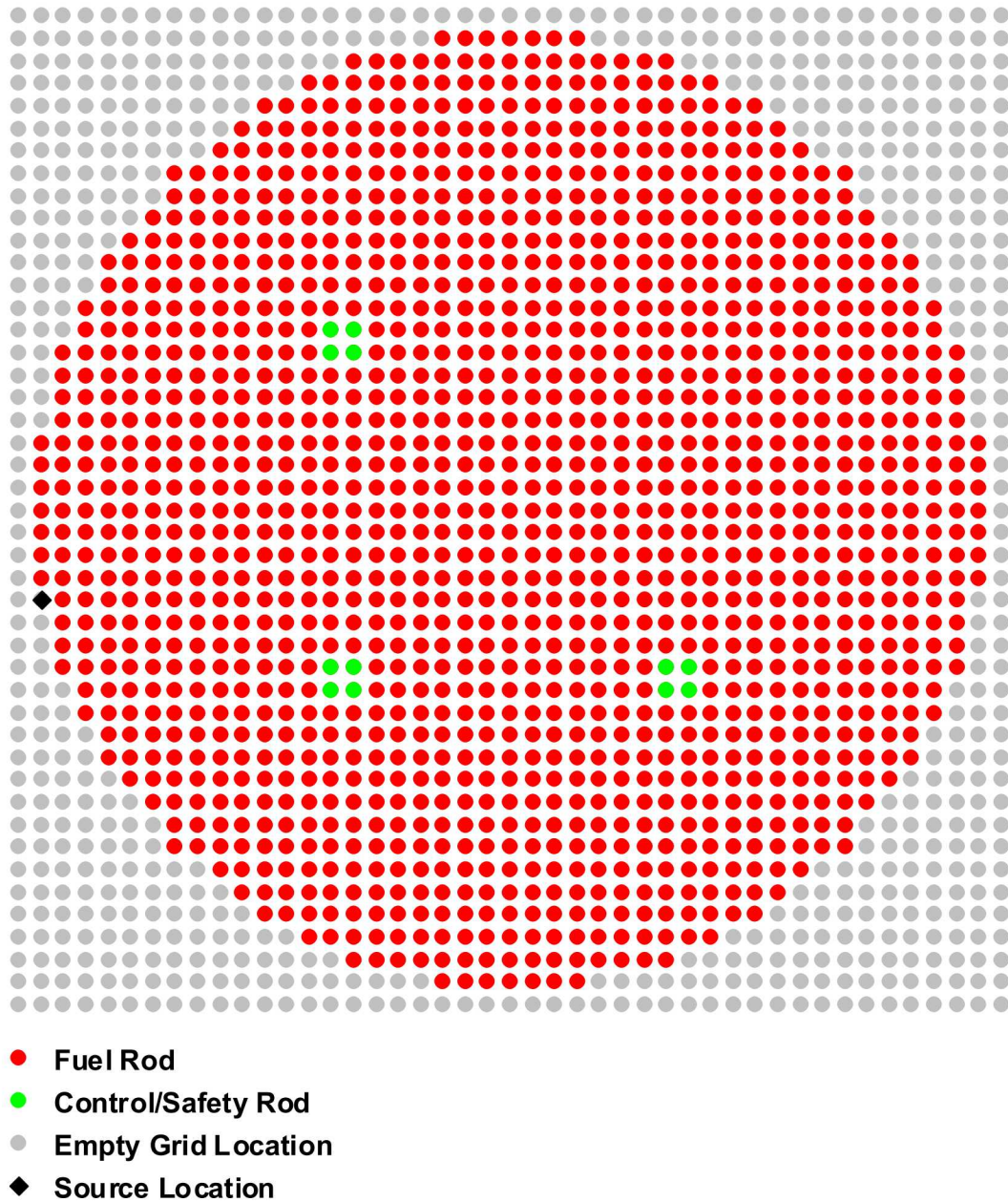


Figure 19. Fuel Rod Layout of the Array Measured for Case 5.

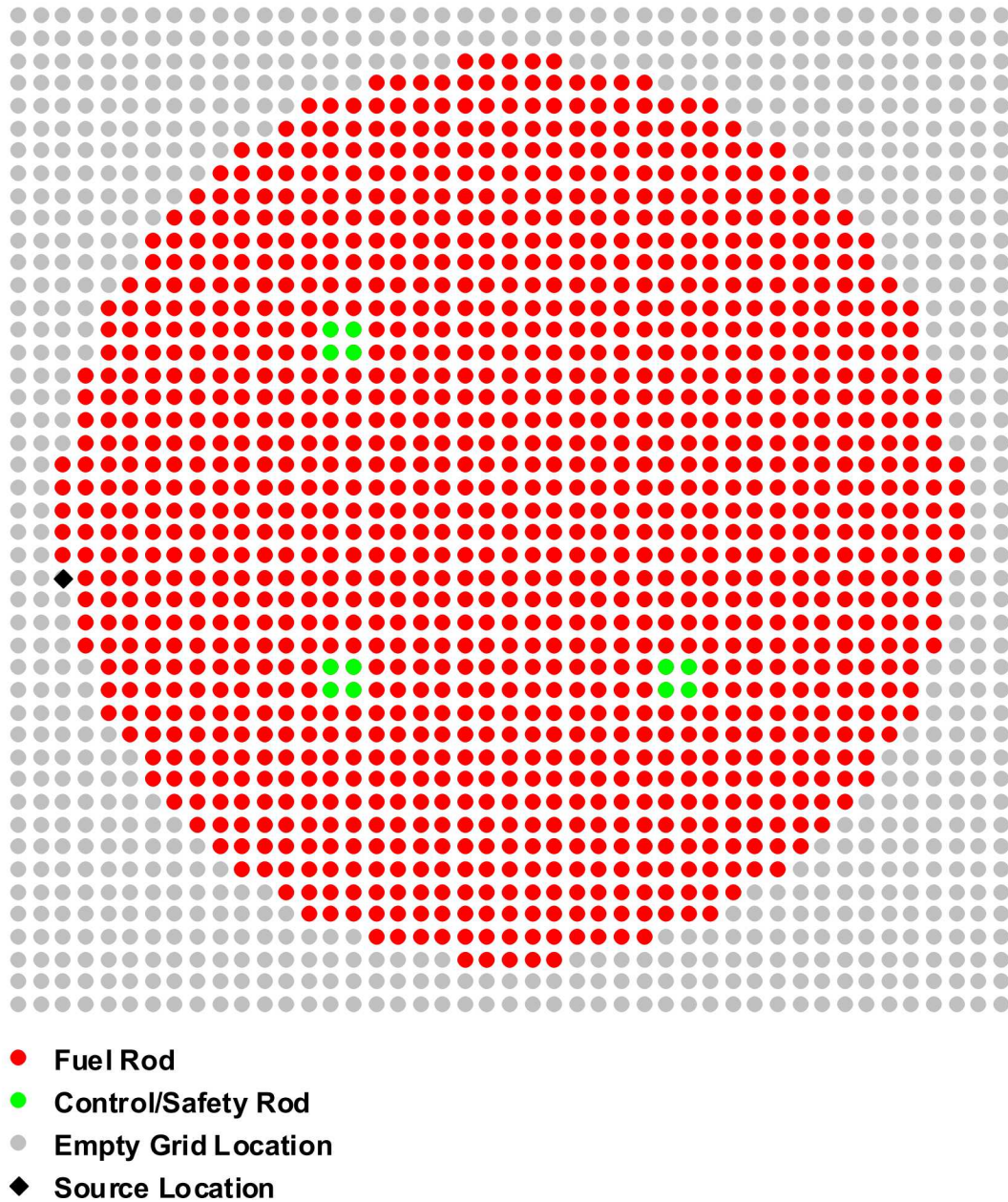


Figure 20. Fuel Rod Layout of the Array Measured for Case 6.

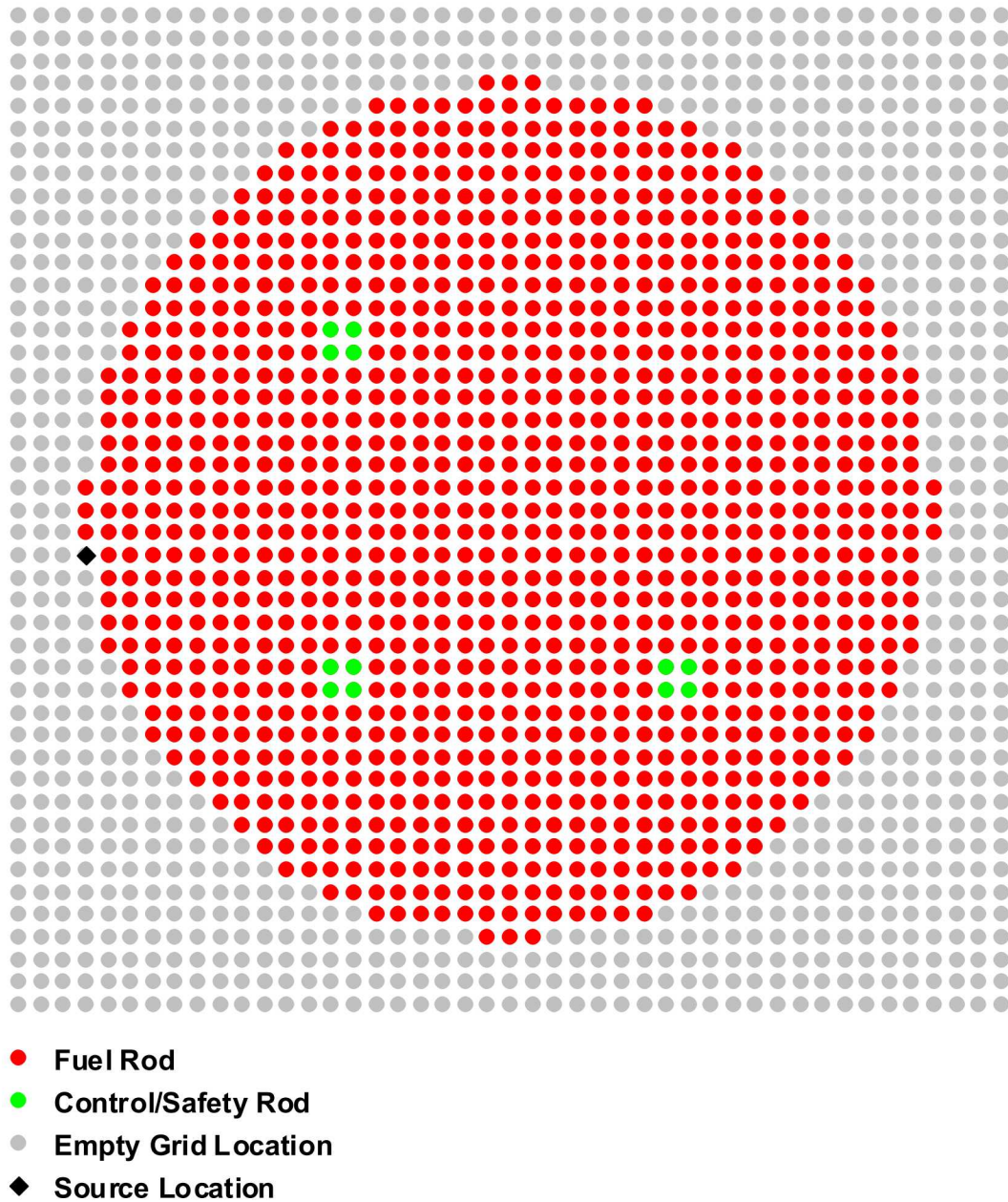


Figure 21. Fuel Rod Layout of the Array Measured for Case 7.

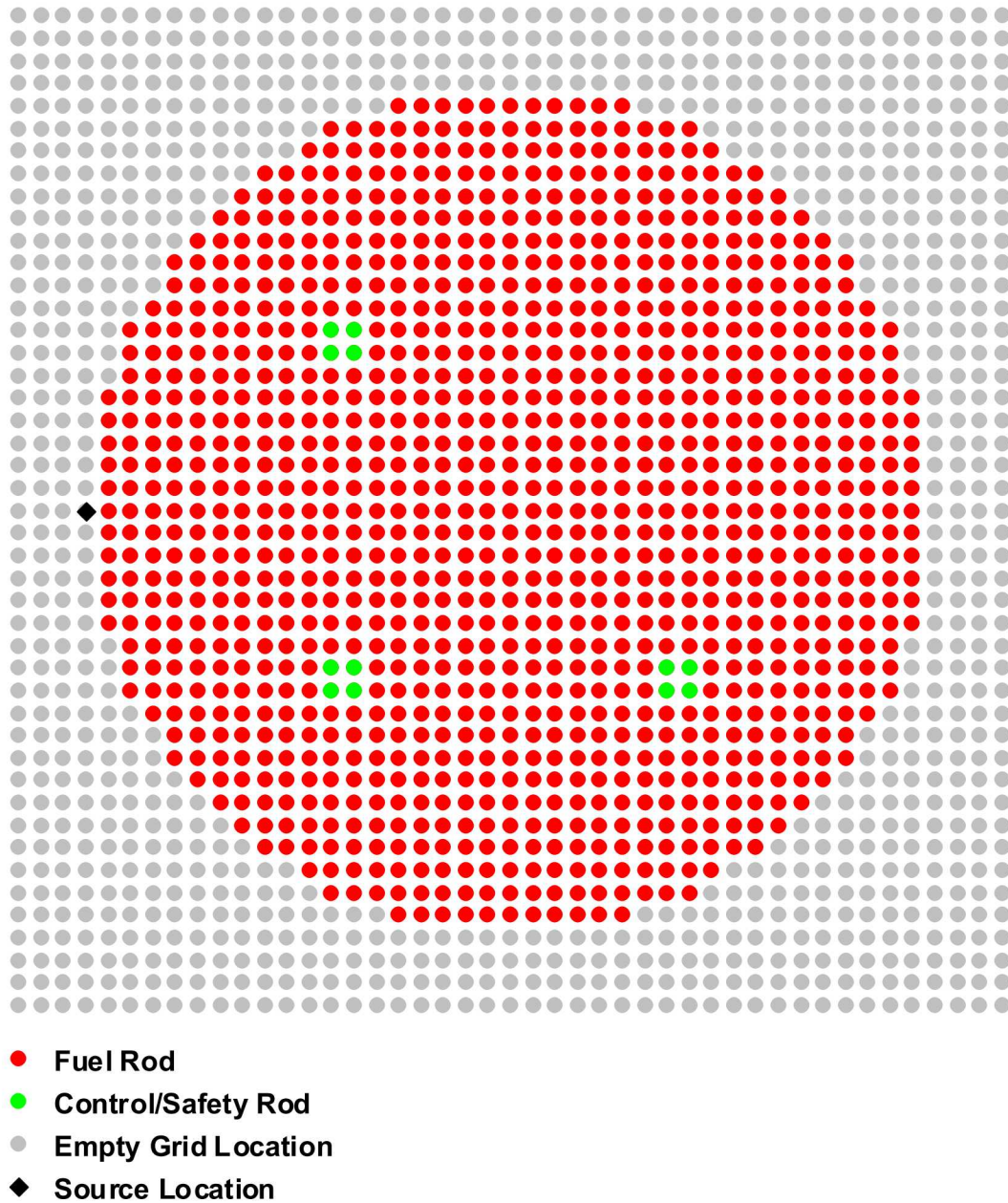


Figure 22. Fuel Rod Layout of the Array Measured for Case 8.

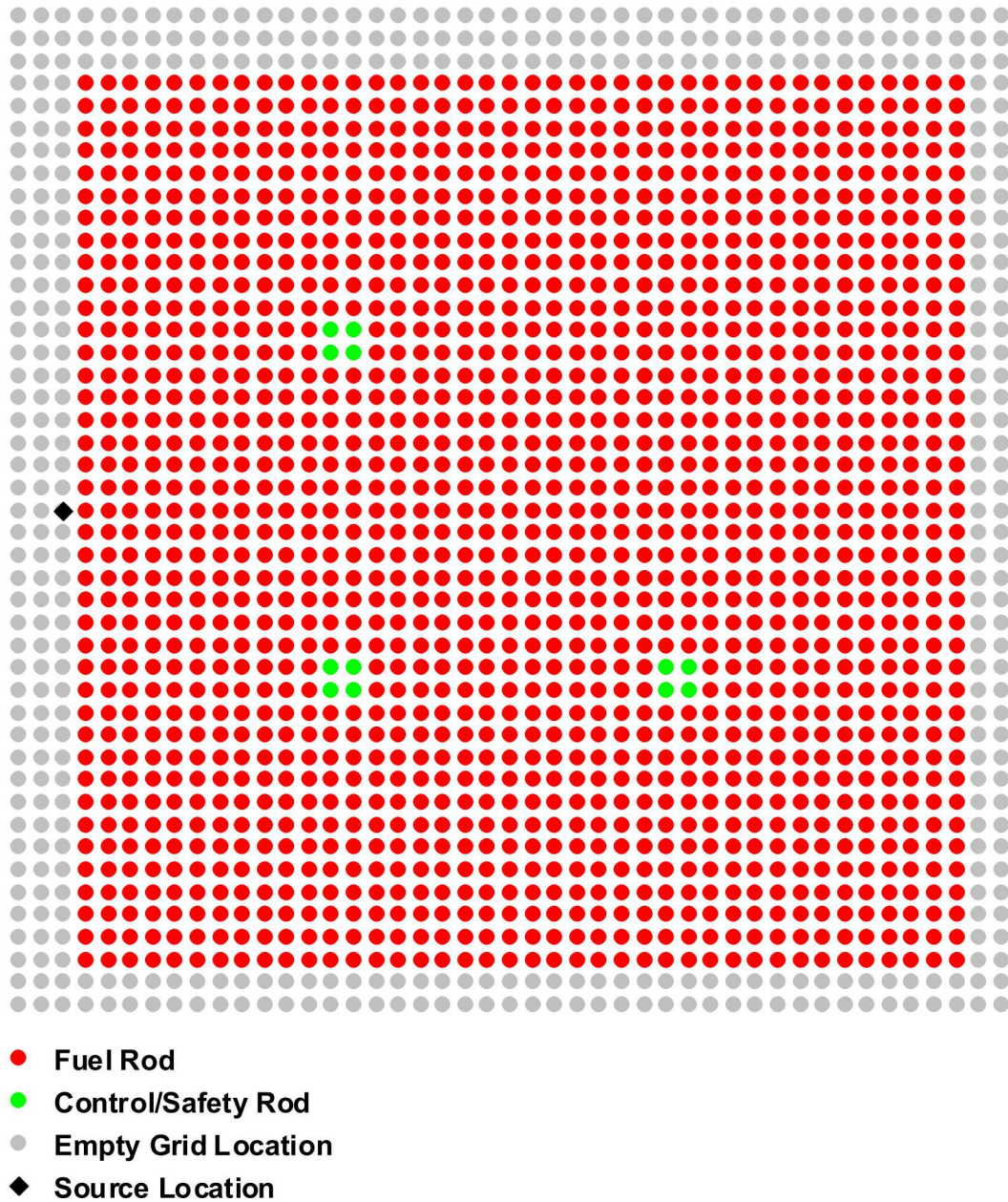


Figure 23. Fuel Rod Layout of the Array Measured for Case 9.

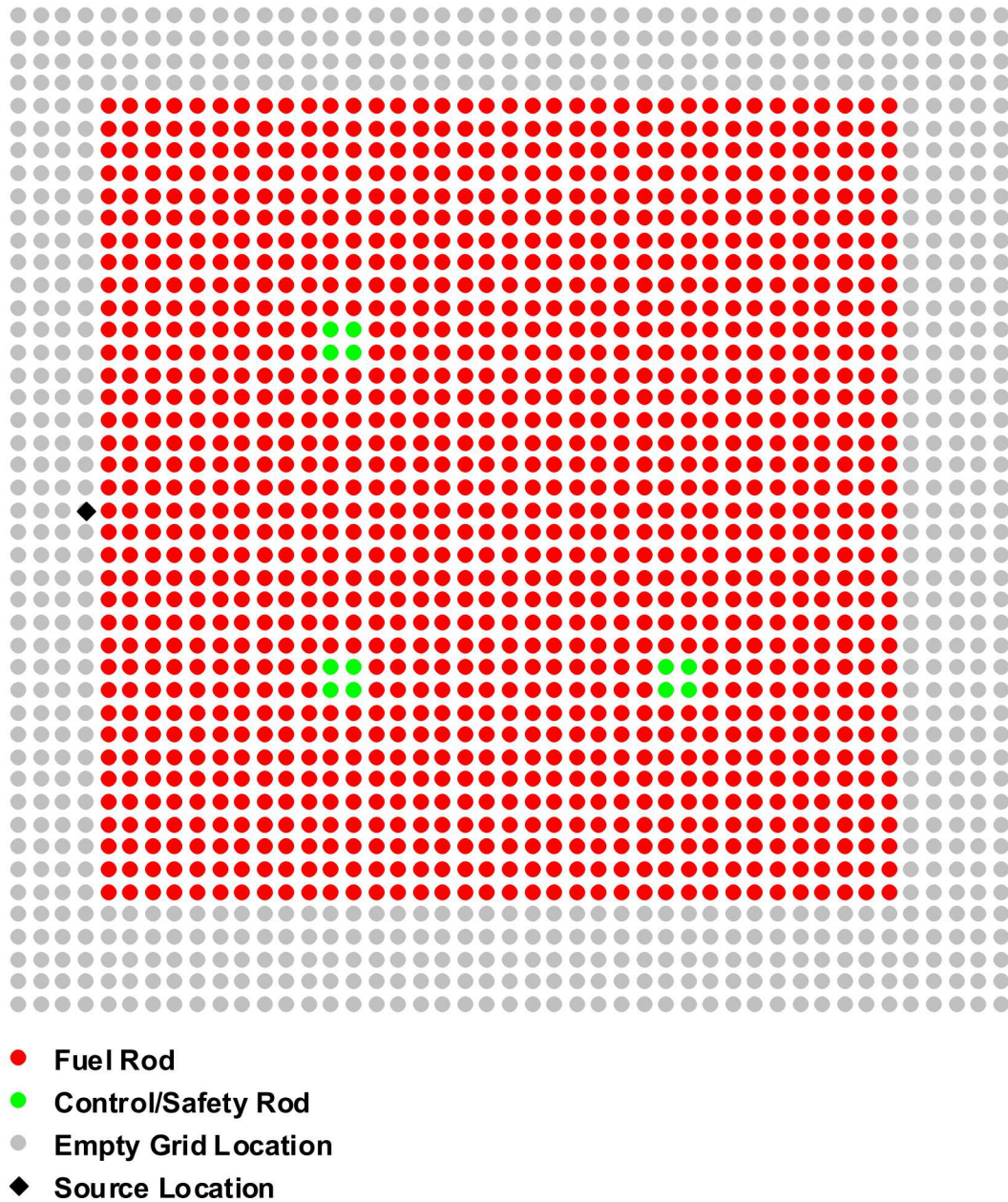


Figure 24. Fuel Rod Layout of the Array Measured for Case 10.

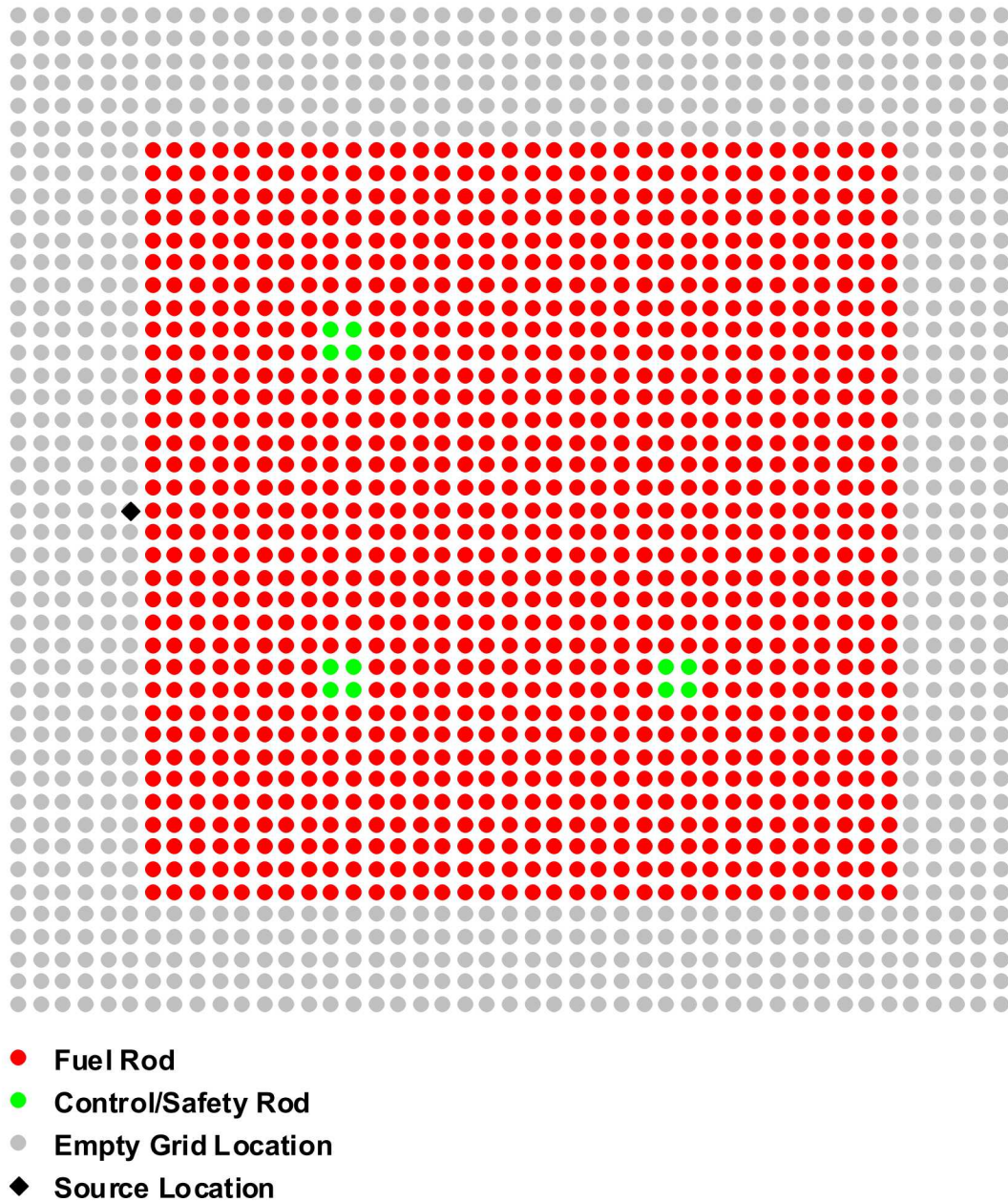


Figure 25. Fuel Rod Layout of the Array Measured for Case 11.

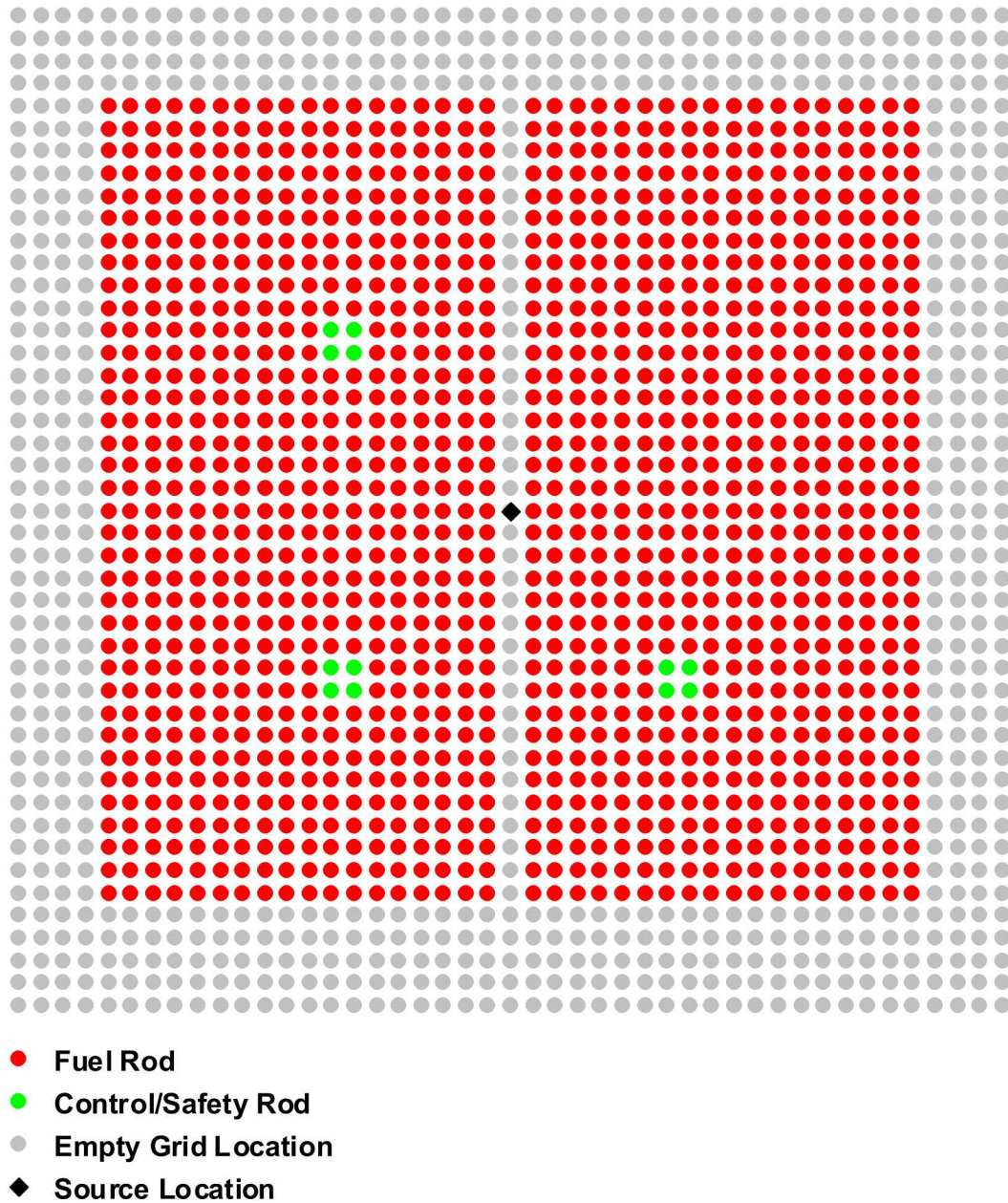


Figure 26. Fuel Rod Layout of the Array Measured for Case 12.

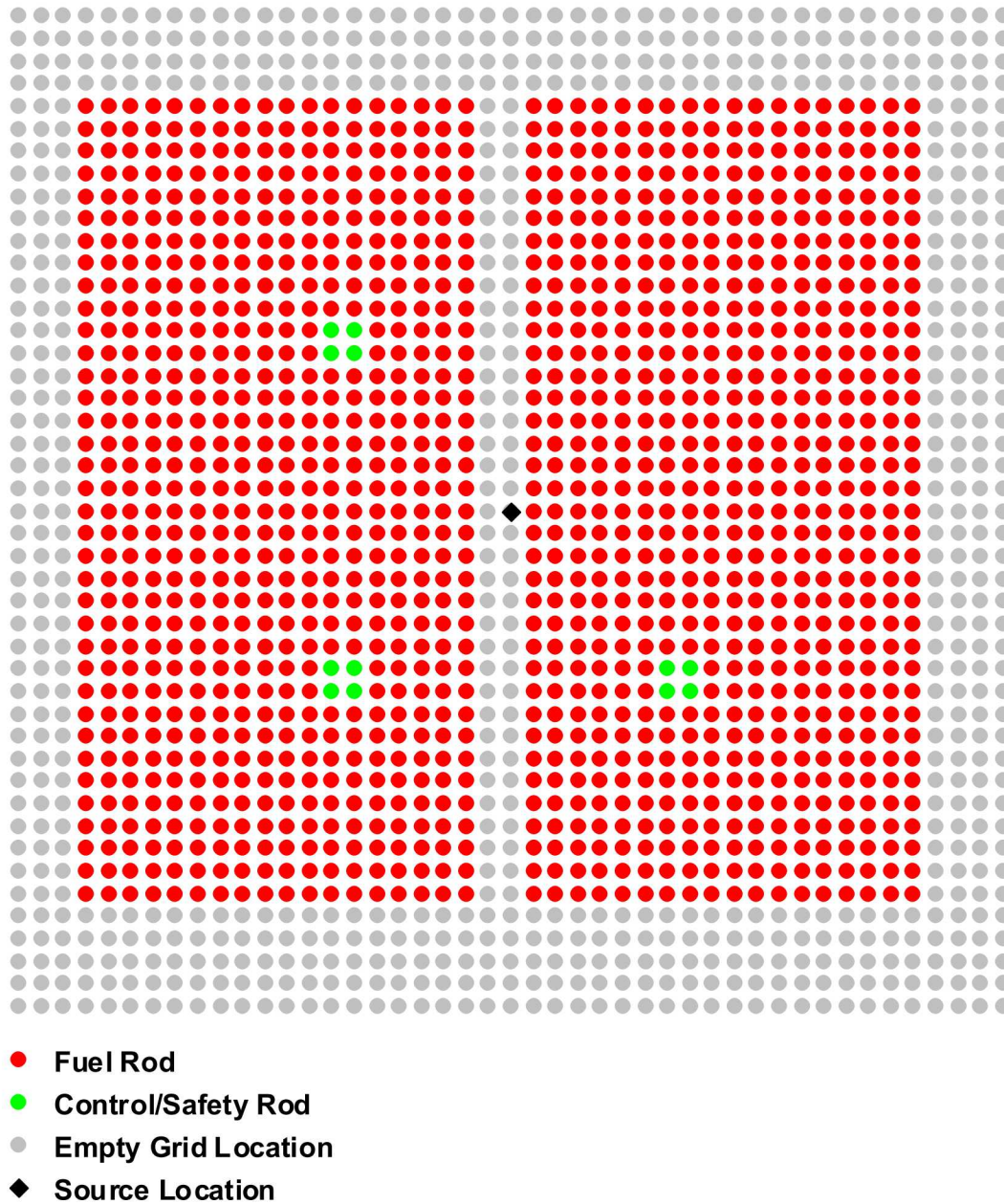


Figure 27. Fuel Rod Layout of the Array Measured for Case 13.

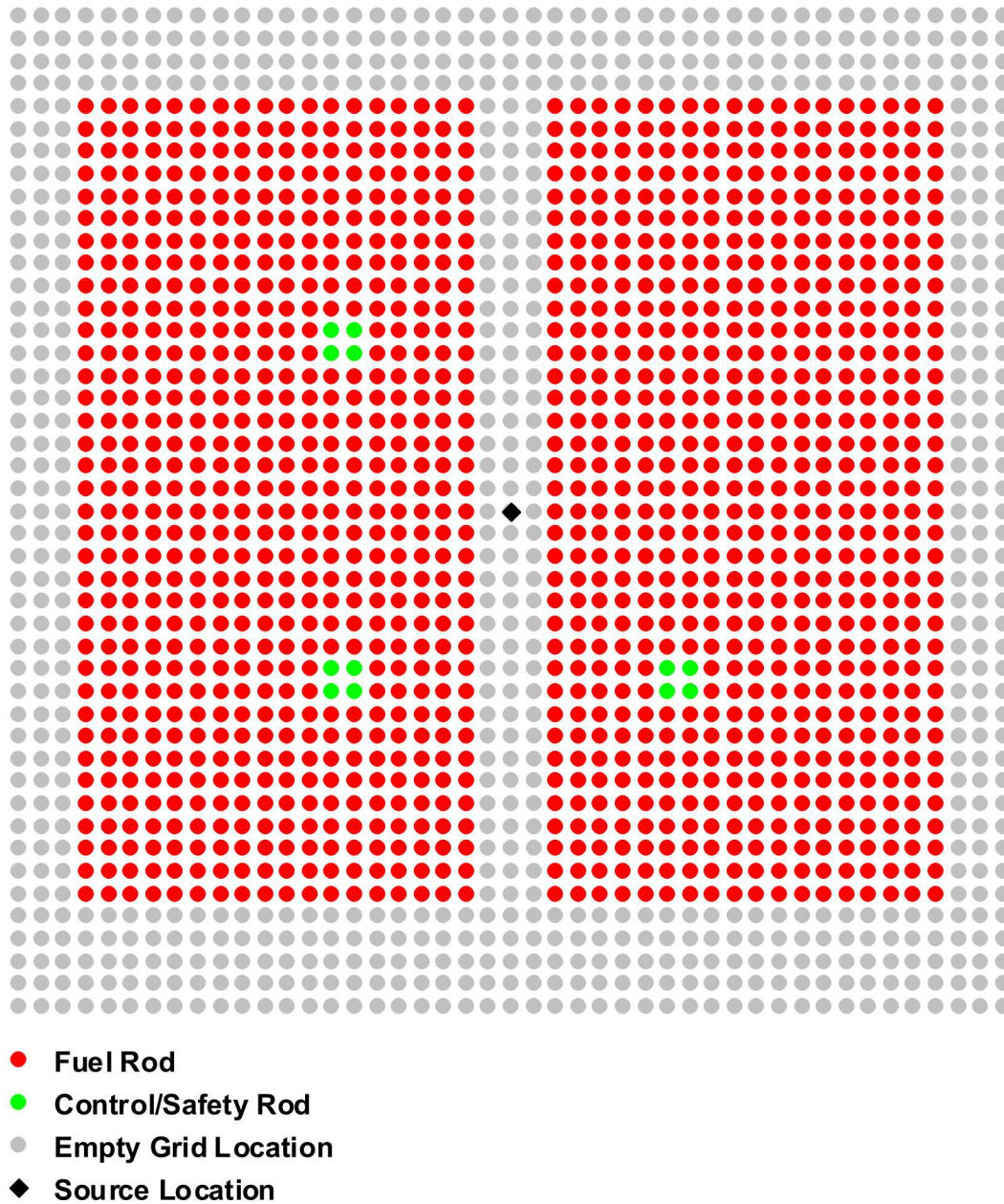


Figure 28. Fuel Rod Layout of the Array Measured for Case 14.

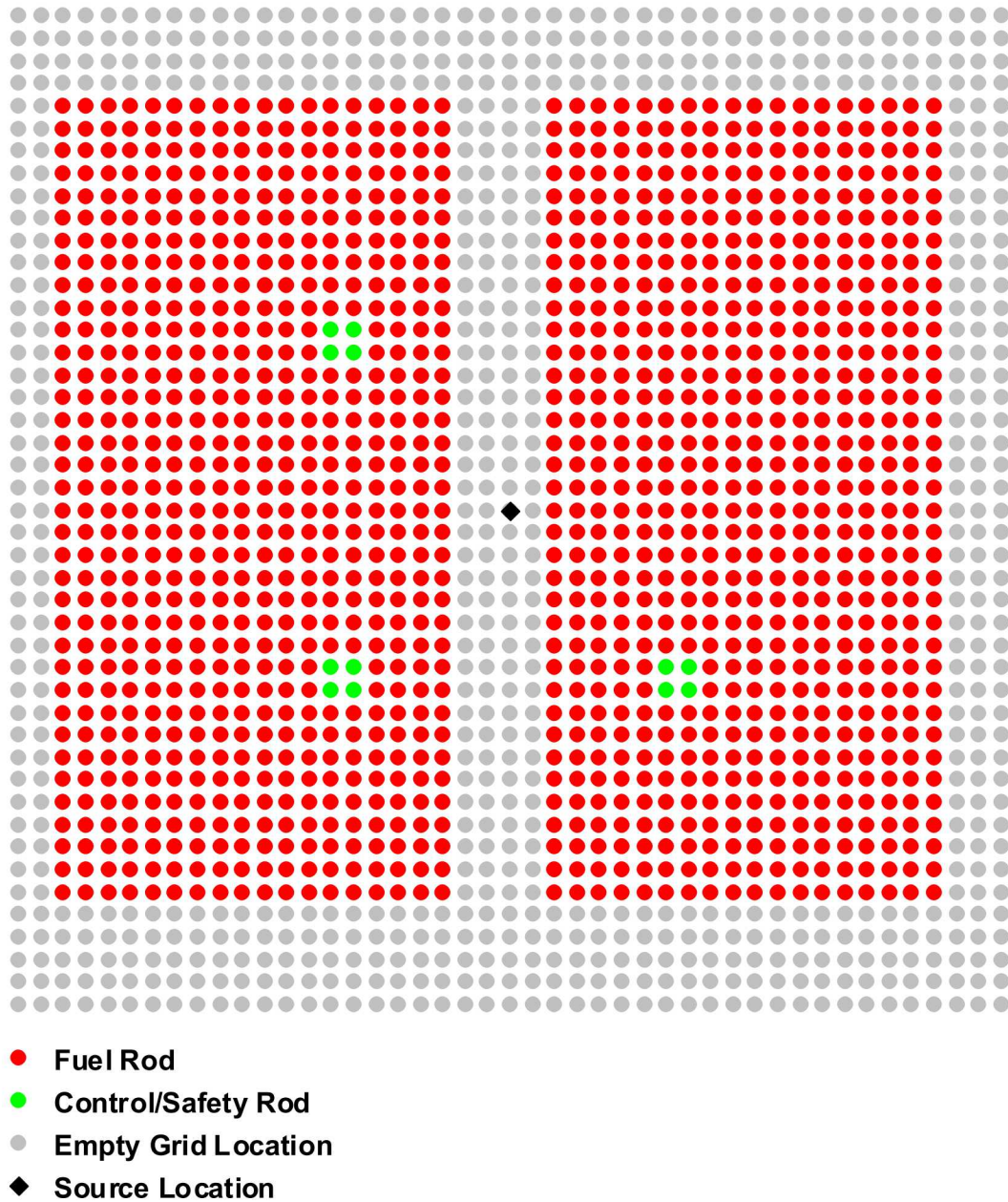


Figure 29. Fuel Rod Layout of the Array Measured for Case 15.

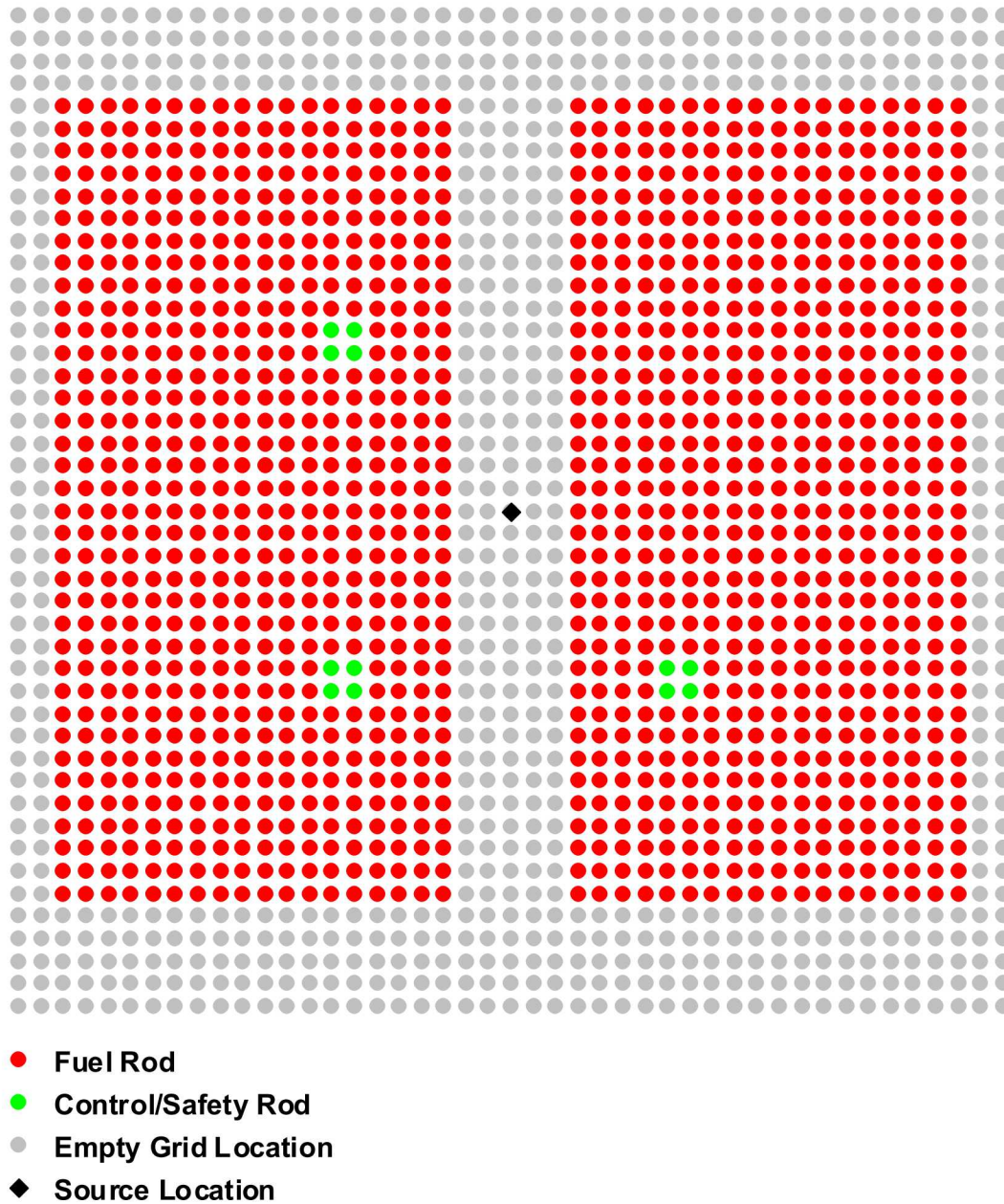


Figure 30. Fuel Rod Layout of the Array Measured for Case 16.

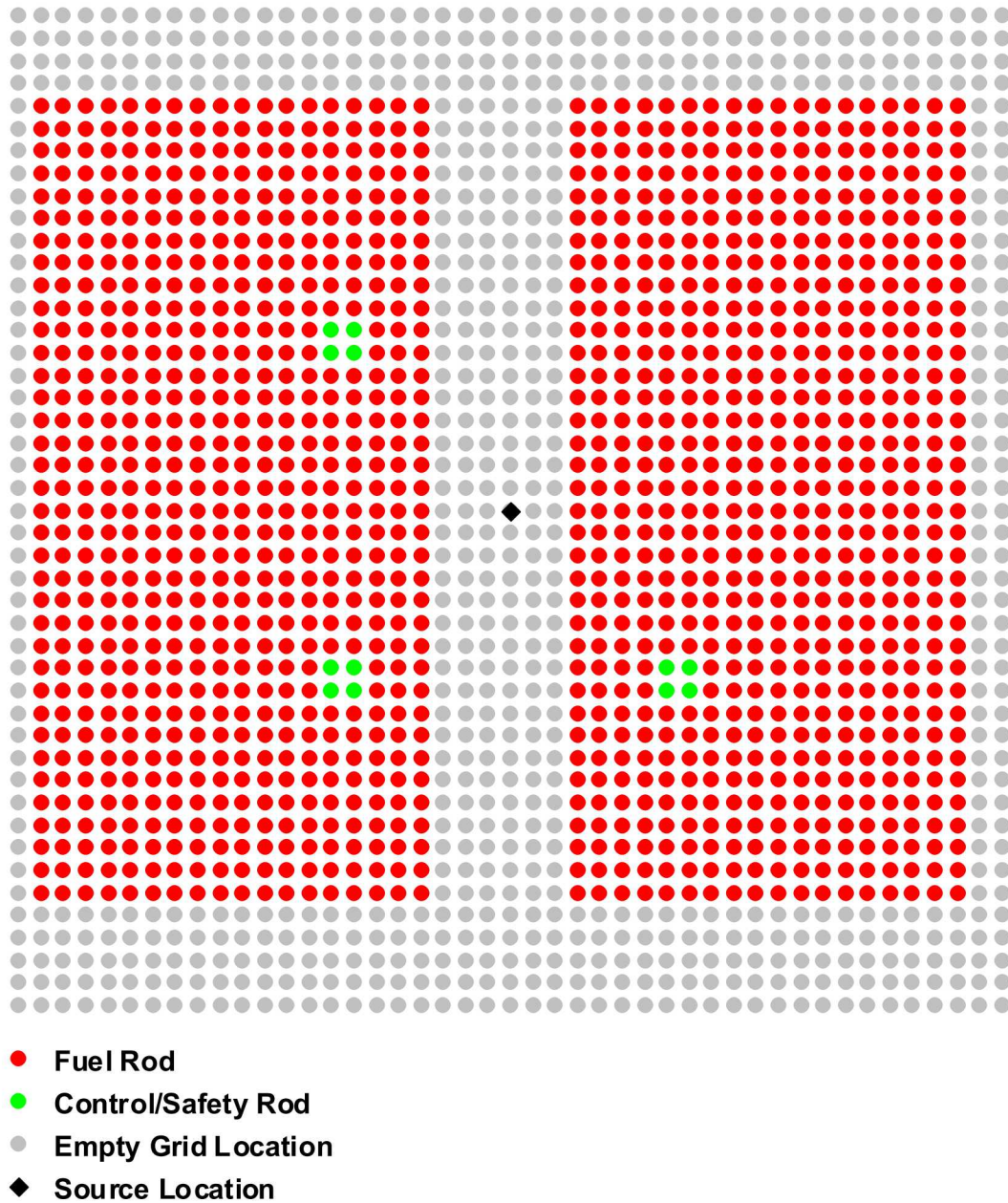


Figure 31. Fuel Rod Layout of the Array Measured for Case 17.

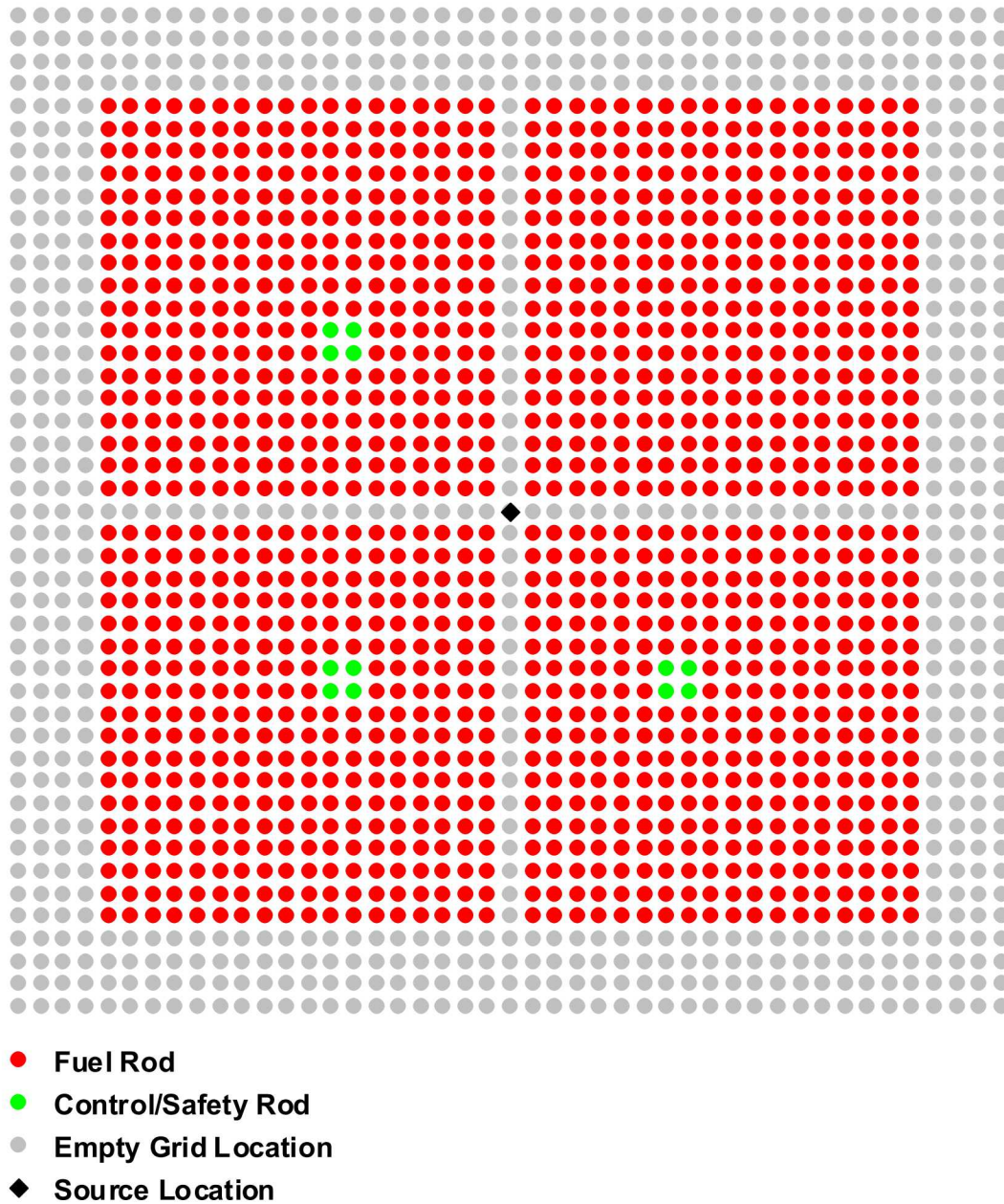


Figure 32. Fuel Rod Layout of the Array Measured for Case 18.

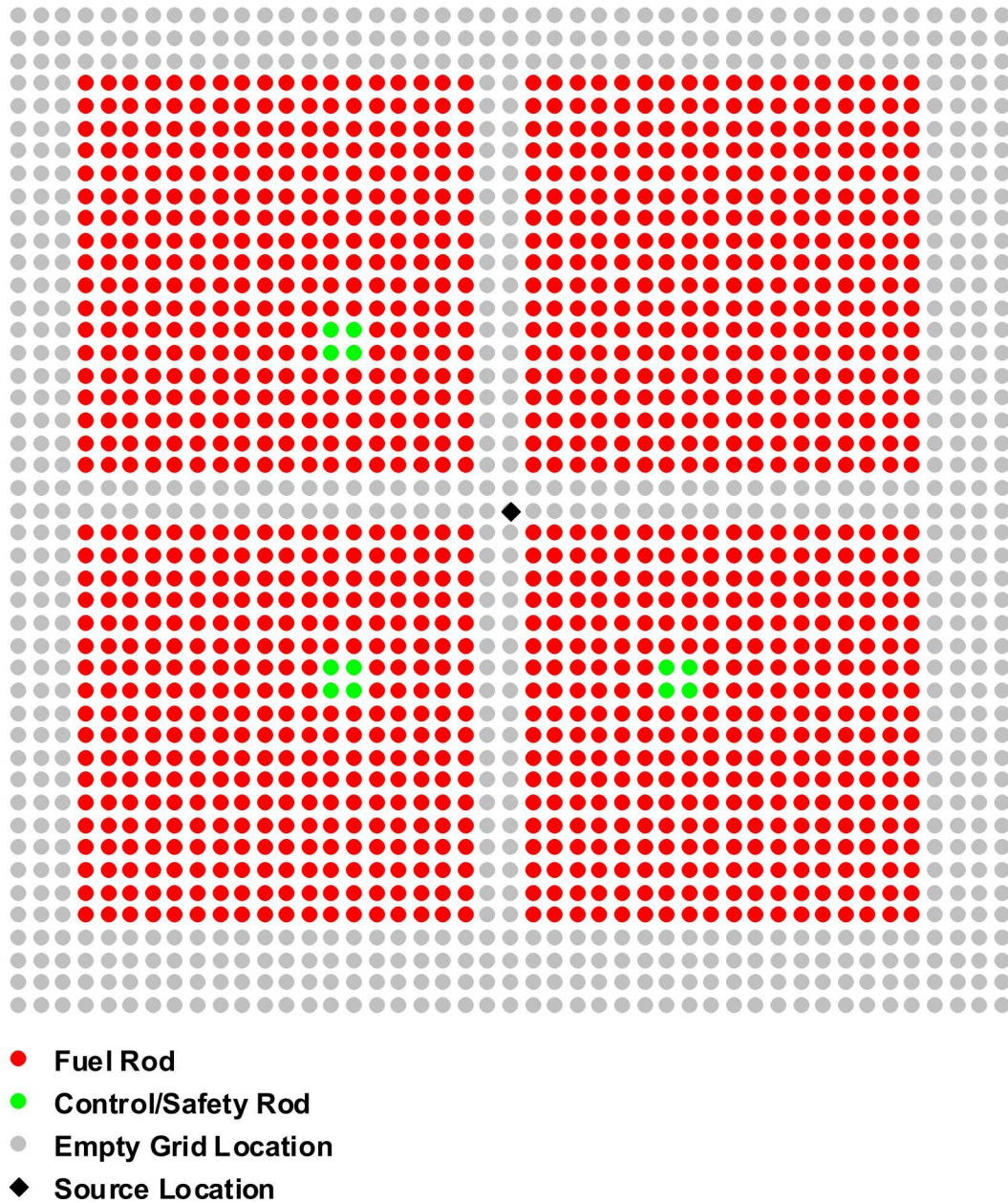


Figure 33. Fuel Rod Layout of the Array Measured for Case 19.

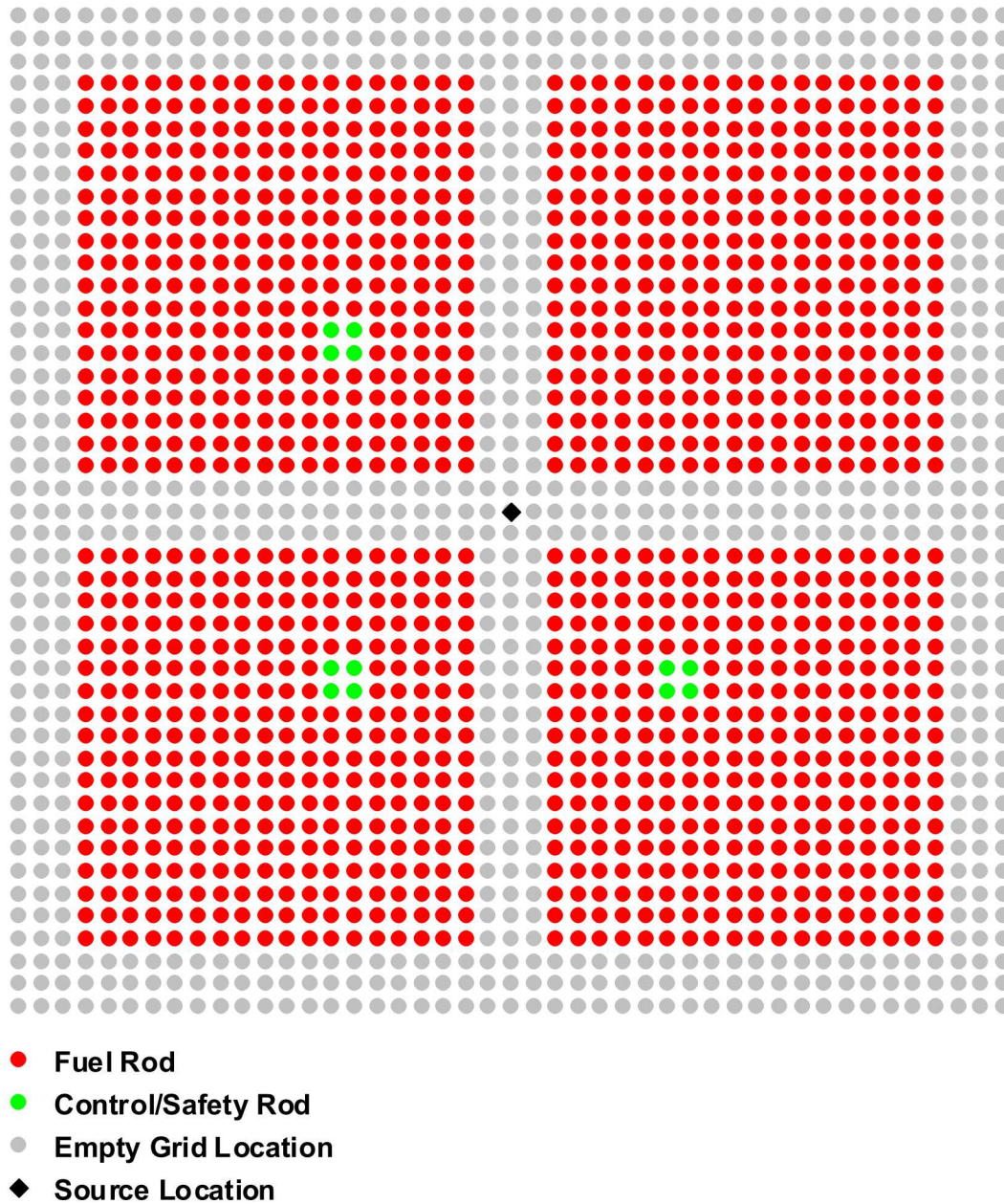


Figure 34. Fuel Rod Layout of the Array Measured for Case 20.



Figure 35. Fuel Rod Layout of the Array Measured for Case 21.

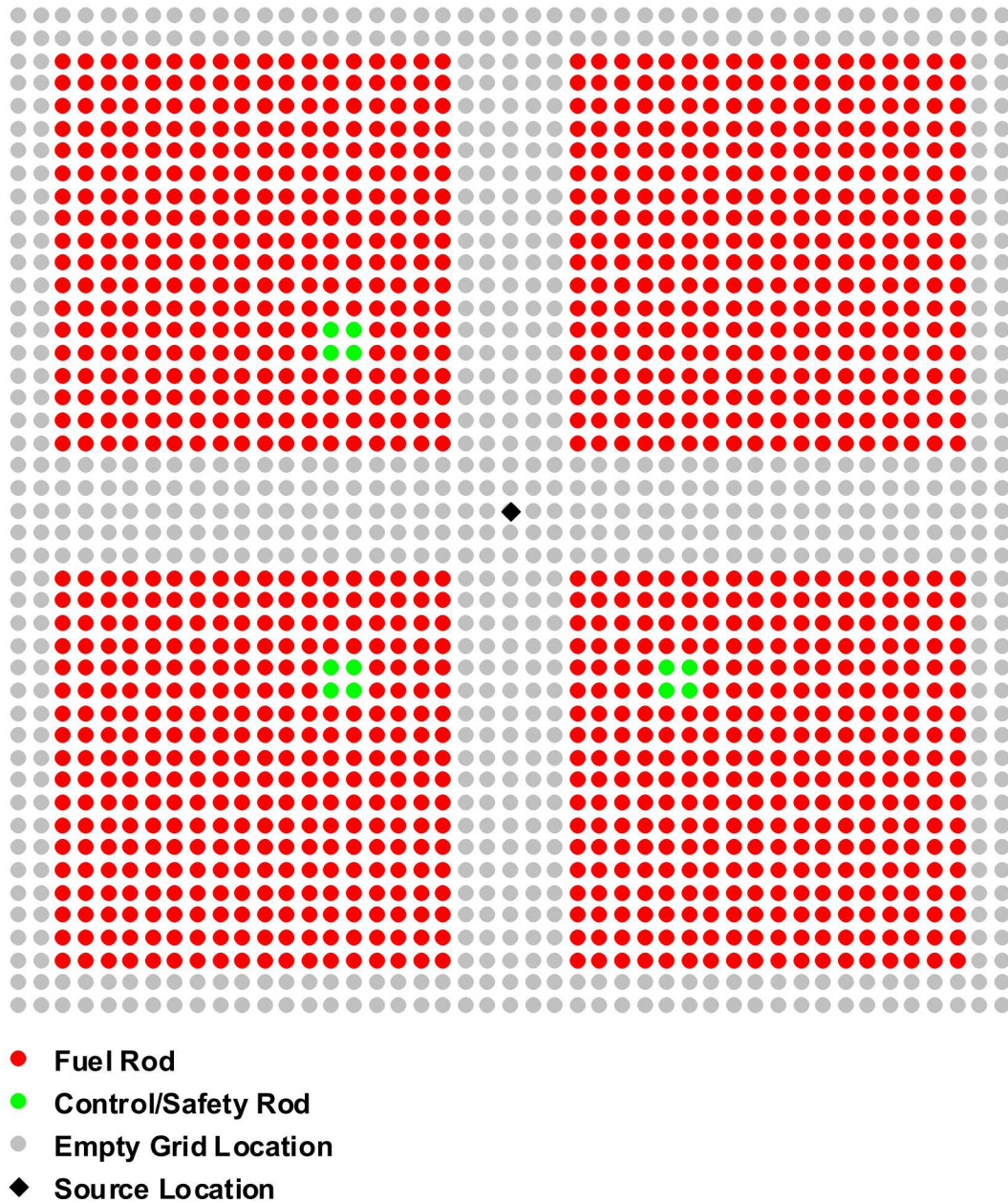


Figure 36. Fuel Rod Layout of the Array Measured for Case 22.

1.3 **Description of Material Data**

1.3.1 UO₂ Fuel – The fuel pellets used in the fuel rods were drawn from the fuel stock that was removed from fuel elements obtained from The Pennsylvania State University. The uranium isotopic data were measured for ten randomly-selected fuel pellets from the pool of fuel pellets used in the fuel rod fabrication using a high-resolution multi-collector inductively coupled plasma mass spectrometer (ICP-MS). The measured uranium isotopic data are given in Table 10. The uncertainties shown with the mass fractions are the standard deviations for the ten measurements. The systematic uncertainties were estimated by the laboratory that made the isotopic measurements.

Table 10. Isotopic Composition of Uranium in 6.90 % Enriched UO₂ Fuel Pellets.

Uranium Isotope	Wt. % ^(a)	Systematic Uncertainty (Wt. %) ^(b)
²³⁴ U	0.02814 ± 0.00008	0.00013
²³⁵ U	6.9034 ± 0.0046	0.0069
²³⁶ U	0.06336 ± 0.00012	0.00063
²³⁸ U	93.0051 ± 0.0046	-
Total	100.000	-

(a) The uncertainties given are the standard deviations for ten measurements.

(b) The systematic uncertainties are given at the one-standard-deviation level.

The oxygen to uranium ratio was not measured.

Metallic impurities were also obtained during the ICP-MS measurements of the ten fuel pellets. The results of the impurity measurements are shown in Table 11.

Table 11. Results of the Fuel Impurity Measurements.

Element	Average ^(a) (g/g)	Standard Deviation ^(a) (g/g)	Maximum ^(b) (g/g)	Minimum ^(c) (g/g)	Reported Detection Limit ^(d) (g/g)	Measurements above Detection Limit
Ag	1.61E-07	2.19E-07	6.67E-07	2.24E-08	2.24E-08	9
B	4.17E-07	4.73E-07	1.56E-06	2.24E-08	2.24E-08	9
Cd	2.25E-07	3.98E-07	9.36E-07	2.21E-08	2.27E-08	5
Co	2.06E-07	5.67E-08	3.13E-07	1.27E-07	-	10
Cr	2.11E-05	1.06E-05	4.03E-05	1.31E-05	-	10
Cu	2.19E-06	1.59E-06	4.95E-06	2.26E-07	2.26E-07	9
Fe	9.31E-05	4.31E-05	1.79E-04	5.27E-05	-	10
Mn	2.52E-06	1.04E-06	4.51E-06	1.50E-06	-	10
Mo	1.93E-06	1.85E-06	5.19E-06	6.34E-07	-	10
Ni	3.32E-05	1.13E-05	5.73E-05	2.31E-05	-	10
V	1.22E-07	2.33E-08	1.56E-07	9.71E-08	-	10
W	1.07E-07	1.14E-08	1.23E-07	8.53E-08	-	10
Sm	5.31E-08	-	5.31E-08	2.21E-08	2.27E-08	1
Dy	-	-	-	-	2.27E-08	0
Eu	-	-	-	-	2.27E-08	0
Gd	-	-	-	-	2.27E-08	0

- (a) The impurities were reported as mass of impurity per unit UO₂ fuel pellet mass. Averages and standard deviations are reported for the measurements that were above the detection limit for the element. Measurements at the detection limits were not included in the averages or the calculation of the standard deviations. Because only one measurement was above the detection limit for Sm, no value is reported for the standard deviation.
- (b) Reported maximum measured value. No value is included when all measurements were at the detection limit.
- (c) Reported minimum measured value when all ten measurements were above the detection limit. Minimum of the reported detection limits when one or more measurements were below the detection limit. No value is included when all measurements were at the detection limit.
- (d) The detection limit varied slightly from sample to sample. The maximum detection limit is recorded. Where all measurements were above the detection limit, no value is entered.

1.3.2 Fuel Rod Cladding – The fabrication drawings for the fuel rods specify the material for the clad tubing and end plugs as aluminum alloy 3003. The composition of the material used was not measured. The specification for the composition of aluminum alloy 3003 is given in Table 12. The density of the cladding material was not measured.

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Table 12. Chemical Composition Limits of Aluminum Alloy 3003.

Element	Weight % ^(a)
Si	0.6 max
Fe	0.7 max
Cu	0.05 – 0.20
Mn	1.0 – 1.5
Zn	0.10 max
Other Elements Each	0.05 max
Other Elements Total	0.15 max
Al	Remainder

(a) From ASTM B210-04

1.3.3 Aluminum Grid Plates – The upper and lower grid plates were fabricated from 1.00 in (2.54 cm) thick plates of aluminum alloy 6061-T651. The measured composition of the grid plates is compared with the 6061 aluminum specification in Table 13. The density of the grid plate material was not measured.

Table 13. Chemical Composition Limits of Aluminum Alloy 6061 Compared to the Measured Composition of the Grid Plates.

Element	Weight %	
	6061 spec. ^(a)	Measured
Si	0.40 – 0.8	0.72
Fe	0.7 max	0.62
Cu	0.15 – 0.40	0.31
Mn	0.15 max	0.09
Mg	0.8 – 1.2	1.04
Cr	0.04 – 0.35	0.20
Zn	0.25 max	0.12
Ti	0.15 max	0.02
V	–	0.01
Zr	–	0.00
Other Elements Each	0.05 max	–
Other Elements Total	0.15 max	0.06
Al	Remainder	Remainder

(a) From ASTM B209-10

1.3.4 Aluminum Guide Plate – The composition of the aluminum tooling plate used in the guide plate was also measured. That composition is given Table 14. The density of the guide plate material was not measured.

Table 14. Chemical Composition of the Aluminum Tooling Plate used in the Guide Plate.

Element	Weight %
Si	0.50
Fe	0.60
Cu	1.2
Mn	0.75
Mg	1.6
Cr	0.06
Zn	3.00
Other Elements Total	0.06
Al	Remainder

1.3.5 Water – The water moderator in the assembly was taken from the de-ionized water supply in the facility. Samples of the moderator were taken during the experiment and archived. No chemical analysis was done on the water samples.

The facility water is taken from the Albuquerque municipal water supply. The deionizer is fed from that source. The Albuquerque municipal water system is divided into nineteen distribution regions. The water quality is monitored in each distribution region. Table 15 lists the impurities detected in the water for the year 2014. Both the city-wide average and the maximum level across the system are listed in the table. Table 16 lists the elements for which testing was done but that were not detected in the system along with the detection limit for those elements.

Table 15. Impurities Measured in the Albuquerque Municipal Water Supply in the Year 2014.

Element	Units ^(a)	City-Wide Average ^(b)	Maximum Detected in the Water System ^(b)
As	PPB	3	8
Ba	PPM	ND ^(c)	0.2
Cr	PPB	ND ^(c)	8
U	PPB	3	6
Fe	PPM	0.022	0.941
Mn	PPM	0.004	0.123
Ca	PPM	48	68
Cl	PPM	31	47
Mg	PPM	5.8	7.3
K	PPM	3.9	8
Na	PPM	32	70

(a) Parts Per Million (PPM) or Parts Per Billion (PPB) by mass.

(b) Data obtained from http://www.abcwua.org/Water_Quality_by_Distribution_Zone.aspx on June 5, 2015.

(c) ND: Not Detected

Table 16. Impurities Tested but not Detected in the Albuquerque Municipal Water Supply in the Year 2014.

Element	Units ^(a)	Detection Limit ^(b)
Sb	PPB	1
Be	PPB	1
Cd	PPB	1
Hg	PPB	0.2
Se	PPB	5
Tl	PPB	1

(a) Parts Per Billion (PPB) by mass.

(b) Data obtained from

http://www.abcwua.org/Substances_Not_Found.aspx on June 5, 2015.

1.3.6 Stainless Steel – The source capsule was fabricated from 316L stainless steel. The specific composition of the material used in the source was not measured. The specification for the composition 316L stainless steel is listed in Table 17. The density of the stainless steel was not measured.

Table 17. Composition of 316L Stainless Steel.

Element	Weight % ^(a)
C	0.030 max
Mn	2.00 max
P	0.045 max
S	0.030 max
Si	1.00 max
Cr	16.0 – 18.0
Ni	10.0 – 14.0
Mo	2.00 – 3.00
Fe	Remainder

(a) From ASTM A276-10

The composition of the corrosion-resistant steel springs in the fuel rods is listed in the manufacturer's catalog as "stainless steel." No further composition data were available on the springs.

1.3.7 Polyethylene – The fuel rods included polyethylene in the part of the rod that was in the reflector. The annuli surrounding the radiation detector dry wells were also polyethylene. Polyethylene has the basic molecular formula CH₂.

1.3.8 Boron Carbide – The boron carbide powder used to fill the absorber sections of the control and safety elements was mixed from two lots of powder mixed equally before loading into the absorber sections. The composition data for the two lots of boron carbide are given in Table 18.

Table 18. Composition and Particle Size Data for the Boron Carbide.

Quantity		Lot 1 ^(b)	Lot 2 ^(b)
Boron Mass Fraction (%)		77.0	77.0
Carbon Mass Fraction (%)		21.7	21.6
B ₂ O ₃ Mass Fraction (%)		0.1	0.1
Silicon Mass Fraction (%)		<0.010	<0.010
Iron Mass Fraction (%)		0.10	0.10
Nitrogen Mass Fraction (%)		0.04	0.07
¹⁰ B Isotopic Abundance (atom %)		20.02	20.01
Particle Size Distribution (micron) ^(a)	3 %	11.23	158.2
	50 %	7.251	80.13
	94 %	3.140	40.47

(a) The particle size above which the specified fraction of the material falls.

(b) The mass fractions do not sum to 100 %. The remainder is unknown and is treated as void.

1.4 Temperature Data

The water temperature in the experiment was measured at three different heights in the reflector of the assembly with thermocouples. The average measured temperature for each case is shown in Table 8.

1.5 Supplemental Experimental Measurements

Additional experimental measurements were not performed.

2.0 EVALUATION OF EXPERIMENTAL DATA

This section provides interpretation of some of the experiment material and geometrical data and provides an analysis of the uncertainties in the experimental configurations. The uncertainties are small for all experiment configurations.

2.1 Material Data

2.1.1 Fuel Rod UO_2 Mass – The UO_2 fuel pellet mass in each fuel rod (2199 total) and control/safety element fueled section (23 total) was measured. Records were kept of these data as well as the location and identity of every rod in all configurations. The fuel mass in each configuration was available from these data. The average fuel mass in the entire population of 2222 fuel rods and control/safety element fueled sections was 108.7165 g with a standard deviation of 0.322 g. The average UO_2 mass for the fuel rods in each configuration is listed in Table 19.

Table 19. Average UO_2 Mass in Each Configuration.

Case	Number of Fuel Rods and Control/Safety Rod Sections	Average UO_2 Mass (g)	
		Value	Standard Deviation
1	2025	108.7241	0.314
2	1836	108.7148	0.315
3	1781	108.7373	0.311
4	1573	108.7544	0.295
5	1425	108.7713	0.300
6	1281	108.7772	0.310
7	1137	108.7835	0.317
8	1109	108.7831	0.320
9	1600	108.7506	0.307
10	1296	108.7641	0.305
11	1156	108.7756	0.308
12	1296	108.7641	0.305
13	1296	108.7641	0.305
14	1296	108.7641	0.305
15	1296	108.7641	0.305
16	1296	108.7641	0.305
17	1296	108.7641	0.305
18	1296	108.7641	0.305
19	1296	108.7641	0.305
20	1296	108.7641	0.305
21	1296	108.7641	0.305
22	1296	108.7641	0.305

2.1.2 Fuel Impurities – The fuel pellets were fresh UO_2 with measured enrichment and impurity content for ten randomly-chosen fuel pellets. Twelve impurity elements were measured above the detection limit in at least five of the measurements. The measured impurity content and standard deviation of the ten measurements is shown in Table 20. The standard deviations shown for three of the listed elements are larger

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than the average mass fraction for three impurities – Ag, B, and Cd. This is because each of these species had one measurement that was much higher than the others. Also shown in the table are the thermal absorption cross section for each impurity species and the fraction of the impurity thermal macroscopic absorption cross section contributed by each species. The uncertainty in the impurity macroscopic cross section is dominated by the contribution from boron which is in turn dominated by the fact that one of the measurements is an outlier compared to the rest of the measurements.

Table 20. Fuel Impurity Analysis.

Species	Mass Fraction ^(a)	Standard Deviation ^(b)	Thermal Absorption Cross Section ^(c) (barns)	Fractional Macroscopic Absorption Cross Section ^(d)	Fractional Contribution to the Macroscopic Absorption Cross Section Uncertainty ^(e)
Ag	1.61E-07	2.19E-07	63	0.0022	0.0037
B	4.17E-07	4.73E-07	760	0.6744	0.9789
Cd	2.25E-07	3.98E-07	2520	0.1160	0.1928
Co	2.06E-07	5.67E-08	37.2	0.0030	0.0011
Cr	2.11E-05	1.06E-05	3.1	0.0289	0.0190
Cu	2.19E-06	1.59E-06	3.8	0.0030	0.0029
Fe	9.31E-05	4.31E-05	2.56	0.0982	0.0594
Mn	2.52E-06	1.04E-06	13.3	0.0140	0.0076
Mo	1.93E-06	1.85E-06	2.5	0.0012	0.0014
Ni	3.32E-05	1.13E-05	4.5	0.0586	0.0261
V	1.22E-07	2.33E-08	5.0	0.0003	6.9E-05
W	1.07E-07	1.14E-08	18.2	0.0002	3.4E-05
Sum	1.55E-04 ^(f)	—	—	1.0000 ^(f)	1.0000 ^(g)

- (a) The average of the reported impurity mass fractions that were above the detection limit.
(b) The standard deviation of the reported impurity mass fractions that were above the detection limit.
(c) Thermal neutron (2200 m/s) absorption cross section from E. M. Baum, et al., Nuclides and Isotopes Sixteenth Edition, KAPL, Inc., 2002.
(d) The impurity macroscopic absorption cross section is the sum of the [product of the species atom density and the species absorption cross section] having a value of 0.00024 cm⁻¹.
(e) The uncertainty in the impurity macroscopic absorption cross section is the sum in quadrature of the [product of the uncertainty in the species atom density and the species absorption cross section] and has a value of 0.00021 cm⁻¹.
(f) Arithmetic sum.
(g) Sum in quadrature.

2.1.3 Fuel Rod Cladding – The clad tubes and end caps for the fuel rods were fabricated from 3003 aluminum. The elemental composition of the 3003 aluminum was not measured. For the work documented here, the composition of the tubes and end caps is assumed to be at the mid-range value where an elemental content is specified as a range and as half of the maximum value where one is given for an element. The composition specification for 3003 aluminum and the composition chosen here are shown in Table 21. The density of the 3003 aluminum was taken as 2.73 g/cm³.^a

^a From <http://matweb.com/search/DataSheet.aspx?MatGUID=fd4a40f87d3f4912925e5e6eab1fbc40> accessed on May 29, 2012. From <http://matweb.com> search for key word “3003” and choose the “Aluminum 3003-O” option.

Table 21. Elemental Composition Specification for Aluminum Alloy 3003 and the Composition Used for the Fuel Rod Cladding in the Analyses.

Element	Specification Composition (Weight %) ^(a)	Assumed Composition (Weight %)
Si	0.6 max	0.3
Fe	0.7 max	0.35
Cu	0.05 – 0.20	0.125
Mn	1.0 – 1.5	1.25
Zn	0.10 max	0.05
Other Elements Each	0.05 max	0
Other Elements Total	0.15 max	0
Al	Remainder	97.925

(a) From ASTM B210-04

2.1.4 Source Capsule Composition – The material in the source capsule was specified as 316L stainless steel. The elemental composition was not measured. The composition for the 316L stainless steel is assumed to be at the mid-range value where an elemental content is specified as a range and as half of the maximum value where one is given for an element. The composition specification for 316L stainless steel and the derived composition used here are shown in Table 22. The density of the 316L stainless steel was taken as 8.0 g/cm³.^a

^a From <http://matweb.com/search/DataSheet.aspx?MatGUID=a2d0107bf958442e9f8db6dc9933fe31> accessed on May 29, 2012. From <http://matweb.com> search for key word “316L” and choose the “AISI Type 316L Stainless Steel, annealed bar” option.

Table 22. Elemental Composition Specification for 316L Stainless Steel and the Composition Used for the Source Capsule in the Analyses.

Element	Specification Composition (Weight %) ^(a)	Assumed Composition (Weight %)
C	0.030 max	0.015
Mn	2.00 max	1.00
P	0.045 max	0.0225
S	0.030 max	0.015
Si	1.00 max	0.50
Cr	16.0 – 18.0	17.0
Ni	10.0 – 14.0	12.0
Mo	2.00 – 3.00	2.50
Fe	Remainder	66.9475

(a) From ASTM A276-10

2.1.5 Fuel Rod Spring Composition – The composition of the springs in the fuel rods and control/safety rod fueled sections was specified in the manufacturer’s catalog as stainless steel. The composition of 304 stainless steel, treated as described above, will be used. Table 23 lists the composition specification for 304 stainless steel spring wire with the derived composition. The springs, as manufactured, had a specified inner diameter of 0.138 in (0.35052 cm) and outer diameter of 0.180 in (0.4572 cm). Where they were included, the springs were modeled as annuli of inner diameter 0.35052 cm and outer diameter 0.4572 cm. The average spring mass was measured as 0.1923 g ± 0.0095 g. As used in the fuel rods, the springs are compressed to a length of 1.75076 cm. The density of the springs in each model was obtained from the dimensions of the annulus and the average spring mass.

Table 23. Elemental Composition Specification for 304 Stainless Steel Spring Wire and the Composition Used for the Fuel Rod Springs in the Analyses.

Element	Specification Composition (Weight %) ^(a)	Assumed Composition (Weight %)
C	0.08 max	0.04
Mn	2.00 max	1.00
P	0.045 max	0.0225
S	0.030 max	0.015
Si	1.00 max	0.50
Cr	18.0 – 20.0	19.0
Ni	8.0 – 10.5	9.25
N	0.10 max	0.05
Fe	Remainder	70.1225

(a) From ASTM A313-10. Note that the composition differs slightly from the composition for bars and shapes given in ASTM A276-10.

2.1.6 Boron Carbide Composition – The boron carbide used in the absorber sections of the control and safety elements was mixed from two batches of boron carbide powder with slightly different compositions. The two batches were mixed equally so the appropriate composition to use is the average of the values for the two batches. The specifications for the two batches included mass fractions for boron and for B₂O₃. It is assumed that the boron included in the B₂O₃ is included in the given boron mass fraction leaving the oxygen at a mass fraction of 0.069 % rounded to two significant figures. Because a maximum value is specified for silicon, half that value is assumed to be present. The elemental mass fractions in the boron carbide powder are shown in Table 24. The ¹⁰B isotopic atom fraction in the boron is 20.015 %.

Table 24. Composition Data for the Boron Carbide Powder.

Quantity	Value
Boron Mass Fraction (%)	77.0
Carbon Mass Fraction (%)	21.65
Oxygen Mass Fraction (%)	0.069
Silicon Mass Fraction (%)	0.005
Iron Mass Fraction (%)	0.10
Nitrogen Mass Fraction (%)	0.055
Sum (%) ^(a)	98.879

(a) The mass fractions do not sum to 100 %. The remainder (1.121 %) is unknown and is treated as void.

2.2 Geometric Data

2.2.1 Fuel Rod Pellet Stack Height – The fuel pellet stack height in each fuel rod and control/safety element fueled section was also measured during fabrication. The average fuel pellet stack length for the entire population of 2222 fuel rods and control/safety element fueled sections was 48.7789 cm with a standard

deviation of 0.125 cm. The average fuel pellet stack height for the specific fuel rods included in the benchmark experiment configurations is listed in Table 25.

Table 25. Average Fuel Pellet Stack Height in Each Configuration.

Case	Number of Fuel Rods and Control/Safety Rod Sections	Average Fuel Pellet Stack Height (cm)	
		Value	Standard Deviation
1	2025	48.7776	0.120
2	1836	48.7708	0.119
3	1781	48.7765	0.119
4	1573	48.7761	0.114
5	1425	48.7745	0.116
6	1281	48.7770	0.118
7	1137	48.7790	0.120
8	1109	48.7790	0.121
9	1600	48.7752	0.116
10	1296	48.7755	0.116
11	1156	48.7777	0.118
12	1296	48.7755	0.116
13	1296	48.7755	0.116
14	1296	48.7755	0.116
15	1296	48.7755	0.116
16	1296	48.7755	0.116
17	1296	48.7755	0.116
18	1296	48.7755	0.116
19	1296	48.7755	0.116
20	1296	48.7755	0.116
21	1296	48.7755	0.116
22	1296	48.7755	0.116

2.2.2 Fuel Rod Diameter – The outer diameter of each fuel rod was measured. The average for the population of 2199 fuel rods was 0.634948 cm with a standard deviation of 0.000218 cm. The average outer diameter of the fuel rods for the specific fuel rods included in the benchmark experiment configurations is listed in Table 26.

Table 26. Average Fuel Rod Outer Diameter in Each Configuration.

Case	Number of Fuel Rods	Average Fuel Rod Outer Diameter (cm)	
		Value	Standard Deviation
1	2013	0.634954	0.000217
2	1824	0.634955	0.000217
3	1769	0.634963	0.000217
4	1561	0.634974	0.000215
5	1413	0.634983	0.000215
6	1269	0.634989	0.000216
7	1125	0.634996	0.000212
8	1097	0.634994	0.000210
9	1588	0.634972	0.000217
10	1284	0.634979	0.000216
11	1144	0.634985	0.000212
12	1284	0.634979	0.000216
13	1284	0.634979	0.000216
14	1284	0.634979	0.000216
15	1284	0.634979	0.000216
16	1284	0.634979	0.000216
17	1284	0.634979	0.000216
18	1284	0.634979	0.000216
19	1284	0.634979	0.000216
20	1284	0.634979	0.000216
21	1284	0.634979	0.000216
22	1284	0.634979	0.000216

2.2.3 Fuel Rod Cladding Inner Diameter – The mass of the assembled clad tube and lower end cap was measured for 100 samples during the fabrication of the fuel rods. The average mass was 13.824 g with a standard deviation of 0.027 g. The volume of the lower end cap was calculated from the dimensions given in the design drawings as 0.354 cm³. Using the tolerances given on the drawing, the uncertainty in the volume is 0.010 cm³. Using a density for 3003 aluminum of 2.73 g/cm³, the calculated mass of the lower end cap is 0.967 g with a one-standard-deviation uncertainty based on drawing tolerances of 0.027 g. The mass of the 29.75 in (75.565 cm) long clad tube is then 12.857 g with an uncertainty of 0.027 g. The average measured outside diameter of the fuel rods is 0.249980 in (0.634948 cm as rounded from the original data) with standard deviation for 2194 measurements of 0.000086 in (0.000218 cm) and an overall uncertainty of 0.000023 in (0.000058 cm) including systematic uncertainties. From these data and using a density of 2.73 g/cm³, an inner diameter of 0.569038 cm (0.224031 in) is obtained with an uncertainty of 0.000164 cm (0.000065 in).

2.2.4 Polyethylene Density – The average mass of the polyethylene spacers in the 2199 fuel rods is 4.454 g. The polyethylene spacer is designed as a cylinder 0.207 in (0.52578 cm) diameter and 8.38 in (21.2852 cm) long. This gives an average density of the polyethylene in the spacer of 0.96377 g/cm³.

The average mass of the polyethylene annuli on the radiation detector dry wells is 2017.28 g. The annuli are 11.82 in (30.0228 cm) tall and have inner diameters of 2.603 in (6.61162 cm) and outer diameters of 4.535 in (11.5189 cm). The average mass and dimensions of the annuli give a polyethylene density of 0.9612 g/cm³. Because this density is nearly the same as the density obtained for the polyethylene spacers in the fuel rods,

the density derived for the spacers in the fuel rods (0.96377 g/cm^3) will be used for both types of polyethylene.

2.2.5 Boron Carbide Powder Density – The average mass of boron carbide powder in the 23 absorber sections that were fabricated is 26.37 g. With an inner diameter of the cladding of 0.569038 cm (0.224031 in) and a height for the absorber of 28.238 in (71.72452 cm), the average density of the boron carbide powder is 1.4457 g/cm^3 as loaded.

2.3 Uncertainty Analyses

A number of uncertainty analyses were done. The direct perturbation analyses in sections 2.3.1 through 2.3.7 were done with KENO V.a using the 252-group ENDF/B-VII.1 cross section set from SCALE 6.2. The sensitivity analysis done in Sections 2.3.8 through 2.3.15 were done using TSUNAMI-3D with 252-group ENDF/B-VII.1 cross sections from SCALE 6.2. The temperature sensitivity analysis in Section 2.3.16 was done with MCNP®6.1.1 using continuous-energy cross sections from ENDF/B-VII.1.

Where uncertainties are given below, the method of handling the uncertainties by type as defined in the *ICSBEP Guide to the Expression of Uncertainties* is followed. Where the uncertainty is given at the one-standard-deviation level, the uncertainty is used as-is. Where an uncertainty is given as a tolerance or a bounding value, it is assumed to specify an outer limit with a constant probability distribution between the limits. The value of the tolerance is divided by the square root of 3 to get the one-standard-deviation uncertainty in the nominal value. This treatment is used in the determination of the uncertainty of the fuel rod pitch and in the uncertainty of the composition of the fuel rod cladding.

In each of the following cases using direct perturbations, the sensitivity of the assembly to a given uncertainty was determined by analyzing arrays in which the parameter varied over a range. A least-squares fit of the k_{eff} data to a line was done. The stochastic uncertainties from the Monte Carlo calculations were propagated through the least-squares equations used in the fit. The sensitivity of the array to the parameter was the slope of the line. The uncertainty in the sensitivity was the uncertainty in the slope. The relative uncertainty in the sensitivity gives a measure of the statistical significance of the fit.

In the uncertainty analysis that follows, a series of linked spreadsheets was used to collect the uncertainty data from each component. The outside data used in the analysis were introduced at the level of precision shown in the tables. Full precision of the intermediate results was maintained in the linked spreadsheets. Intermediate results given in Tables 27 through 47 are rounded to the precision shown and are presented for illustrative purposes.

2.3.1 Fuel Rod Pitch – The uncertainty in the fuel rod pitch contributes to the uncertainty in the amount of water moderator in the core. This uncertainty is related to the uncertainty in the placement of the holes in the grid plates during fabrication, to the width of the nominal gap between the outside of the fuel rods and the inside of the grid plate holes, to the uncertainty in the diameter of the holes in the grid plates, to the uncertainty in the outside diameter of the fuel rods, and to the number of rows of fuel rods in the core. The fabrication tolerance in the placement of each hole is that it be within ± 0.005 in (0.0127 cm) of its intended location relative to the center of the grid plate. The gap between the outside of the fuel rods for the core with the smallest average fuel rod outside diameter (Case 1) and the inside of the grid plate holes is 0.00626 in (0.0159 cm). The uncertainty in the diameter of the grid plate holes is one-sided ($+0.005/-0.000$ in). Assuming that the nominal value of hole diameter falls at the center of this range, the tolerance is then ± 0.0025 in (0.00635 cm). The outer diameters of the fuel rods were measured. The uncertainty in the average value for the configuration with the fewest rods (Case 8 with 1109 rods) is 0.0000026 in (0.000085

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divided by the square root of 1109) added in quadrature to the systematic uncertainty in the diameter measurements of 0.000022 in resulting in a one-standard-deviation uncertainty of 0.000022 in (0.000056 cm). Multiplying this value by the square root of 3 to get 0.000038 in (0.000097 cm) maintains the level of significance associated with the tolerances. Summing these four values in quadrature yields

$$\sqrt{0.005^2 + 0.00626^2 + 0.0025^2 + 0.000038^2} = 0.008392 \text{ in (0.02132 cm)}$$

The tolerance in the fuel rod pitch is twice this value divided by [the diameter of the core divided by the fuel rod pitch]. Note that this last factor reduces to one less than the number of fuel rods on a chord across the core.

For Cases 1 through 4, there were 45 fuel rods on a chord across the core. In this case, the diameter of the core divided by the fuel rod pitch is 44. By the above method, the tolerance in the pitch is

$$(2 \times 0.008393 \text{ in})/44 = 0.0003815 \text{ in (0.0009690 cm)}.$$

Dividing the above tolerance by the square root of three gives the one-standard-deviation value for the uncertainty in the fuel rod pitch, 0.0002203 in (0.0005595 cm). The pitch uncertainty for the remaining cases is obtained similarly with the appropriate number of fuel rods on a chord.

Arrays with fuel rod pitch up to 0.01 cm on either side of the nominal value in 0.005 cm increments were analyzed to obtain the effect of pitch on k_{eff} . The results were used in a least-squares linear fit to determine the sensitivity of the experiment to the fuel rod pitch. The sensitivity was combined with the pitch uncertainty to obtain the uncertainty in the benchmark experiment k_{eff} . The results of these calculations are shown in Table 27.

Table 27. Results of the Analysis of the Pitch Uncertainty.

Case	Fuel Rods on Chord	Uncertainty Value (cm)	Sensitivity (cm ⁻¹)		Δk_{eff}	
			Value	Uncertainty	Value	Uncertainty
1	45	0.0005594	0.9533	0.0040	0.000533	0.000002
2	45	0.0005594	0.8047	0.0039	0.000450	0.000002
3	45	0.0005594	0.9850	0.0038	0.000551	0.000002
4	45	0.0005594	1.0085	0.0039	0.000564	0.000002
5	43	0.0005860	1.0319	0.0038	0.000605	0.000002
6	41	0.0006153	1.0457	0.0040	0.000643	0.000002
7	39	0.0006477	1.0644	0.0039	0.000689	0.000003
8	37	0.0006837	1.0710	0.0038	0.000732	0.000003
9	40	0.0006311	1.0003	0.0040	0.000631	0.000003
10	36	0.0007033	1.0196	0.0038	0.000717	0.000003
11	34	0.0007459	1.0461	0.0038	0.000780	0.000003
12	36	0.0007033	0.9526	0.0039	0.000670	0.000003
13	36	0.0007033	0.8811	0.0040	0.000620	0.000003
14	36	0.0007033	0.8055	0.0038	0.000567	0.000003
15	36	0.0007033	0.7312	0.0036	0.000514	0.000003
16	36	0.0007033	0.6885	0.0038	0.000484	0.000003
17	36	0.0007033	0.6541	0.0037	0.000460	0.000003
18	36	0.0007033	0.8944	0.0041	0.000629	0.000003
19	36	0.0007033	0.7509	0.0040	0.000528	0.000003
20	36	0.0007033	0.5959	0.0038	0.000419	0.000003
21	36	0.0007033	0.4854	0.0039	0.000341	0.000003
22	36	0.0007033	0.4007	0.0038	0.000282	0.000003

2.3.2 Clad Outer Diameter – The outer diameter of the fuel rod clad tubes was measured for the 2194 rods available for the experiments. The population average for the measurements was 0.249980 in (0.634948 cm as rounded from the original data) with a standard deviation of 0.000086 in (0.000218 cm). The uncertainty in the mean value is 0.0000026 in (0.0000066 cm), the standard deviation divided by the square root of 1109, the lowest number of fuel rods in any of the benchmark experiment configurations. Because the outside diameter was known for each fuel rod and the identity of each fuel rod in every configuration was known, the distribution of the fuel rod diameters does not contribute to the uncertainty in the experiments. The systematic uncertainty in the measurements was 0.000022 in (0.000056 cm). The resolution of the instruments used was 0.000001 in (0.00000254 cm) and the repeatability was 0.000005 in (0.0000127 cm). The random uncertainty in the diameter measurements was 0.000030 in (0.0000762 cm) and will be treated as a systematic uncertainty. The sum in quadrature of the systematic uncertainties (0.000022 in, 0.000001 in, 0.000005 in, and 0.000030 in) is 0.0000375 in (0.0000954 cm). Arrays with fuel rod clad diameters up to 0.00508 cm on either side of the nominal value were analyzed to determine the sensitivity of the experiments to the clad tube diameter. The mass of the clad tube was kept constant during these variations.

The results of the analysis of the clad outer diameter uncertainty for a sample of the cases are shown in Table 28. The bounding value of the k_{eff} uncertainties given in the table is shown in the last line.

Table 28. Results of the Analysis of the Clad Outer Diameter Uncertainty.

Case	Uncertainty Value (cm)	Sensitivity (cm ⁻¹)		Δk_{eff}	
		Value	Uncertainty	Value	Uncertainty
1	0.0000954	-1.0596	0.0091	-0.000101	0.000001
2	0.0000954	-0.8943	0.0086	-0.000085	0.000001
7	0.0000954	-1.0227	0.0084	-0.000098	0.000001
10	0.0000954	-1.0328	0.0086	-0.000099	0.000001
19	0.0000954	-0.8277	0.0084	-0.000079	0.000001
22	0.0000954	-0.6061	0.008	-0.000058	0.000001
Bounding Value				-0.000101	

2.3.3 Clad Inner Diameter – The method of obtaining the inside diameter of the fuel clad tubes based on the tube outer diameter and the measured mass of the assembly of the clad tube and the lower end cap is described above. Using that method, the uncertainty in the inner diameter of the clad tube is 0.000164 cm. Arrays with fuel rod clad inside diameters up to 0.04 cm on either side of the nominal value were analyzed. The outside diameter of the fuel rod clad tubes was held constant for these calculations.

The results of the analysis of the clad inner diameter uncertainty for a sample of the cases are shown in Table 29. The bounding value of the k_{eff} uncertainties given in the table is shown in the last line.

Table 29. Results of the Analysis of the Clad Inner Diameter Uncertainty.

Case	Uncertainty Value (cm)	Sensitivity (cm ⁻¹)		Δk_{eff}	
		Value	Uncertainty	Value	Uncertainty
1	0.000164	-0.1213	0.0013	-0.000020	0.0000002
2	0.000164	-0.111	0.0013	-0.000018	0.0000002
7	0.000164	-0.0925	0.0013	-0.000015	0.0000002
10	0.000164	-0.0987	0.0013	-0.000016	0.0000002
19	0.000164	-0.0908	0.0013	-0.000015	0.0000002
22	0.000164	-0.0437	0.0012	-0.000007	0.0000002
Bounding Value				-0.000020	

2.3.4 Fuel Outer Diameter – The outer diameter of 123 randomly-selected fuel pellets was measured. The average diameter was 0.20694 in (0.52563 cm) with a standard deviation of 0.00019 in (0.00048 cm). The systematic uncertainties in the fuel pellet outer diameter measurements are 0.000001 in resolution, 0.000005 in repeatability, 0.000022 in absolute uncertainty, and 0.000030 in reproducibility. Considering the number of measurements and the systematic uncertainties in the measurements, the uncertainty in the average diameter is 0.000041 in (0.000105 cm). Arrays with fuel pellet diameters up to 0.004 in on either side of nominal were analyzed. The density of the fuel was modified in the analysis to keep the fuel mass in the fuel rods constant.

The results of the analysis of the fuel outer diameter uncertainty for a sample of the cases are shown in Table 30. The bounding value of the k_{eff} uncertainties given in the table is shown in the last line.

Table 30. Results of the Analysis of the Fuel Outer Diameter Uncertainty.

Case	Uncertainty Value (cm)	Sensitivity (cm ⁻¹)		Δk_{eff}	
		Value	Uncertainty	Value	Uncertainty
1	0.000105	-0.0374	0.0022	-0.0000039	0.0000002
2	0.000105	-0.0294	0.0022	-0.0000031	0.0000002
7	0.000105	-0.0373	0.0022	-0.0000039	0.0000002
10	0.000105	-0.0376	0.0022	-0.0000039	0.0000002
19	0.000105	-0.0201	0.0022	-0.0000021	0.0000002
22	0.000105	-0.0046	0.0021	-0.0000005	0.0000002
Bounding Value				-0.0000039	

2.3.5 Moderator/Reflector Height – The height of the water in the core tank is set by the remotely adjustable overflow standpipe. The water height was measured by four ultrasonic sensors operated in two sets of two sensors located in diametrically opposed positions across the assembly core. Averaging the measurements from the two sensors in a set gives the height of the moderator at the center of the core.

The extrapolated water height at delayed critical for each case is given above. Also given above is the uncertainty in each extrapolated water height considering

1. The random uncertainties in the radiation detection process propagated through the extrapolation,
2. The random uncertainties in the level measurements propagated through the extrapolation, and
3. The uncertainties in the calibration of the level sensors

The two random uncertainties were combined in the propagation through the linear extrapolation of the water level and inverse count rate data and the calibration uncertainty was added to the result in quadrature.

Arrays with moderator/reflector heights of the measured height ± 0.5 cm in 0.1 cm increments were analyzed. The results of the analysis of the moderator/reflector height uncertainty for all cases are shown in Table 31.

Table 31. Results of the Analysis of the Moderator/Reflector Height Uncertainty.

Case	Uncertainty Value (mm)	Sensitivity (mm^{-1})		Δk_{eff}	
		Value	Uncertainty	Value	Uncertainty
1	0.73	0.0009041	0.0000030	0.000660	0.000002
2	0.51	0.0010708	0.0000030	0.000546	0.000002
3	0.46	0.0007934	0.0000058	0.000365	0.000003
4	0.67	0.0006530	0.0000060	0.000438	0.000004
5	0.32	0.0005401	0.0000048	0.000173	0.000002
6	0.32	0.0004405	0.0000042	0.000141	0.000001
7	0.50	0.0002992	0.0000030	0.000150	0.000002
8	0.30	0.0002436	0.0000042	0.000073	0.000001
9	0.60	0.0006488	0.0000059	0.000389	0.000004
10	0.29	0.0004162	0.0000030	0.000121	0.000001
11	0.38	0.0002986	0.0000057	0.000113	0.000002
12	0.49	0.0005026	0.0000059	0.000246	0.000003
13	0.22	0.0005546	0.0000058	0.000122	0.000001
14	0.29	0.0005323	0.0000059	0.000154	0.000002
15	0.33	0.0004822	0.0000059	0.000159	0.000002
16	0.35	0.0004079	0.0000057	0.000143	0.000002
17	0.36	0.0002845	0.0000057	0.000102	0.000002
18	0.53	0.0005739	0.0000059	0.000304	0.000003
19	0.49	0.0006414	0.0000031	0.000314	0.000002
20	0.26	0.0005952	0.0000058	0.000155	0.000002
21	0.39	0.0004901	0.0000057	0.000191	0.000002
22	0.29	0.0003127	0.0000028	0.000091	0.000001

2.3.6 Fuel Rod UO_2 Mass – The UO_2 fuel mass in the driver fuel rods was measured giving a standard deviation for 2222 measurements of 0.322 g. Because the fuel mass was known for each fuel rod and the identity of each fuel rod in every configuration was known, the distribution of the fuel rod UO_2 mass does not contribute to the uncertainty in the experiments. The fuel mass measurements were made using an instrument with a repeatability of 0.01 g, linearity of 0.02 g, and readability of 0.01 g. The uncertainty in the fuel mass is the sum in quadrature of the systematic uncertainties in the mass measurements (0.01 g, 0.02 g, and 0.01 g) and is 0.024 g. Arrays with the fuel rod UO_2 mass varying from 1 g below to 1 g above the nominal value were analyzed to determine the sensitivity of the experiments to this uncertainty. The variations were done by changing the fuel density while keeping the fuel dimensions constant.

The results of the analysis of the fuel rod UO_2 mass uncertainty for a sample of the cases are shown in Table 32. The bounding value of the k_{eff} uncertainties given in the table is shown in the last line.

Table 32. Results of the Analysis of the Fuel Rod UO₂ Mass Uncertainty.

Case	Uncertainty Value (g)	Sensitivity (g ⁻¹)		Δk_{eff}	
		Value	Uncertainty	Value	Uncertainty
1	0.024	0.000947	0.000022	0.0000227	0.0000005
2	0.024	0.001041	0.000023	0.0000250	0.0000006
7	0.024	0.000799	0.000022	0.0000192	0.0000005
10	0.024	0.000799	0.000022	0.0000192	0.0000005
19	0.024	0.001076	0.000022	0.0000258	0.0000005
22	0.024	0.001019	0.000022	0.0000245	0.0000005
Bounding Value				0.0000258	

2.3.7 Fuel Rod Pellet Stack Height – The fuel pellet stack height was measured during fabrication for all fuel rods to the nearest millimeter. The systematic uncertainty in this measurement is estimated to be 0.5 mm. The standard deviation for 2222 fuel columns was 0.125 cm. Because the pellet stack height was known for each fuel rod and the identity of each fuel rod in every configuration was known, the distribution of the fuel rod UO₂ column height does not contribute to the uncertainty in the experiments. The uncertainty in the average fuel pellet stack height is the estimated systematic uncertainty in the measurement or 0.05 cm. Arrays with fuel pellet stack heights 1 cm on either side of the nominal value were analyzed to determine the sensitivity of the experiments to the uncertainty in the pellet stack height. The mass of fuel in the fuel rods was held constant by varying the fuel density to compensate for pellet stack height changes.

The results of the analysis of the fuel rod pellet stack height uncertainty for a sample of the cases are shown in Table 33. The bounding value of the k_{eff} uncertainties given in the table is shown in the last line.

Table 33. Results of the Analysis of the Fuel Rod Pellet Stack Height Uncertainty.

Case	Uncertainty Value (cm)	Sensitivity (cm ⁻¹)		Δk_{eff}	
		Value	Uncertainty	Value	Uncertainty
1	0.05	-0.002027	0.000041	-0.000101	0.000002
2	0.05	-0.002217	0.00004	-0.000111	0.000002
7	0.05	-0.001219	0.000038	-0.000061	0.000002
10	0.05	-0.001646	0.000039	-0.000082	0.000002
19	0.05	-0.002276	0.00004	-0.000114	0.000002
22	0.05	-0.00189	0.000036	-0.000095	0.000002
Bounding Value				-0.000114	

2.3.8 Fuel Enrichment – The fuel isotopics were measured on ten randomly-selected fuel pellet samples drawn from the pellet stock used in the experiment fuel rods. The standard deviation of the ²³⁵U enrichment measurements was 0.0046 wt. %. The systematic uncertainty was 0.0069 wt. %. Considering the random uncertainty and the number of measurements and adding in quadrature to the systematic uncertainty, the uncertainty in the ²³⁵U enrichment of the fuel is 0.0071 wt. %.

The TSUNAMI-3D module of the SCALE6.2 code package was used to calculate the k_{eff} sensitivities to the materials in a detailed model of the experiment configurations. When appropriately combined, these sensitivities can be used to assess uncertainties in the benchmark k_{eff} that result from uncertainties of different

material properties of the system in question. For example, the sensitivity of k_{eff} to the enrichment of the fuel S_E can be obtained by combining the sensitivities of k_{eff} to the ^{235}U and ^{238}U in the fuel by

$$S_E = \frac{A_U N_U}{A_{235} N_{235}} S_{235} - \frac{A_U N_U}{A_{238} N_{238}} S_{238}$$

where A_U , A_{235} , and A_{238} are the atomic masses for the fuel uranium, ^{235}U , and ^{238}U ; the N_U , N_{235} , and N_{238} are the atom densities for uranium, ^{235}U , and ^{238}U in the fuel; and S_{235} and S_{238} are the sensitivities of the system k_{eff} to the fuel ^{235}U and ^{238}U . This formulation is based on the assumption that changes in ^{235}U mass are compensated by equivalent but opposite changes in ^{238}U mass in the fuel, holding the overall fuel mass and volume constant. The sensitivity S_E can be combined with the uncertainty in the fuel enrichment to obtain the contribution to the benchmark uncertainty due to uncertainties in the fuel enrichment.

The results of the sensitivity-based treatment of the fuel enrichment uncertainty are shown in Table 34.

Table 34. Results of the Analysis of the Fuel Enrichment Uncertainty.

Case	Uncertainty Value	Sensitivity		Δk_{eff}	
		Value	Uncertainty	Value	Uncertainty
1	0.000071	1.6914	0.0045	0.000120	0.000000
2	0.000071	1.8151	0.0048	0.000129	0.000000
3	0.000071	1.7051	0.0045	0.000121	0.000000
4	0.000071	1.6858	0.0045	0.000120	0.000000
5	0.000071	1.6820	0.0045	0.000119	0.000000
6	0.000071	1.6906	0.0045	0.000120	0.000000
7	0.000071	1.6829	0.0045	0.000119	0.000000
8	0.000071	1.6986	0.0045	0.000121	0.000000
9	0.000071	1.6812	0.0046	0.000119	0.000000
10	0.000071	1.7116	0.0045	0.000122	0.000000
11	0.000071	1.6779	0.0045	0.000119	0.000000
12	0.000071	1.7490	0.0048	0.000124	0.000000
13	0.000071	1.8216	0.0050	0.000129	0.000000
14	0.000071	1.8352	0.0053	0.000130	0.000000
15	0.000071	1.8543	0.0054	0.000132	0.000000
16	0.000071	1.8797	0.0054	0.000133	0.000000
17	0.000071	1.8549	0.0053	0.000132	0.000000
18	0.000071	1.7911	0.0050	0.000127	0.000000
19	0.000071	1.8835	0.0055	0.000134	0.000000
20	0.000071	1.9634	0.0058	0.000139	0.000000
21	0.000071	2.0357	0.0059	0.000145	0.000000
22	0.000071	2.0214	0.0058	0.000144	0.000000

2.3.9 Fuel ^{234}U Content – The ^{234}U content of the fuel was also measured. The standard deviation of the ten ^{234}U measurements was 0.00008 wt. %. The systematic uncertainty was 0.00013 wt. %. Considering the random uncertainty and the number of measurements and adding in quadrature to the systematic uncertainty, the uncertainty in the ^{234}U content of the fuel is 0.00013 wt. %.

Similar techniques to those described above for the fuel enrichment can be used to obtain the sensitivity of the benchmark k_{eff} to uncertainties in the ^{234}U content of the fuel. In the equation for the sensitivity above, the data for ^{234}U would replace that for ^{235}U . The sensitivity so obtained can be combined with the uncertainty in the ^{234}U content of the fuel to obtain the k_{eff} uncertainty due to the ^{234}U content uncertainty.

The results of the sensitivity-based treatment of the ^{234}U uncertainty are shown in Table 35.

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Table 35. Results of the Analysis of the ^{234}U Uncertainty.

Case	Uncertainty Value	Sensitivity		Δk_{eff}	
		Value	Uncertainty	Value	Uncertainty
1	0.0000013	-4.5072	0.0070	-0.000006	0.000000
2	0.0000013	-4.1741	0.0065	-0.000005	0.000000
3	0.0000013	-4.5068	0.0069	-0.000006	0.000000
4	0.0000013	-4.4941	0.0069	-0.000006	0.000000
5	0.0000013	-4.4827	0.0068	-0.000006	0.000000
6	0.0000013	-4.4617	0.0067	-0.000006	0.000000
7	0.0000013	-4.4421	0.0067	-0.000006	0.000000
8	0.0000013	-4.4317	0.0066	-0.000006	0.000000
9	0.0000013	-4.4936	0.0069	-0.000006	0.000000
10	0.0000013	-4.4431	0.0067	-0.000006	0.000000
11	0.0000013	-4.4124	0.0066	-0.000006	0.000000
12	0.0000013	-4.2985	0.0066	-0.000006	0.000000
13	0.0000013	-4.1548	0.0064	-0.000005	0.000000
14	0.0000013	-4.0462	0.0062	-0.000005	0.000000
15	0.0000013	-3.9661	0.0060	-0.000005	0.000000
16	0.0000013	-3.9119	0.0059	-0.000005	0.000000
17	0.0000013	-3.9110	0.0059	-0.000005	0.000000
18	0.0000013	-4.1727	0.0065	-0.000005	0.000000
19	0.0000013	-3.9288	0.0061	-0.000005	0.000000
20	0.0000013	-3.7237	0.0057	-0.000005	0.000000
21	0.0000013	-3.6050	0.0055	-0.000005	0.000000
22	0.0000013	-3.5479	0.0053	-0.000005	0.000000

2.3.10 Fuel ^{236}U Content – The ^{236}U content of the fuel was also measured. The standard deviation of the ten ^{236}U measurements was 0.00012 wt. %. The systematic uncertainty was 0.00063 wt. %. Considering the random uncertainty and the number of measurements and adding in quadrature to the systematic uncertainty, the uncertainty in the ^{236}U content of the fuel is 0.00063 wt. %.

As for the ^{234}U uncertainties, the techniques described above for the fuel enrichment can be used to obtain the sensitivity of the benchmark k_{eff} to uncertainties in the ^{236}U content of the fuel. In the equation for the sensitivity above, the data for ^{236}U would replace that for ^{235}U . The sensitivity so obtained can be combined with the uncertainty in the ^{236}U content of the fuel to obtain the k_{eff} uncertainty due to the ^{236}U content uncertainty.

The results of the sensitivity-based treatment of the ^{236}U uncertainty are shown in Table 36.

Table 36. Results of the Analysis of the ^{236}U Uncertainty.

Case	Uncertainty Value	Sensitivity		Δk_{eff}	
		Value	Uncertainty	Value	Uncertainty
1	0.0000063	-1.5602	0.0029	-0.000010	0.000000
2	0.0000063	-1.3784	0.0027	-0.000009	0.000000
3	0.0000063	-1.5601	0.0029	-0.000010	0.000000
4	0.0000063	-1.5517	0.0028	-0.000010	0.000000
5	0.0000063	-1.5441	0.0028	-0.000010	0.000000
6	0.0000063	-1.5299	0.0028	-0.000010	0.000000
7	0.0000063	-1.5154	0.0027	-0.000010	0.000000
8	0.0000063	-1.5119	0.0027	-0.000010	0.000000
9	0.0000063	-1.5413	0.0028	-0.000010	0.000000
10	0.0000063	-1.5195	0.0028	-0.000010	0.000000
11	0.0000063	-1.5042	0.0027	-0.000009	0.000000
12	0.0000063	-1.4434	0.0027	-0.000009	0.000000
13	0.0000063	-1.3628	0.0026	-0.000009	0.000000
14	0.0000063	-1.3026	0.0025	-0.000008	0.000000
15	0.0000063	-1.2629	0.0025	-0.000008	0.000000
16	0.0000063	-1.2364	0.0024	-0.000008	0.000000
17	0.0000063	-1.2279	0.0024	-0.000008	0.000000
18	0.0000063	-1.3757	0.0027	-0.000009	0.000000
19	0.0000063	-1.2398	0.0025	-0.000008	0.000000
20	0.0000063	-1.1363	0.0023	-0.000007	0.000000
21	0.0000063	-1.0703	0.0022	-0.000007	0.000000
22	0.0000063	-1.0354	0.0021	-0.000007	0.000000

2.3.11 Fuel Stoichiometry – The oxygen-to-uranium ratio in the fuel was not measured and was assumed to be 2.00. A range of 0.1 was assumed to bound the uncertainty in the oxygen-to-uranium ratio.

Under the assumption that the fuel mass and volume are held constant, the sensitivity of the system k_{eff} to the oxygen-to-uranium ratio in the fuel S_S can be obtained from the sensitivities of the system k_{eff} to the constituents of the fuel by

$$S_S = \frac{N_U(A_U N_U S_O - A_O N_O S_U)}{N_O(A_O N_O + A_U N_U)}$$

with the variables A, N, and S indicating similar quantities as described above and the subscript O referring to the oxygen in the fuel and the subscript U referring to the uranium content of the fuel. As before, this sensitivity is combined with the uncertainty in the oxygen-to-uranium ratio in the fuel to obtain the uncertainty in the system k_{eff} introduced by the uncertainty in the fuel oxygen-to-uranium ratio.

The results of the sensitivity-based treatment of the fuel stoichiometry uncertainty are shown in Table 37.

Table 37. Results of the Analysis of the Fuel Stoichiometry Uncertainty.

Case	Uncertainty Value	Sensitivity		Δk_{eff}	
		Value	Uncertainty	Value	Uncertainty
1	0.1	0.00934	0.00008	0.000934	0.000008
2	0.1	0.00796	0.00008	0.000796	0.000008
3	0.1	0.00896	0.00008	0.000896	0.000008
4	0.1	0.00862	0.00008	0.000862	0.000008
5	0.1	0.00816	0.00008	0.000816	0.000008
6	0.1	0.00753	0.00008	0.000753	0.000008
7	0.1	0.00680	0.00008	0.000680	0.000008
8	0.1	0.00645	0.00008	0.000645	0.000008
9	0.1	0.00848	0.00008	0.000848	0.000008
10	0.1	0.00720	0.00008	0.000720	0.000008
11	0.1	0.00659	0.00008	0.000659	0.000008
12	0.1	0.00707	0.00008	0.000707	0.000008
13	0.1	0.00644	0.00008	0.000644	0.000008
14	0.1	0.00591	0.00008	0.000591	0.000008
15	0.1	0.00510	0.00008	0.000510	0.000008
16	0.1	0.00431	0.00007	0.000431	0.000007
17	0.1	0.00377	0.00007	0.000377	0.000007
18	0.1	0.00693	0.00008	0.000693	0.000008
19	0.1	0.00579	0.00008	0.000579	0.000008
20	0.1	0.00440	0.00007	0.000440	0.000007
21	0.1	0.00282	0.00007	0.000282	0.000007
22	0.1	0.00169	0.00007	0.000169	0.000007

2.3.12 Impurities in the UO_2 Fuel – The impurities in the fuel fell into two classes – those for which a definite value was measured and those that were determined to be less than the detection limit for the analysis system. For the impurities that were detected, an uncertainty at the one-standard-deviation level of 50 % of the detected value was assumed. For the impurities that were below a detection limit, the uncertainty at one standard deviation was assumed to be equal to the detection limit.

Under the assumption that the fuel mass and volume are held constant, the sensitivity of the system $k_{\text{eff}} S_C$ due to the uncertainty in any given impurity can be obtained from

$$S_C = \frac{S_I}{N_I} - \frac{A_I S_{\text{UO}_2}}{M_{\text{UO}_2} N_{\text{UO}_2}}$$

where the symbols S , N , and A indicate the same quantities as above; the subscript I refers to the impurity species and the subscript UO_2 refers to the UO_2 in the fuel; and M_{UO_2} is the molecular weight of the UO_2 in the fuel. The uncertainty in S_C is obtained by propagating the uncertainties in S_I and S_{UO_2} through the definition of S_C . Table 38 lists the uncertainty in the atom density of each fuel impurity, the sensitivity of the system k_{eff} to the atom density uncertainties, and the k_{eff} uncertainty that results from the uncertainty in each impurity for Case 1. The k_{eff} uncertainties for the individual impurities are summed in quadrature to obtain the overall contribution to the uncertainty in the system k_{eff} .

Table 38. Atom Density Uncertainty and k_{eff} Sensitivity for the Fuel Impurities for Case 1.

Impurity	Uncertainty ($\text{b}^{-1}\text{cm}^{-1}$)	Sensitivity (b cm)		Δk_{eff}
		Value	Unc.	
Ag	4.616E-09	-2.386E+02	3.56E-01	-0.000001
B	1.193E-07	-5.906E+02	2.44E-01	-0.000070
Cd	6.190E-09	-3.460E+03	1.71E+00	-0.000021
Co	1.081E-08	-4.643E+01	1.07E-01	-0.000001
Cr	1.255E-06	-2.146E+00	5.60E-03	-0.000003
Cu	1.066E-07	-3.492E+00	5.74E-03	0.000000
Fe	5.156E-06	-1.963E+00	7.62E-03	-0.000010
Mn	1.419E-07	-1.118E+01	5.21E-02	-0.000002
Mo	6.222E-08	-9.013E+00	2.50E-02	-0.000001
Ni	1.749E-06	-3.378E+00	1.03E-02	-0.000006
V	7.407E-09	-3.092E+00	1.43E-02	0.000000
W	1.798E-09	-9.802E+01	3.91E-01	0.000000
Sm	1.053E-09	-7.677E+03	1.44E-02	-0.000008
Dy	8.564E-10	-9.547E+02	1.21E-02	-0.000001
Eu	9.158E-10	-3.826E+03	1.17E-02	-0.000004
Gd	8.850E-10	-2.047E+04	5.45E-01	-0.000018
Sum in Quadrature				0.000078

The results of the sensitivity-based treatment of the fuel impurities uncertainty for all cases are shown in Table 39.

Table 39. Results of the Analysis of the Fuel Impurities Uncertainty.

Case	Δk_{eff}	
	Value	Uncertainty
1	0.000078	0.000000
2	0.000078	0.000000
3	0.000078	0.000000
4	0.000078	0.000000
5	0.000078	0.000000
6	0.000078	0.000000
7	0.000078	0.000000
8	0.000078	0.000000
9	0.000078	0.000000
10	0.000078	0.000000
11	0.000078	0.000000
12	0.000078	0.000000
13	0.000078	0.000000
14	0.000078	0.000000
15	0.000078	0.000000
16	0.000078	0.000000
17	0.000079	0.000000
18	0.000078	0.000000
19	0.000078	0.000000
20	0.000078	0.000000
21	0.000078	0.000000
22	0.000079	0.000000

2.3.13 Fuel Clad Composition – The composition range for 3003 aluminum tubing is shown in Table 21. The composition limits are specified either as two bounding values giving minimum and maximum content of a given element or as a single bounding value giving the maximum allowed content of a given element. The assumption was made that any level of content between the limiting values is equally probable. Therefore, the probability distribution between the limits is constant. As a result, one standard deviation is the width of the interval divided by $\sqrt{3}$.

Under the assumption that the mass and volume of the cladding material are held constant and that changes in a constituent are counterbalanced by changes in the aluminum content, the sensitivity of the system k_{eff} S_C due to the uncertainty in any given constituent of the alloy can be obtained from

$$S_C = \frac{S_I}{N_I} - \frac{A_I S_{Al}}{A_{Al} N_{Al}}$$

where the symbols S , N , and A indicate the same quantities as above; the subscript I refers to the constituent species and the subscript Al refers to the aluminum in the cladding material. The uncertainty in S_C is obtained by propagating the uncertainties in S_I and S_{Al} through the definition of S_C . Table 40 lists the uncertainty in the atom density of each fuel clad constituent, the sensitivity of the system k_{eff} to the atom density uncertainties, and the k_{eff} uncertainty that results from the uncertainty in each fuel clad constituent for Case 1. The k_{eff}

uncertainties for the individual constituents are summed in quadrature to obtain the overall contribution to the uncertainty in the system k_{eff} .

Table 40. Atom Density Uncertainty and k_{eff} Sensitivity for the Fuel Clad Constituents for Case 1.

Constituent	Uncertainty ($\text{b}^{-1}\text{cm}^{-1}$)	Sensitivity (b cm)		Δk_{eff}
		Value	Unc.	
Si	1.01E-04	-4.68E-03	1.67E-03	0.000000
Fe	5.95E-05	-7.86E-01	3.56E-03	-0.000047
Cu	1.12E-05	-1.32E+00	3.43E-03	-0.000015
Mn	4.32E-05	-3.81E+00	1.46E-02	-0.000165
Zn	7.25E-06	-4.65E-01	3.51E-03	-0.000003
Sum in Quadrature				0.000172

The results of the sensitivity-based treatment of the fuel clad constituents uncertainty for all cases are shown in Table 41.

Table 41. Results of the Analysis of the Fuel Clad Constituents Uncertainty.

Case	Δk_{eff}	
	Value	Uncertainty
1	0.000172	0.000001
2	0.000172	0.000001
3	0.000170	0.000001
4	0.000167	0.000001
5	0.000165	0.000001
6	0.000164	0.000001
7	0.000163	0.000001
8	0.000163	0.000001
9	0.000168	0.000001
10	0.000164	0.000001
11	0.000163	0.000001
12	0.000164	0.000001
13	0.000164	0.000001
14	0.000163	0.000001
15	0.000162	0.000000
16	0.000162	0.000000
17	0.000161	0.000000
18	0.000164	0.000001
19	0.000164	0.000001
20	0.000163	0.000000
21	0.000160	0.000000
22	0.000159	0.000000

2.3.14 Aluminum Grid Plate Composition – The elemental composition of the 6061 aluminum grid plates was measured and reported by the supplier of the grid plates. No uncertainties were given for the measurements. The measured composition for the aluminum grid plates is shown in Table 13 above. The

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aluminum was treated in a manner similar to the 3003 aluminum cladding. Because the composition was measured, the uncertainty in any given value is assumed to be 25 % of that value.

The sensitivity of the system k_{eff} to any given constituent of the grid plates and its uncertainty is obtained in the same manner as described above for the constituents of the cladding material. Table 42 lists the uncertainty in the atom density of each grid plate constituent, the sensitivity of the system k_{eff} to the atom density uncertainties, and the k_{eff} uncertainty that results from the uncertainty in each grid plate constituent for Case 1. The k_{eff} uncertainties for the individual constituents are summed in quadrature to obtain the overall contribution to the uncertainty in the system k_{eff} .

Table 42. Atom Density Uncertainty and k_{eff} Sensitivity for the Grid Plate Constituents for Case 1.

Constituent	Uncertainty ($\text{b}^{-1}\text{cm}^{-1}$)	Sensitivity (b cm)		Δk_{eff}
		Value	Unc.	
Si	1.042E-04	3.514E-02	1.47E-03	0.000004
Fe	4.513E-05	-4.505E-01	4.53E-03	-0.000020
Cu	1.983E-05	-7.208E-01	3.58E-03	-0.000014
Mn	6.659E-06	-2.374E+00	1.21E-02	-0.000016
Mg	1.739E-04	1.517E-01	1.88E-03	0.000026
Cr	1.564E-05	-5.792E-01	2.54E-03	-0.000009
Zn	7.458E-06	-1.276E-01	3.09E-03	-0.000001
Ti	1.698E-06	-1.079E+00	4.61E-03	-0.000002
V	7.980E-07	-5.970E-01	6.44E-03	0.000000
Sum in Quadrature				0.000041

The results of the sensitivity-based treatment of the grid plate constituents uncertainty for all cases are shown in Table 43.

Table 43. Results of the Analysis of the Grid Plate Constituents Uncertainty.

Case	Δk_{eff}	
	Value	Uncertainty
1	0.000041	0.000000
2	0.000046	0.000000
3	0.000036	0.000000
4	0.000030	0.000000
5	0.000025	0.000000
6	0.000021	0.000000
7	0.000017	0.000000
8	0.000016	0.000000
9	0.000029	0.000000
10	0.000020	0.000000
11	0.000017	0.000000
12	0.000023	0.000000
13	0.000024	0.000000
14	0.000024	0.000000
15	0.000022	0.000000
16	0.000020	0.000000
17	0.000017	0.000000
18	0.000026	0.000000
19	0.000028	0.000000
20	0.000028	0.000000
21	0.000023	0.000000
22	0.000017	0.000000

2.3.15 Water Composition – The impurities measured in the municipal water supply that feeds the facility in 2014 are listed in Table 15 above. For conservatism, the maximum impurity levels were assumed to be the 1- σ uncertainties. Table 16 lists several impurity species for which testing was done but that could not be detected. Also listed in the table is the minimum detection level for each species. For these impurities, the 1- σ uncertainties are assumed to be the minimum detection levels.

Under the assumption that the water mass and volume are held constant, the sensitivity of the system k_{eff} S_C due to the uncertainty in any given impurity in the water can be obtained from

$$S_C = \frac{S_I}{N_I} - \frac{A_I S_W}{M_W N_W}$$

where the symbols S , N , and A indicate the same quantities as above; the subscript I refers to the impurity species and the subscript W refers to the Water; and M_W is the molecular weight of water. The uncertainty in S_C is obtained by propagating the uncertainties in S_I and S_W through the definition of S_C . Table 44 lists the uncertainty in the atom density of each water impurity, the sensitivity of the system k_{eff} to the atom density uncertainties, and the k_{eff} uncertainty that results from the uncertainty in each impurity for Case 1. The k_{eff} uncertainties for the individual impurities are summed in quadrature to obtain the overall contribution to the uncertainty in the system k_{eff} .

Table 44. Atom Density Uncertainty and k_{eff} Sensitivity for the Water Impurities for Case 1.

Impurity	Uncertainty ($\text{b}^{-1}\text{cm}^{-1}$)	Sensitivity (b cm)		Δk_{eff}
		Value	Unc.	
As	6.413E-11	-1.075E+02	6.48E-01	0.000000
Ba	8.746E-10	-1.130E+02	1.19E+00	0.000000
Cr	9.240E-11	-4.939E+01	4.50E-01	0.000000
U	1.514E-11	-2.534E+02	2.06E+00	0.000000
Fe	1.012E-08	-5.026E+01	4.83E-01	-0.000001
Mn	1.345E-09	-8.704E+01	4.75E-01	0.000000
Ca	1.019E-06	-3.200E+01	3.47E-01	-0.000033
Cl	7.962E-07	-1.465E+02	3.07E-01	-0.000117
Mg	1.804E-07	-1.676E+01	2.10E-01	-0.000003
K	1.229E-07	-3.742E+01	3.38E-01	-0.000005
Na	1.829E-06	-1.698E+01	1.99E-01	-0.000031
Sb	4.932E-12	-1.929E+02	1.05E+00	0.000000
Be	6.664E-11	-3.951E+00	7.80E-02	0.000000
Cd	5.343E-12	-1.389E+04	9.72E-01	0.000000
Hg	5.988E-13	-1.411E+03	1.74E+00	0.000000
Se	3.803E-11	-1.054E+02	6.83E-01	0.000000
Sum in Quadrature				0.000125

The results of the sensitivity-based treatment of the water impurities uncertainty for all cases are shown in Table 45.

Table 45. Results of the Analysis of the Water Impurities Uncertainty.

Case	Δk_{eff}	
	Value	Uncertainty
1	0.000125	0.000000
2	0.000135	0.000000
3	0.000129	0.000000
4	0.000129	0.000000
5	0.000132	0.000000
6	0.000137	0.000000
7	0.000142	0.000000
8	0.000144	0.000000
9	0.000131	0.000000
10	0.000141	0.000000
11	0.000145	0.000000
12	0.000144	0.000000
13	0.000151	0.000000
14	0.000160	0.000000
15	0.000173	0.000000
16	0.000186	0.000000
17	0.000196	0.000000
18	0.000147	0.000000
19	0.000161	0.000000
20	0.000183	0.000000
21	0.000206	0.000000
22	0.000227	0.000000

2.3.16 Temperature – The experiments were run near a temperature of 25 °C and the data were corrected to that temperature. A bounding estimate of the uncertainty in the measured experiment temperature is 1 °C. The sensitivity of the arrays to moderator/reflector temperature was determined by analyzing arrays at temperatures from 5 to 50 °C in 5 °C increments using MCNP6.1.1 and ENDF/B-VII.1 cross sections. In the analysis, the water temperature was varied as well as the water density. Thermal scattering kernel data appropriate for each water temperature were used during the variations. The sensitivity of the arrays to fuel temperature was also computed with the same code/cross sections using the temperature-dependent uranium cross sections included with the code. Thermal expansion of the UO₂ was included in the analysis. The variations in the calculated k_{eff} data in both cases necessitated the use of a second-order polynomial fit. The sensitivity was taken as the slope of the polynomial at the experiment temperature. The stochastic uncertainties in the Monte Carlo calculations were propagated through the fit. The two sensitivities were combined to obtain the overall temperature sensitivity of the assemblies. The uncertainties in the two sensitivities were combined in quadrature.

The results of the analysis of the temperature uncertainty for all cases are shown in Table 46.

Table 46. Results of the Analysis of the Temperature Uncertainty.

Case	Uncertainty Value (°C)	Sensitivity (°C ⁻¹)		Δk_{eff}	
		Value	Uncertainty	Value	Uncertainty
1	1	-0.0000697	0.0000012	-0.000070	0.000001
2	1	-0.0000747	0.0000012	-0.000075	0.000001
3	1	-0.0000736	0.0000014	-0.000074	0.000001
4	1	-0.0000646	0.0000012	-0.000065	0.000001
5	1	-0.0000591	0.0000015	-0.000059	0.000001
6	1	-0.0000460	0.0000015	-0.000046	0.000001
7	1	-0.0000365	0.0000012	-0.000036	0.000001
8	1	-0.0000325	0.0000015	-0.000033	0.000001
9	1	-0.0000535	0.0000017	-0.000054	0.000002
10	1	-0.0000350	0.0000012	-0.000035	0.000001
11	1	-0.0000239	0.0000013	-0.000024	0.000001
12	1	-0.0000390	0.0000012	-0.000039	0.000001
13	1	-0.0000257	0.0000012	-0.000026	0.000001
14	1	-0.0000012	0.0000012	-0.000001	0.000001
15	1	0.0000364	0.0000012	0.000036	0.000001
16	1	0.0000752	0.0000012	0.000075	0.000001
17	1	0.0001110	0.0000012	0.000111	0.000001
18	1	-0.0000448	0.0000023	-0.000045	0.000002
19	1	-0.0000180	0.0000022	-0.000018	0.000002
20	1	0.0000321	0.0000022	0.000032	0.000002
21	1	0.0001075	0.0000022	0.000108	0.000002
22	1	0.0001793	0.0000014	0.000179	0.000001

2.3.17 Uncertainty Values – The effects of several uncertainty components in the critical experiments on the k_{eff} of the configurations are analyzed above. For one group of uncertainties, the effect on the k_{eff} uncertainty was determined for each case. For a second group, the k_{eff} uncertainty was determined for a sampling of the cases and a bounding value determined for those cases. The total uncertainty for each case was obtained by combining in quadrature the case-wise results of the first group and the bounding results of the second group. The total uncertainty so obtained for each case is listed in Table 47. These values represent the uncertainty in the experiments at the one-standard-deviation level.

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Table 47. Results of the Uncertainty Analysis.

Case	Δk_{eff}
1	0.00130
2	0.00111
3	0.00116
4	0.00116
5	0.00107
6	0.00105
7	0.00103
8	0.00103
9	0.00117
10	0.00107
11	0.00107
12	0.00105
13	0.00095
14	0.00089
15	0.00081
16	0.00075
17	0.00070
18	0.00103
19	0.00090
20	0.00071
21	0.00060
22	0.00053

3.0 BENCHMARK SPECIFICATIONS

3.1 Description of Model

The models of the experiments consist of square-pitched arrays of UO_2 fuel rods supported by aluminum grid plates and partially submerged in water. The arrays are centered in a 93.6752 cm diameter cylinder of water with 16.51 cm of water below the lower grid plate. This section describes the reactivity effects of several simplifications included in the benchmark models.

The following modeling approximations were made:

- The population average value of the UO_2 fuel mass was used.
- The population average value of the UO_2 fuel pellet stack height was used.
- The population average value of the fuel rod outer diameter was used.
- The slight misalignment of the aluminum plugs above the fuel pellet stack with the upper grid plate was ignored.
- The parts of the critical assembly more than 68.2752 cm above the top of the bottom grid plate were removed.
- The guide plate and upper grid plate support bosses and posts were removed and replaced with water.
- The control and safety elements were each replaced with four fuel rods.
- The neutron source was replaced by an empty position in the fuel assembly.
- All materials outside of the water reflector were removed.
- The density of the polyethylene annuli around the detectors was set equal to the density of the polyethylene plugs in the fuel rods.

Each of these modeling approximations was investigated in one or more of evaluations [LEU-COMP-THERM-080](#), [LEU-COMP-THERM-078](#), and [LEU-COMP-THERM-096](#) and was found to be small. It was judged that individual analyses for each approximation were not necessary here. An analysis of the bias from all of the approximations is given below.

3.1.1 Integral Calculation of the Benchmark Model Bias – The k_{eff} for all cases was calculated using the detailed MCNP6.1.1 model and compared to the calculated k_{eff} for a model in which all the simplifications described above had been made. The ENDF/B-VII.1 cross sections distributed with the MCNP6.1.1 code were used. Table 48 lists the calculated reactivity biases attributable to the model simplifications. The bias associated with simplification of the benchmark model is small in all cases. The biases listed in the table will be applied to the benchmark model k_{eff} .

Table 48. Benchmark Model Reactivity Bias and Uncertainty.

Case	Simplified Model Reactivity Bias	Uncertainty in the Bias
1	-0.00041	0.00002
2	-0.00032	0.00002
3	-0.00030	0.00002
4	-0.00020	0.00002
5	-0.00015	0.00002
6	-0.00013	0.00002
7	-0.00008	0.00002
8	-0.00008	0.00002
9	-0.00021	0.00002
10	-0.00013	0.00002
11	-0.00012	0.00002
12	-0.00002	0.00002
13	-0.00007	0.00002
14	-0.00011	0.00002
15	-0.00009	0.00002
16	-0.00012	0.00002
17	-0.00016	0.00002
18	-0.00006	0.00002
19	-0.00008	0.00002
20	-0.00016	0.00002
21	-0.00015	0.00002
22	-0.00019	0.00002

3.1.2 Temperature Corrections to Experiment k_{eff} – The benchmark experiments were run near a temperature of 25°C and this temperature was chosen as the benchmark model temperature. The experiment k_{eff} for all cases was 1. A correction to the experiment k_{eff} , Δk_T , for a temperature difference ΔT between the benchmark model temperature and the experiment temperature is given by

$$\Delta k_T = \Delta T \bullet S_T$$

where S_T is the temperature sensitivity of the configuration involved and includes the effects of temperature on the fuel and moderator/reflector.

Detailed models of all cases were analyzed for water temperatures in 5 °C increments from 5 °C to 50 °C using MCNP6.1.1 with continuous-energy ENDF/B-VII.1 cross sections using thermal scattering data and water densities appropriate to each temperature. The water temperature sensitivity of each model was determined by fitting a second-order polynomial to the k_{eff} results as a function of water temperature and finding the slope of the fitting function at 25 °C.

Detailed models of all cases were analyzed at fuel temperatures of 250, 293, 600, 900, and 1200 K using MCNP6.1.1 with continuous-energy uranium cross sections at those temperatures. Thermal expansion of the UO_2 was included in the analysis. As for the moderator, the temperature sensitivity of each model was determined by fitting a second-order polynomial to the k_{eff} result and finding the slope of the fitting function at 25 °C. The overall temperature sensitivity S_T was taken as the sum of the water and fuel sensitivities. The

combined temperature sensitivity S_T , the experiment temperature, and the Δk_T correction to the experiment k_{eff} are shown in Table 49.

Table 49. Temperature Corrections to the Experiment Reactivity.

Case	Temperature Sensitivity S_T ($\times 10^{-5} \text{ } ^\circ\text{C}^{-1}$)		Experiment Temperature ($^\circ\text{C}$)	Temperature Correction Reactivity	
	Value	σ		Value	σ
1	-6.97	0.12	24.9	-0.00001	0.00000
2	-7.47	0.12	25.3	0.00002	0.00000
3	-7.36	0.14	23.6	-0.00010	0.00000
4	-6.46	0.12	25.0	0.00000	0.00000
5	-5.91	0.15	23.5	-0.00009	0.00000
6	-4.60	0.15	24.3	-0.00003	0.00000
7	-3.65	0.12	25.0	0.00000	0.00000
8	-3.25	0.15	23.5	-0.00005	0.00000
9	-5.35	0.17	23.2	-0.00010	0.00000
10	-3.50	0.12	23.5	-0.00005	0.00000
11	-2.39	0.13	23.5	-0.00004	0.00000
12	-3.90	0.12	24.3	-0.00003	0.00000
13	-2.57	0.12	24.3	-0.00002	0.00000
14	-0.12	0.12	25.1	0.00000	0.00000
15	3.64	0.12	25.1	0.00000	0.00000
16	7.52	0.12	25.2	-0.00002	0.00000
17	11.10	0.12	25.0	0.00000	0.00000
18	-4.48	0.23	24.5	-0.00002	0.00000
19	-1.80	0.22	24.6	-0.00001	0.00000
20	3.21	0.22	24.4	0.00002	0.00000
21	10.75	0.22	24.6	0.00004	0.00000
22	17.93	0.14	25.1	-0.00002	0.00000

3.2 Dimensions

The critical assembly can be modeled as a cylinder of water with two grid plates in it supporting a 45×45 square-pitched array of fuel rods centered on the axis of the cylinder. The water only partially covers the fuel in the experiment. Except in Case 1, not all of the array positions are fueled – some have no fuel rod. The model includes two dry wells surrounded by polyethylene outside of the fuel array that were used for radiation detection instruments. A cut-away perspective view of the benchmark model for Case 4 is shown in Figure 37. A layout of the benchmark model for Case 7 is shown in Figure 38.

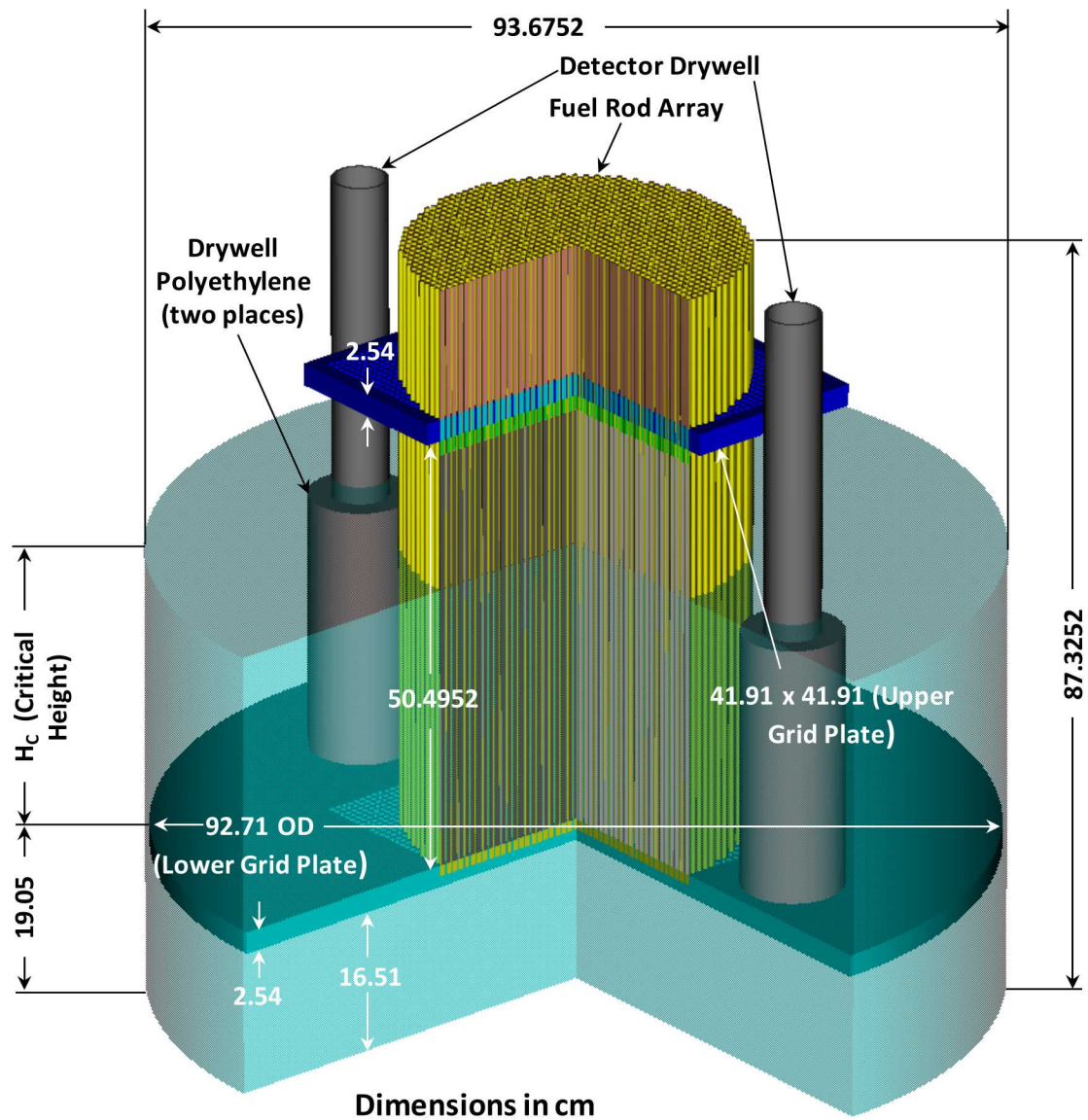


Figure 37. Cut-Away Perspective View of the Benchmark Model of Case 4.

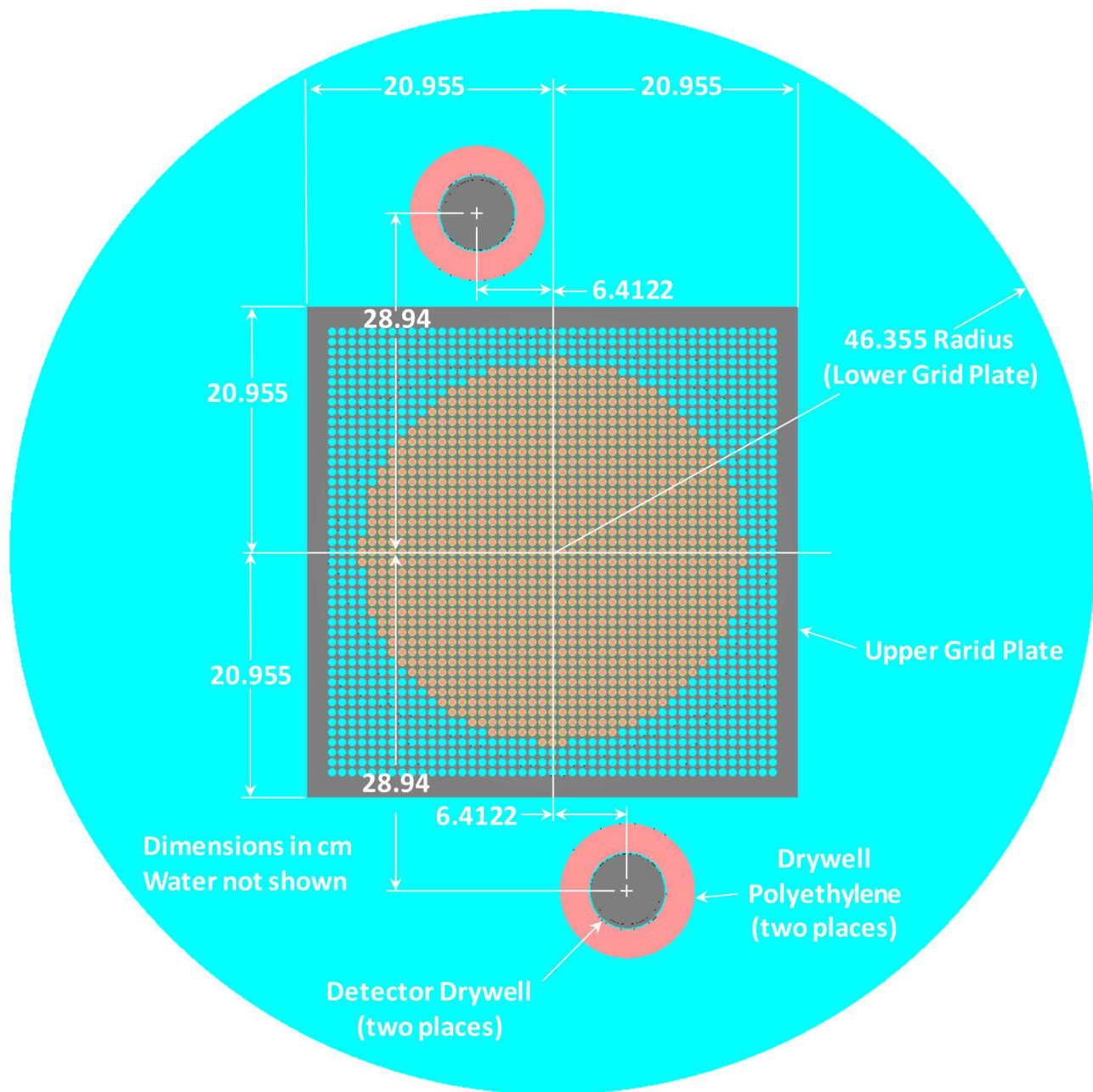


Figure 38. Layout of the Benchmark Model of Case 7.

The water moderator and reflector is a right circular cylinder 93.6752 cm in diameter and height that depends on the configuration. The benchmark model water heights, referenced to the top of the lower grid plate, are given in Table 50. The benchmark model water heights are identical to the extrapolated critical water heights.

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Table 50. Benchmark Model Water Heights.

Case	Benchmark Model Water Height H_C (cm)
1	28.031
2	25.763
3	29.906
4	32.773
5	35.651
6	39.729
7	46.187
8	48.138
9	33.051
10	40.340
11	46.530
12	37.321
13	36.002
14	36.313
15	37.872
16	40.904
17	45.610
18	35.023
19	33.290
20	34.283
21	37.912
22	45.212

The lower grid plate is a 6061 aluminum cylinder 92.71 cm diameter and 2.54 cm thick centered on the axis of the moderator cylinder. The top of the lower grid plate is 19.05 cm above the bottom of the water cylinder. The lower grid plate has a 45×45 square-pitched array of blind 0.333375 cm radius cylindrical holes bored from the top surface 1.27 cm deep that support the fuel rods from the bottom. The upper grid plate is a 41.91 cm square 2.54 cm thick centered on the axis of the water cylinder. The bottom of the upper grid plate is 50.4952 cm above the top surface of the lower grid plate. The upper grid plate has a 45×45 square-pitched array of 0.333375 cm radius through holes bored in it to locate the fuel rods in the array. The pitch of the fuel rod array is 0.854964 cm.

The fuel rods in the model extend from the bottom of the holes in the lower grid plate to the top of the model 68.2752 cm above the top of the lower grid plate. In the description that follows, the upper surface of the lower grid plate, also the axial location of the bottom of the fuel in the fuel rods, is the origin of the axial coordinates. The fuel rods are 0.317474 cm radius right-circular cylinders. Figure 39 shows a schematic of several fuel rods in the model. Table 51 lists modeling information by axial interval for the fuel rods. Table 52 lists similar information for array positions that are unfueled.

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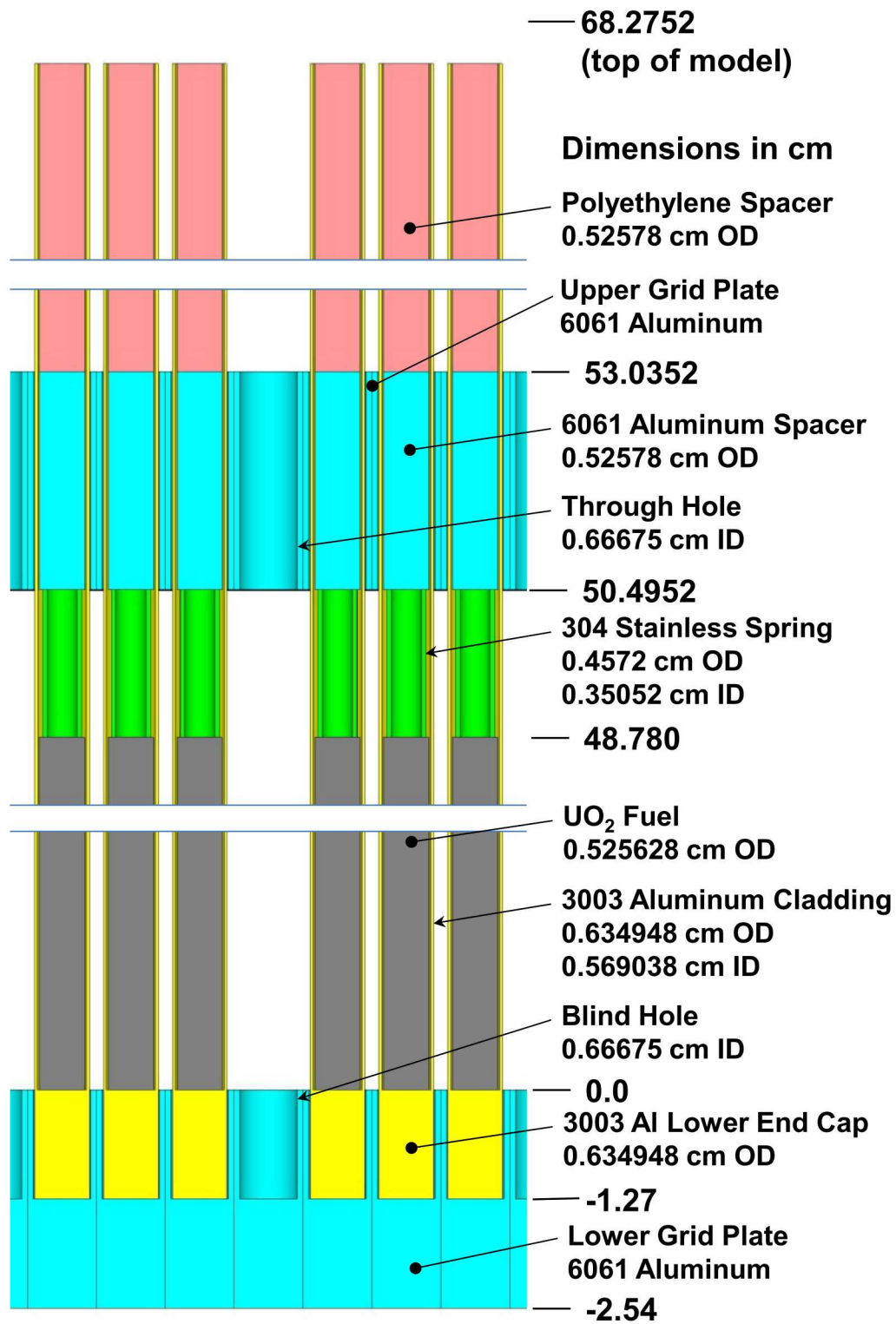
Table 51. Axial and Radial Modeling Information for a Fuel Rod.

Position (cm)				Material
Axial ^(a)		Radial ^(b)		
From	To	From	To	
-2.54	-1.27	0.0	Cell ^(c)	Grid Plate 6061 Aluminum
-1.27	0.0	0.0	0.317474	Cladding 3003 Aluminum
		0.317474	0.333375	Water
		0.333375	Cell	Grid Plate 6061 Aluminum
0.0	48.780	0.0	0.262814	UO ₂
		0.262814	0.284519	Void
		0.284519	0.317474	Cladding 3003 Aluminum
		0.317474	Cell	Water to H _e , Void Above
48.780	50.4952	0.0	0.17526	Void
		0.17526	0.2286	Spring 304 Stainless Steel
		0.2286	0.284519	Void
		0.284519	0.317474	Cladding 3003 Aluminum
		0.317474	Cell	Void
50.4952	53.0352	0.0	0.26289	6061 Aluminum
		0.26289	0.284519	Void
		0.284519	0.317474	Cladding 3003 Aluminum
		0.317474	0.333375	Void
		0.333375	Cell	Grid Plate 6061 Aluminum
53.0352	68.2752	0.0	0.26289	Polyethylene
		0.26289	0.284519	Void
		0.284519	0.317474	Cladding 3003 Aluminum
		0.317474	Cell	Void

(a) The origin of the axial coordinates is the top of the lower grid plate.

(b) The origin of the radial coordinates is the axial center of the 0.854964×0.854964 cm square cell.

(c) “Cell” refers to the boundary of the square cell in the array. Each surface of the cell is 0.427482 cm from the central axis of the cell.



Lower Reflector Extends to -19.05 cm

Figure 39. Schematic of the Fuel Rods in the Model. [VERIFY PRINT QA OF FIGURE]

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Table 52. Axial and Radial Modeling Information for an Empty Grid Location.

Position (cm)				Material
Axial ^(a)		Radial ^(b)		
From	To	From	To	
-2.54	-1.27	0.0	Cell ^(c)	Grid Plate 6061 Aluminum
-1.27	0.0	0.0	0.333375	Water
		0.333375	Cell	Grid Plate 6061 Aluminum
0.0	50.4952	0.0	Cell	Water to H _c , Void Above
50.4952	53.0352	0.0	0.333375	Void
		0.333375	Cell	Grid Plate 6061 Aluminum
53.0352	68.2752	0.0	Cell	Void

- (a) The origin of the axial coordinates is the top of the lower grid plate.
(b) The origin of the radial coordinates is the axial center of the 0.854964×0.854964 cm square cell.
(c) “Cell” refers to the boundary of the square cell in the array. Each surface of the cell is 0.427482 cm from the central axis of the cell.

All configurations include two 6.35 cm outside diameter 6061 aluminum tubes surrounded by polyethylene that function as dry wells for the assembly instrumentation. The inner diameter of the tubes is 5.715 cm. The bottom of each tube is closed by a 0.635 cm thick 6061 aluminum plate in contact with the lower grid plate. Each tube is surrounded by a polyethylene annulus 30.0228 cm tall with an inside diameter of 6.61162 cm and an outside diameter of 11.5189 cm. The bottom of the annulus is 0.762 cm above the lower grid plate. With the origin of the coordinate system at the center of the top surface of the lower grid plate and the z-axis aligned with the axis of the water cylinder, the axis of one of the dry wells is located at x=28.94 cm, y=6.4122 cm while the axis of the other is located at x=-28.94 cm, y=-6.4122 cm. Figure 40 shows an elevation view of the assembly with a cut-away view of one of the detector wells. Table 53 gives modeling details for the dry wells.

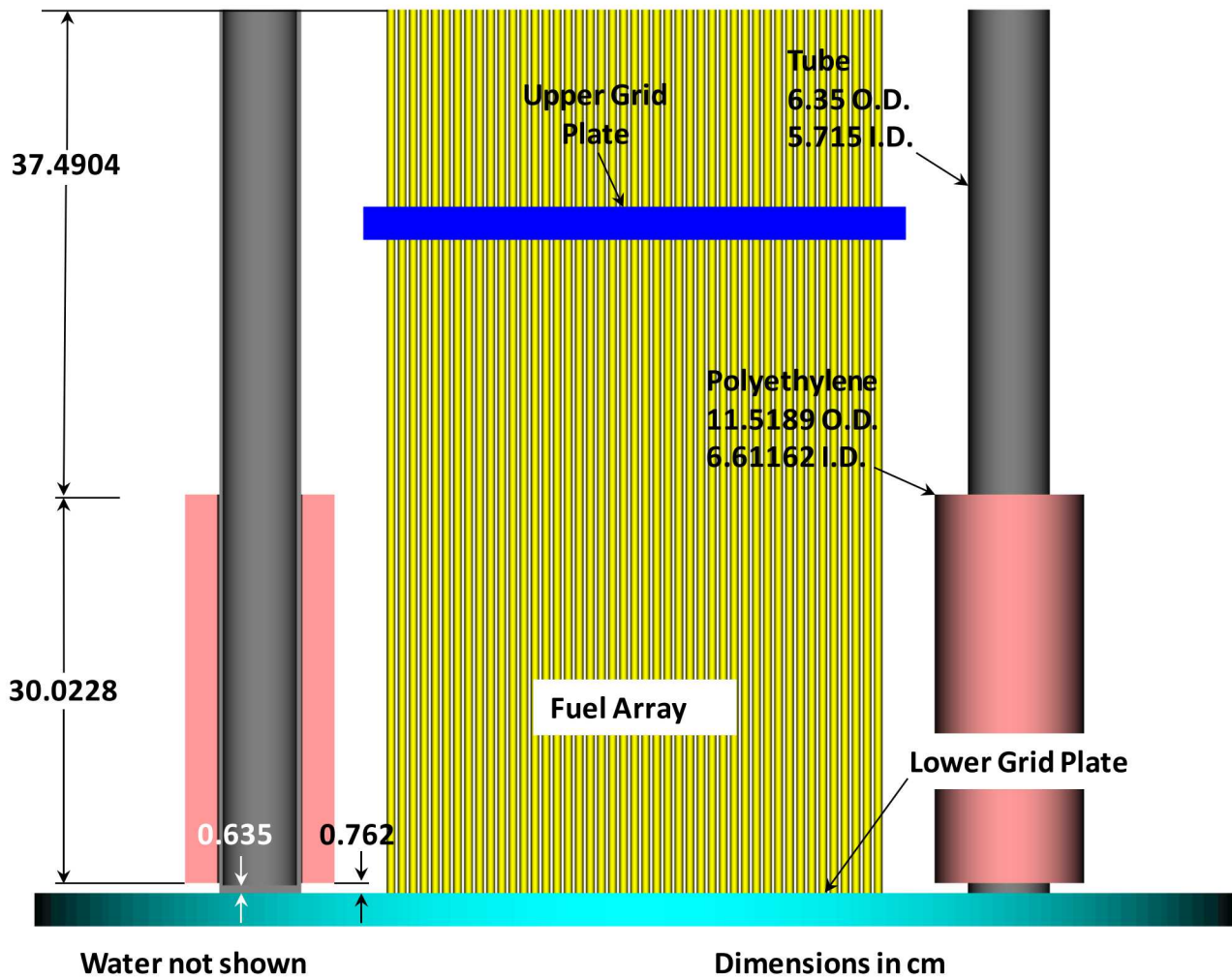


Figure 40. Elevation View of the Benchmark Model showing a Cut-Away View of One of the Detector Wells

Table 53. Axial and Radial Modeling Information for a Dry Well.

Position (cm)				Material
Axial ^(a)		Radial ^(b)		
From	To	From	To	
0.0	0.635	0.0	3.175	6061 Aluminum
0.635	0.762	0.0	2.8575	Void
		2.8575	3.175	6061 Aluminum
0.762	30.7848	0.0	2.8575	Void
		2.8575	3.175	6061 Aluminum
		3.175	3.30581	Water
		3.30581	5.75945	Polyethylene
30.7848	68.2752	0.0	2.8575	Void
		2.8575	3.175	6061 Aluminum

(a) The origin of the axial coordinates is the top of the lower grid plate.

(b) The origin of the radial coordinates is the axial center of the dry well

The layout of the fuel rods in the 45×45 array in Cases 1 through 22 are shown in Figures 41 through 62.

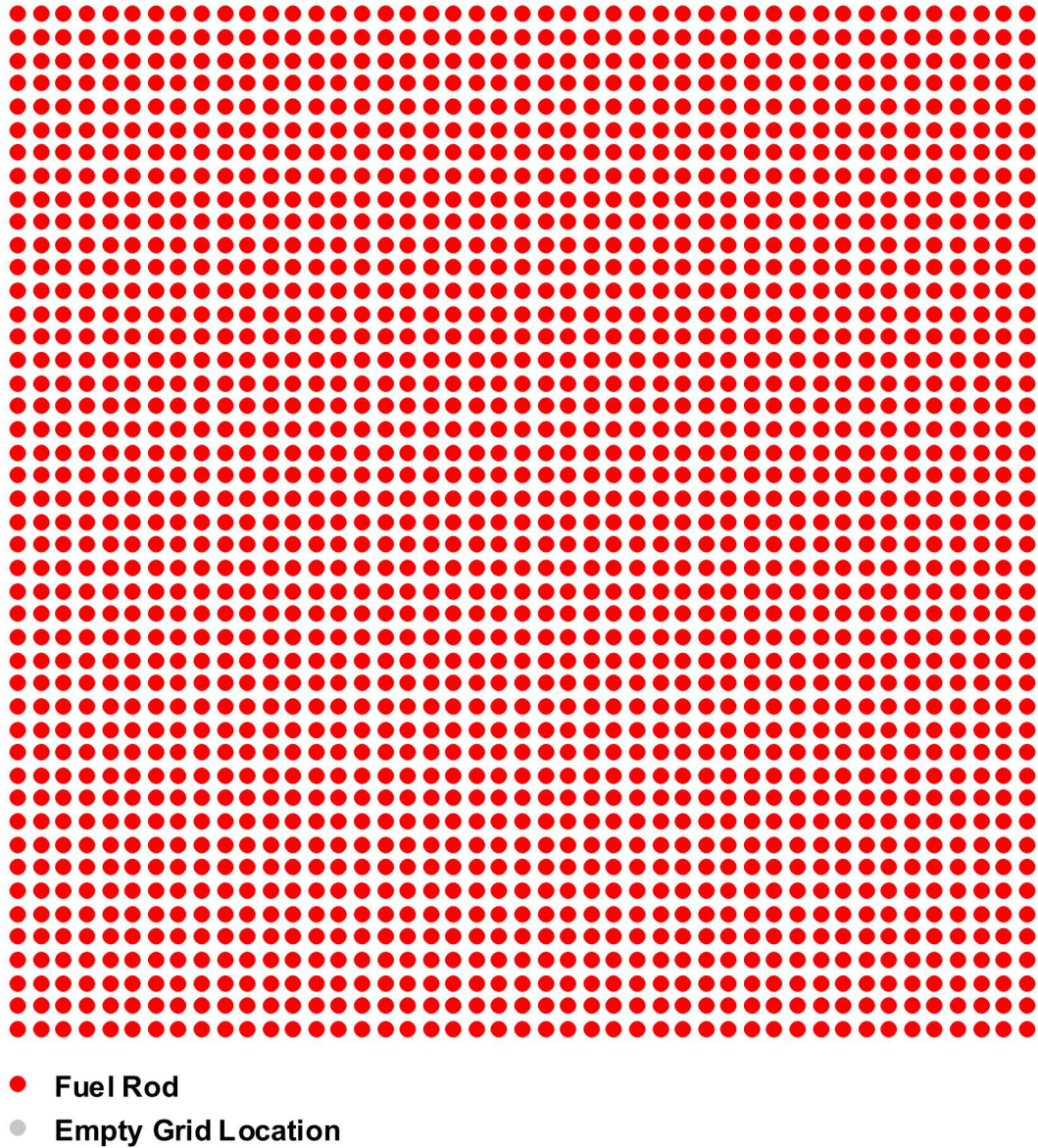


Figure 41. Fuel Rod Layout for Case 1 (2025 fuel rods).

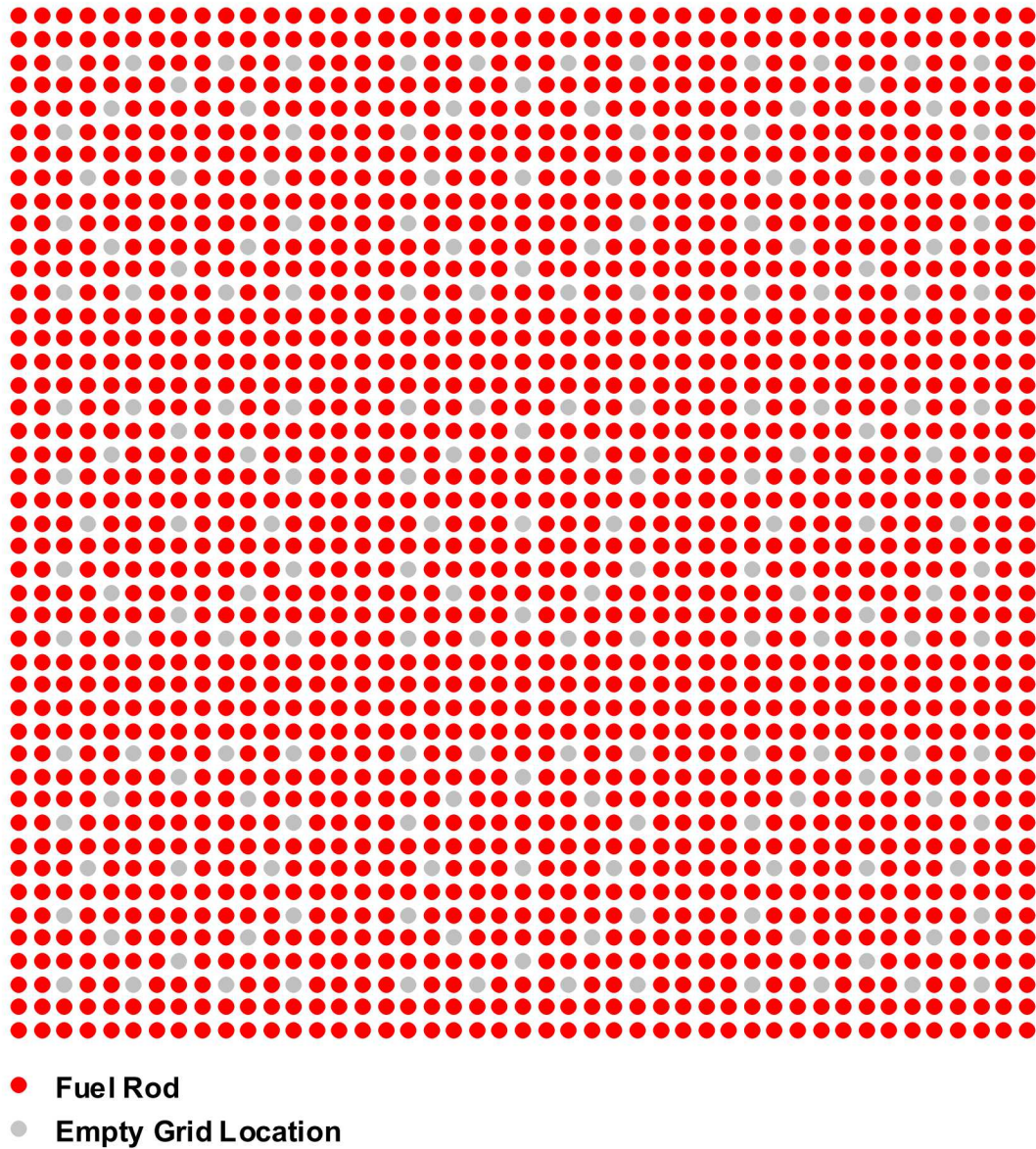


Figure 42. Fuel Rod Layout for Case 2 (1836 fuel rods).

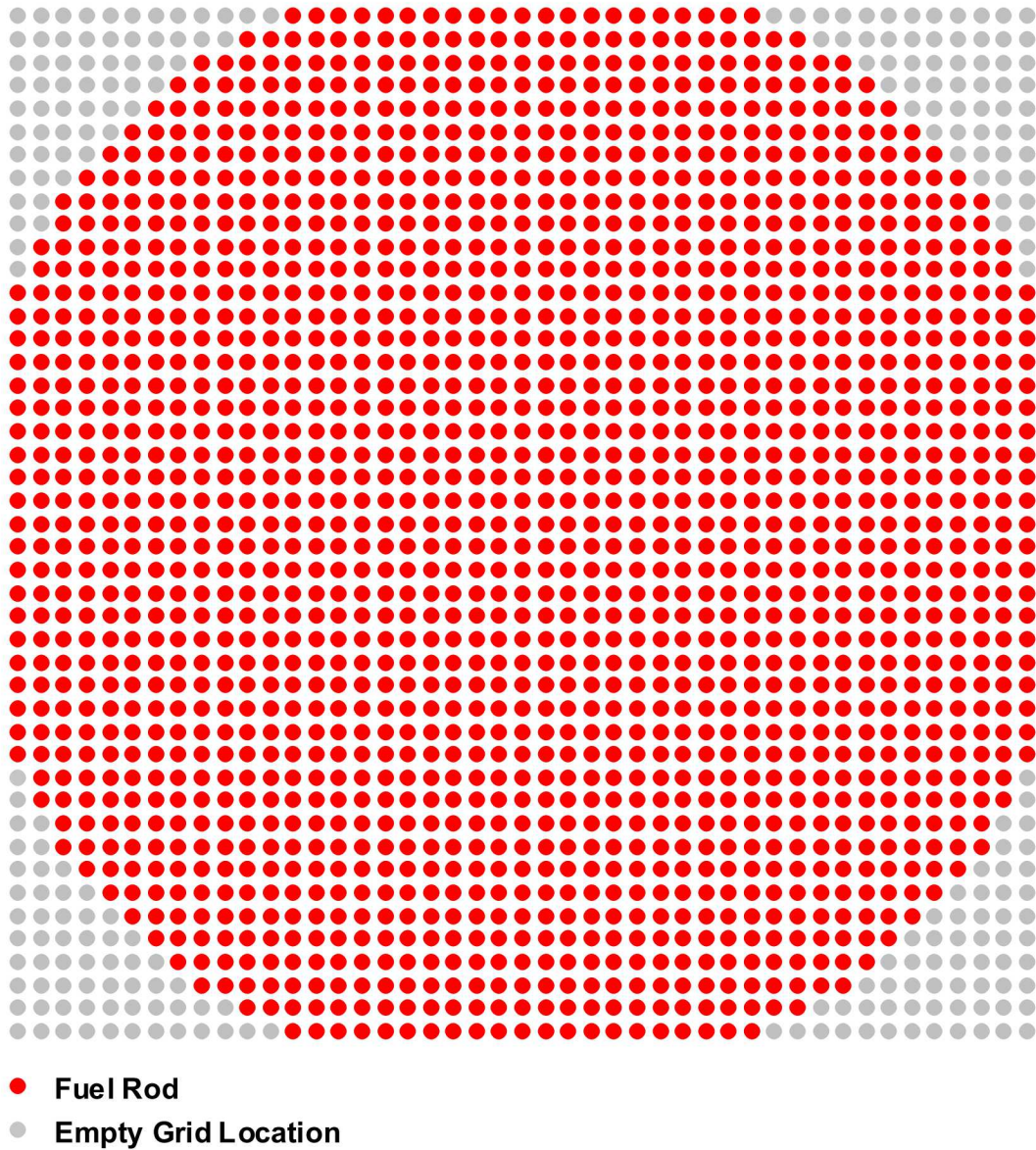


Figure 43. Fuel Rod Layout for Case 3 (1781 fuel rods).

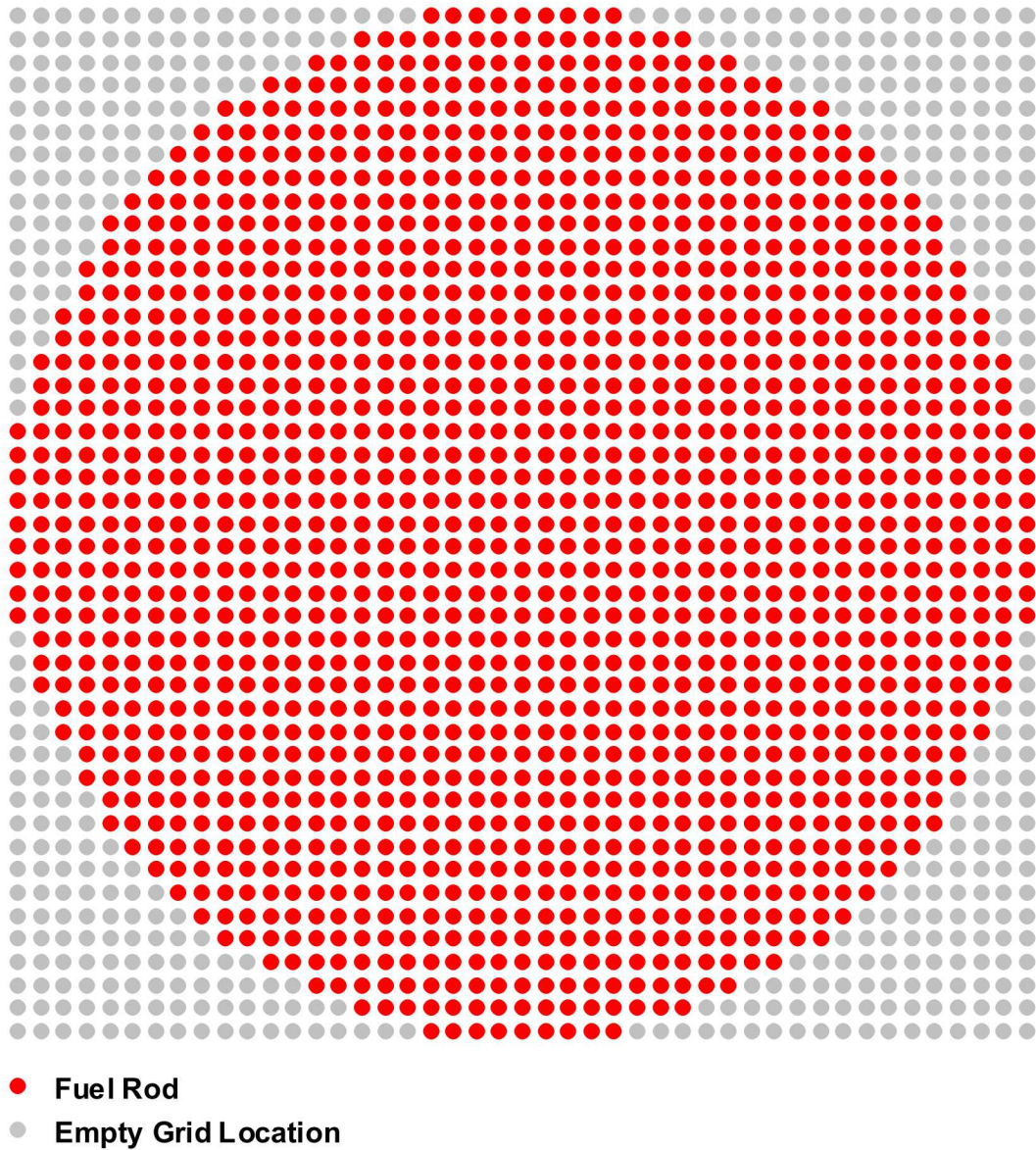


Figure 44. Fuel Rod Layout for Case 4 (1573 fuel rods).

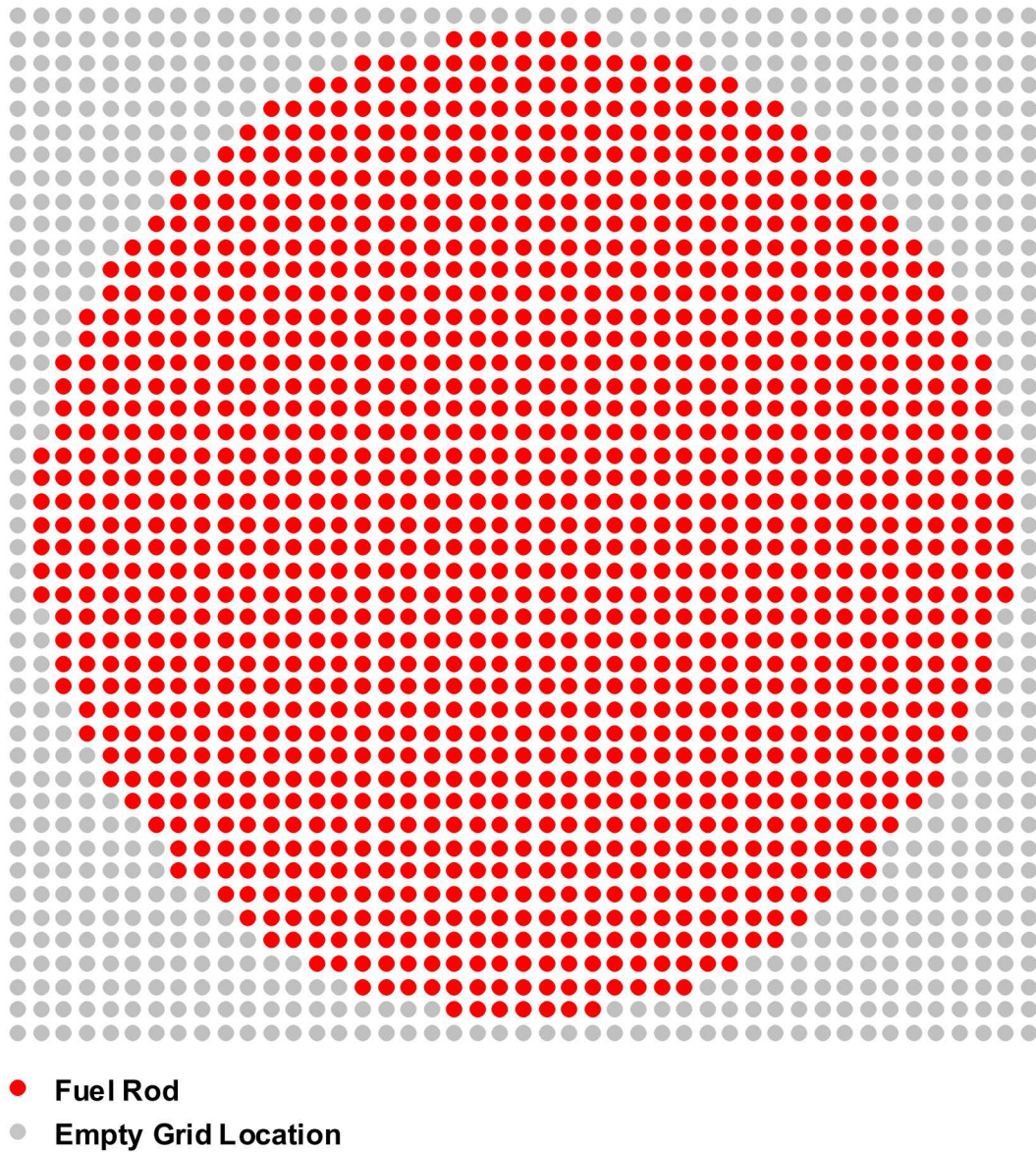


Figure 45. Fuel Rod Layout for Case 5 (1425 fuel rods).

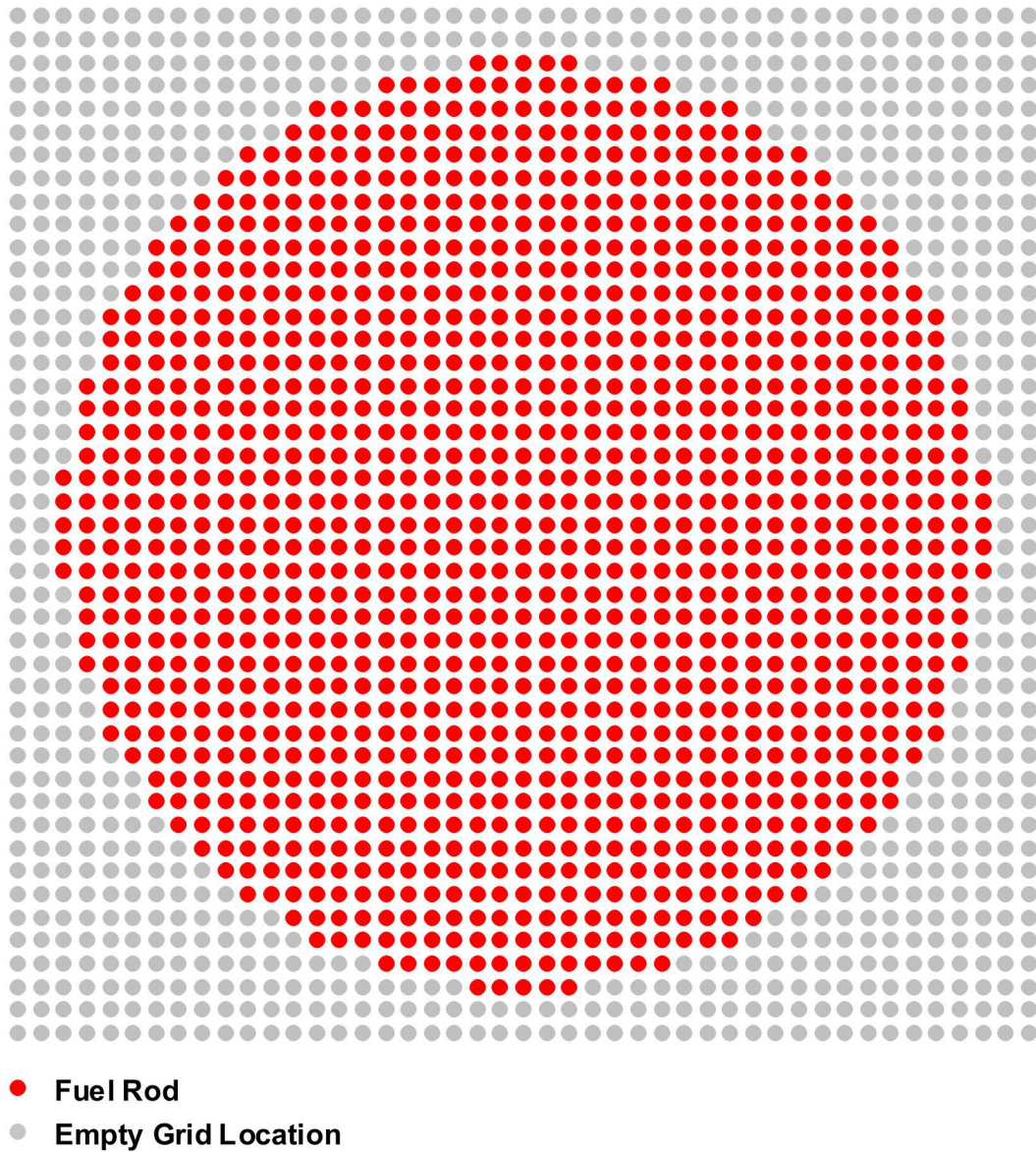


Figure 46. Fuel Rod Layout for Case 6 (1281 fuel rods).

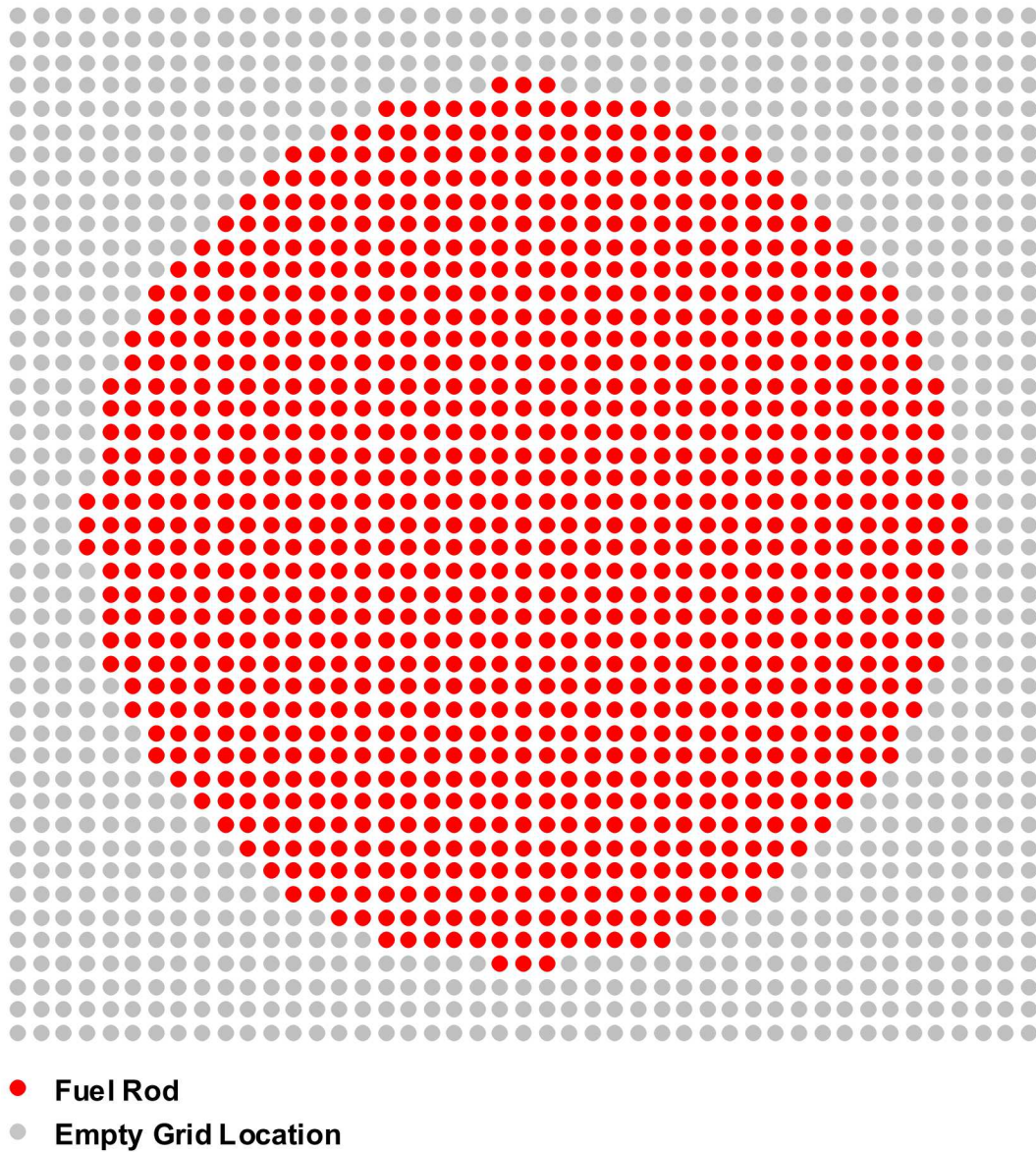


Figure 47. Fuel Rod Layout for Case 7 (1137 fuel rods).

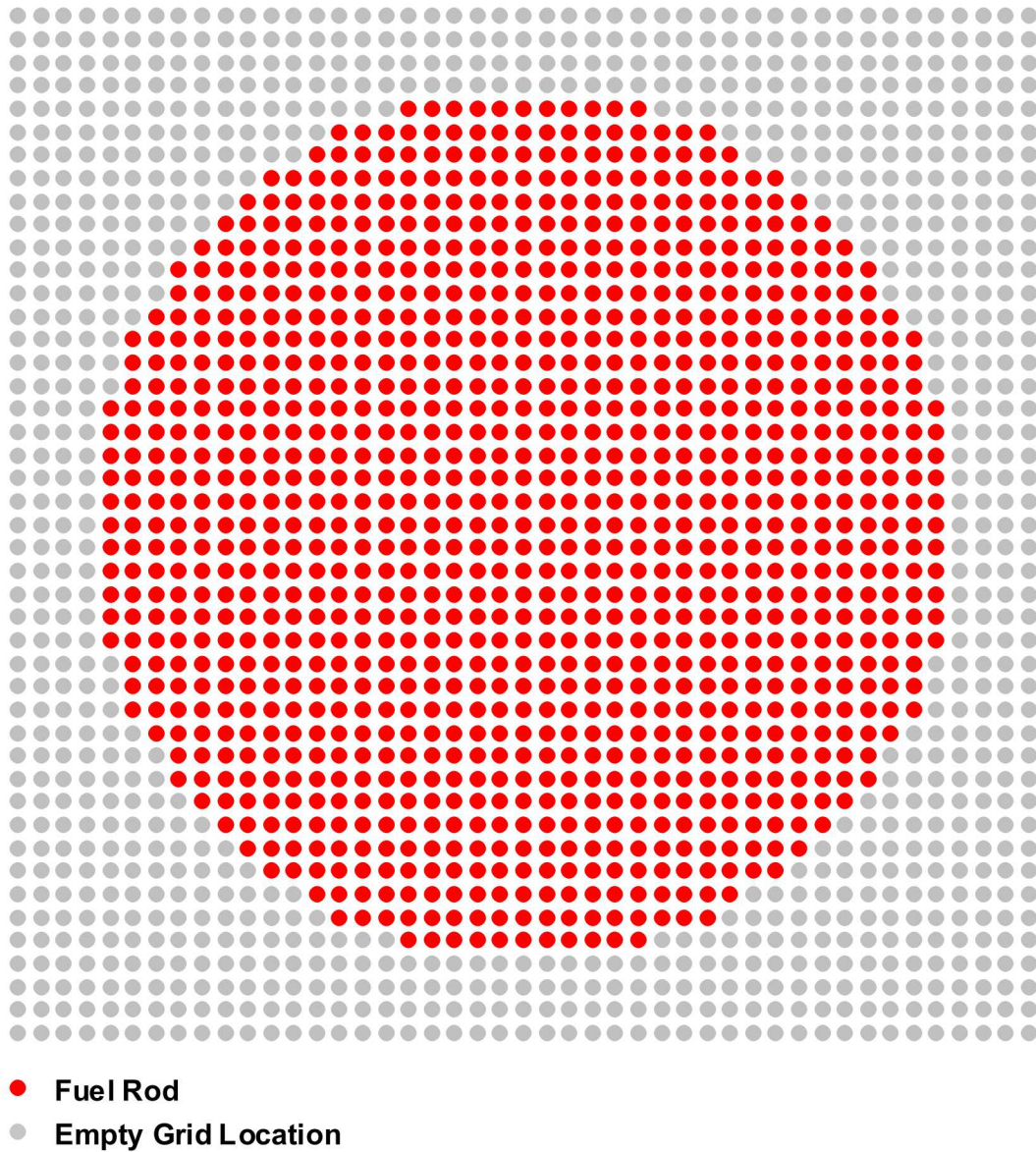


Figure 48. Fuel Rod Layout for Case 8 (1109 fuel rods).

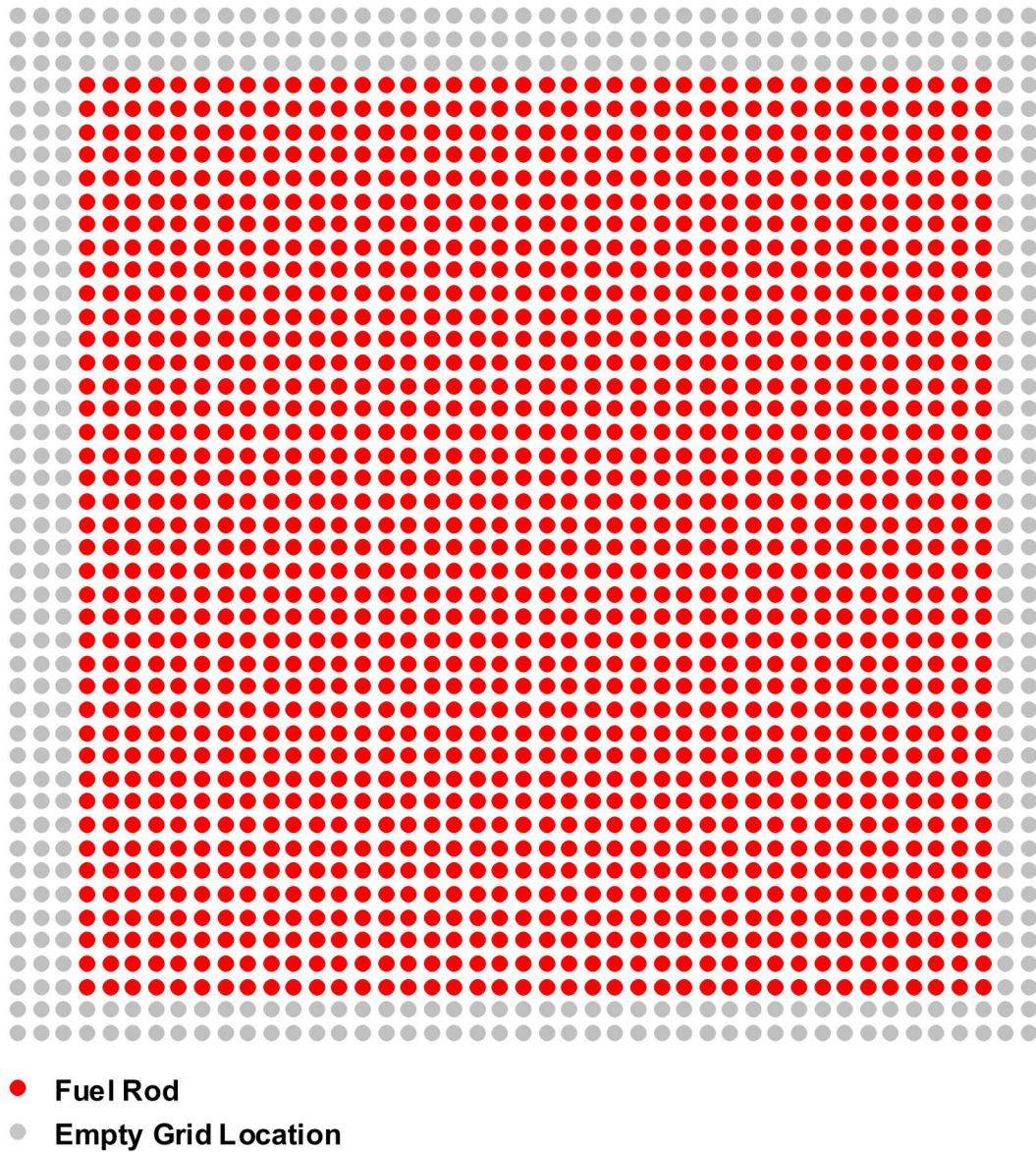


Figure 49. Fuel Rod Layout for Case 9 (1600 fuel rods).

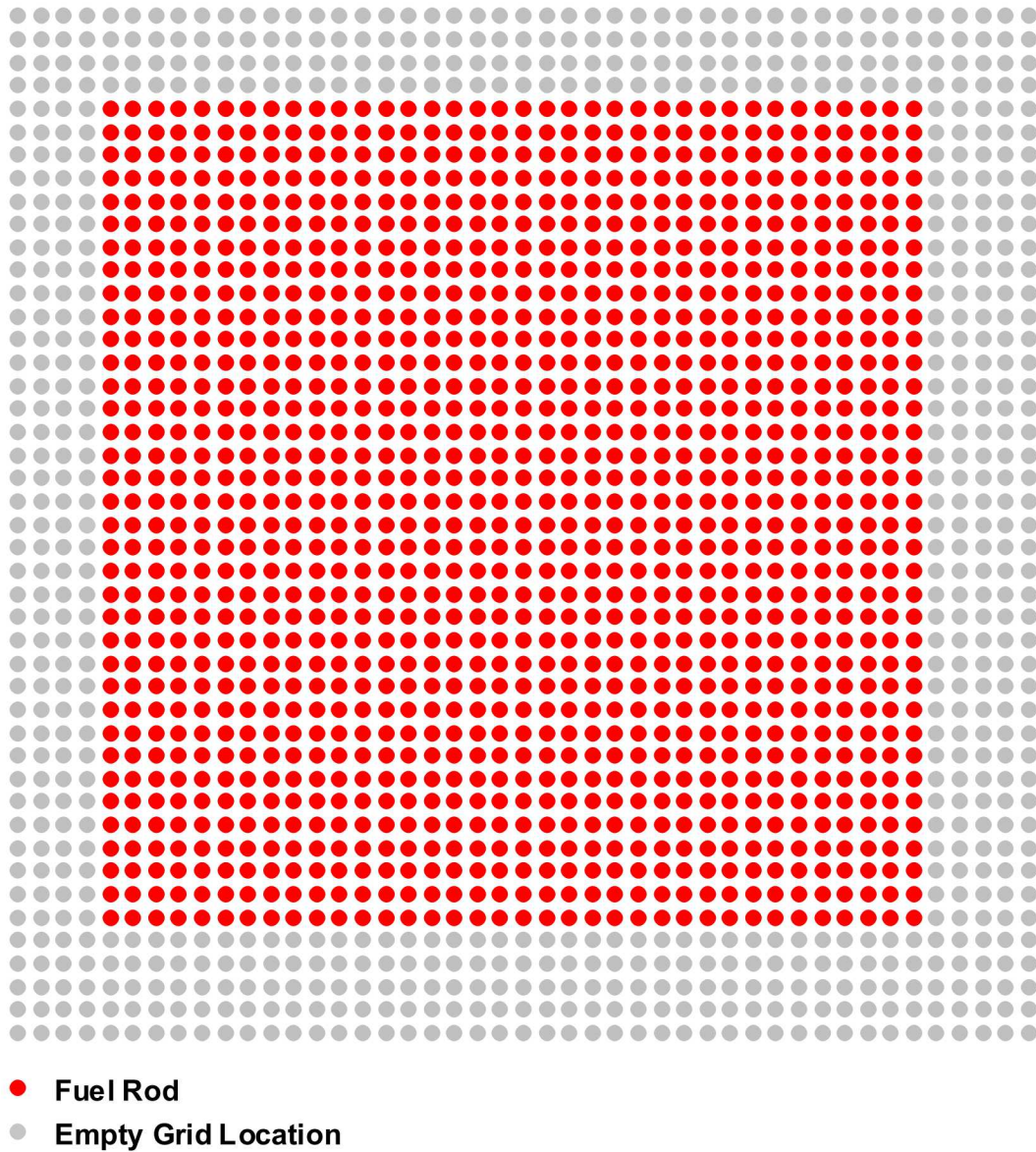


Figure 50. Fuel Rod Layout for Case 10 (1296 fuel rods).

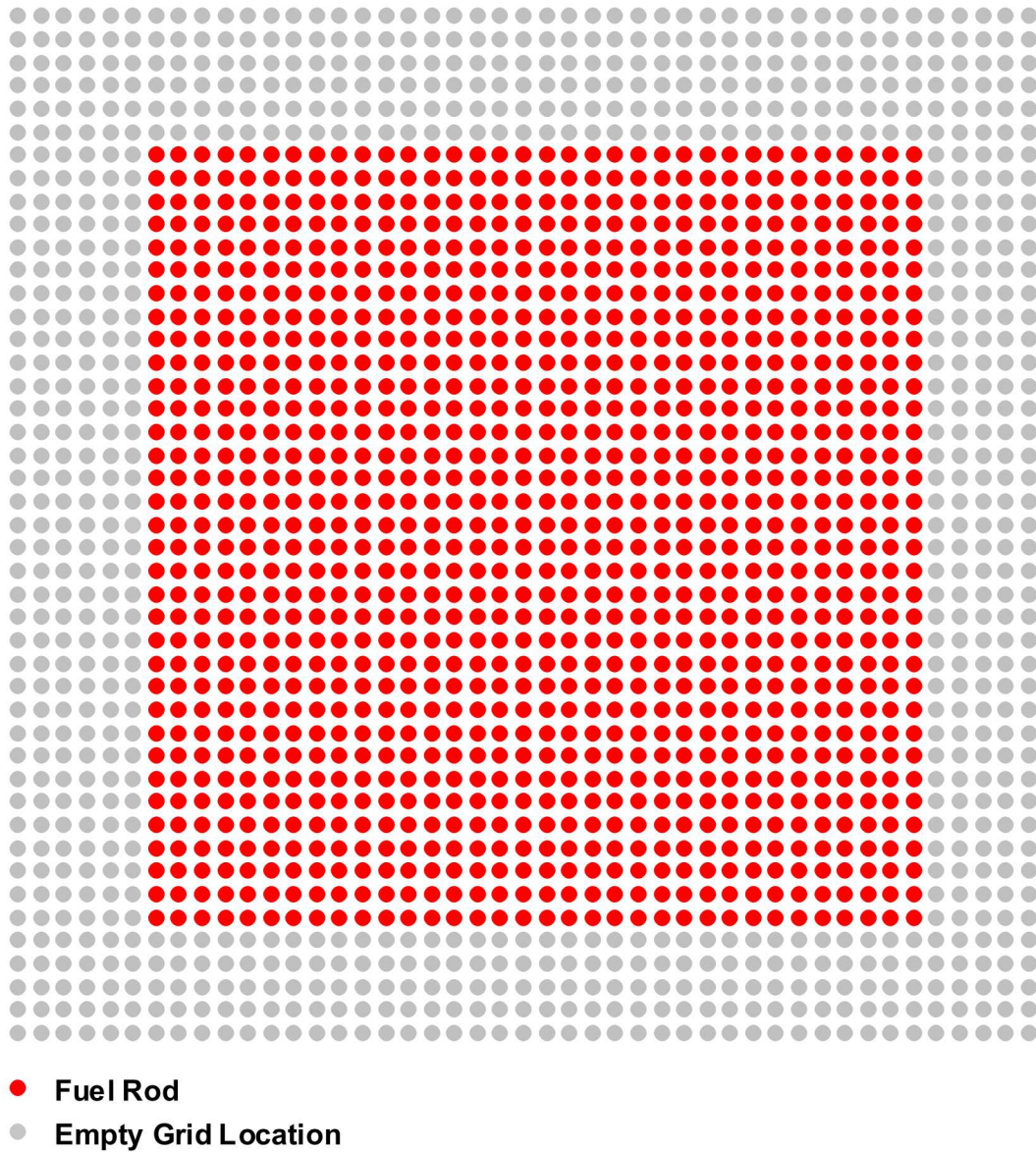


Figure 51. Fuel Rod Layout for Case 11 (1156 fuel rods).

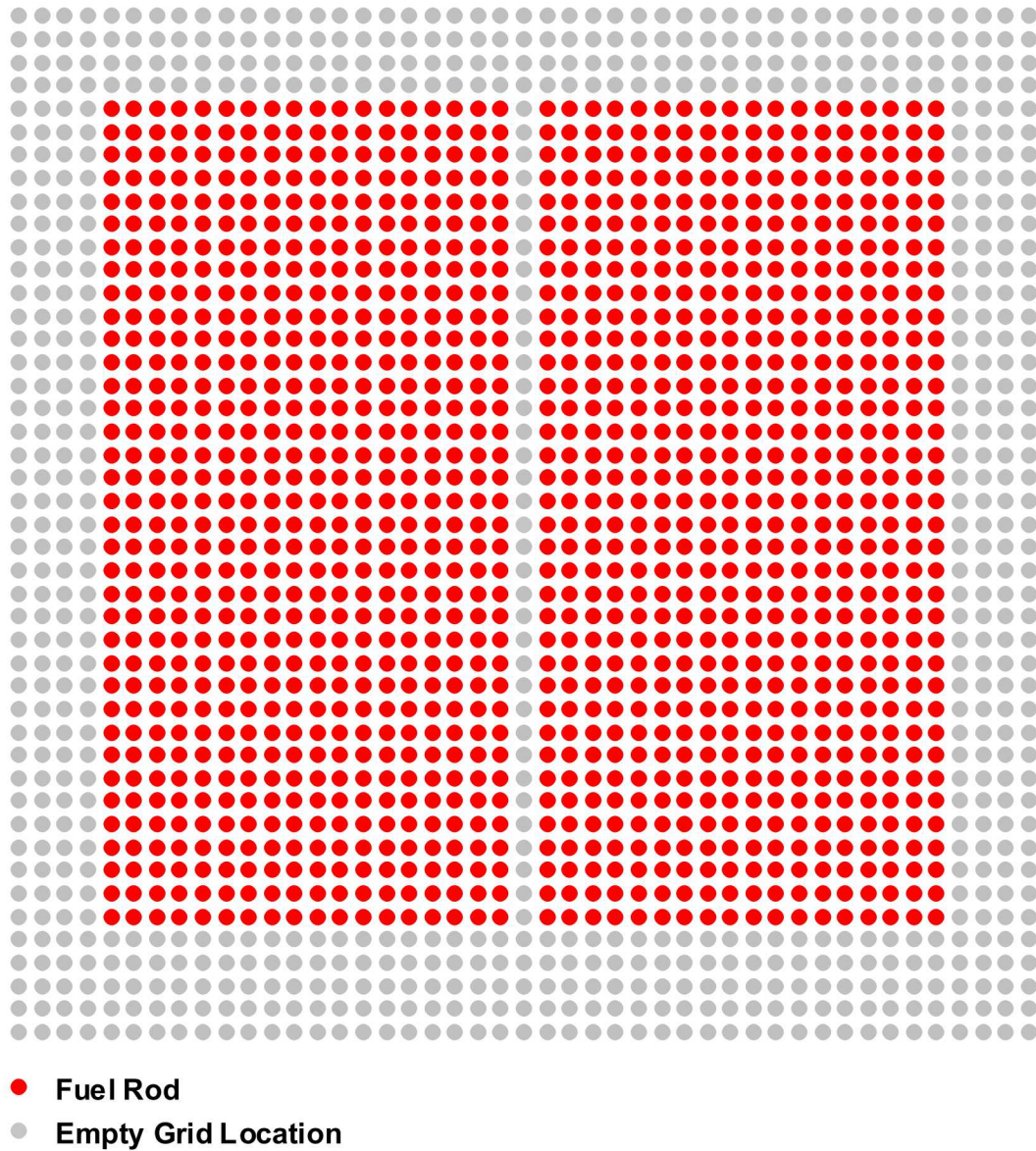


Figure 52. Fuel Rod Layout for Case 12 (1296 fuel rods).

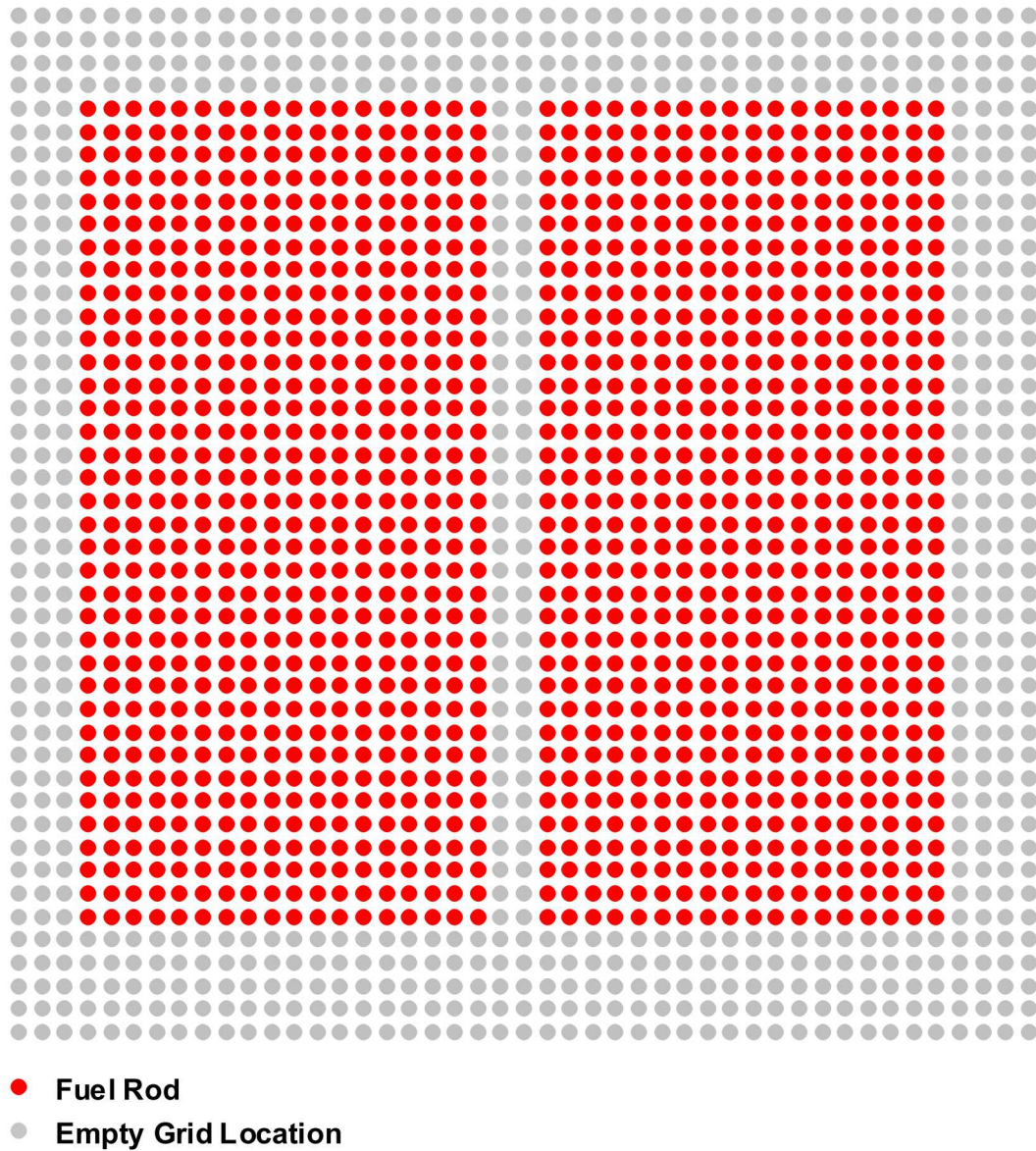


Figure 53. Fuel Rod Layout for Case 13 (1296 fuel rods).

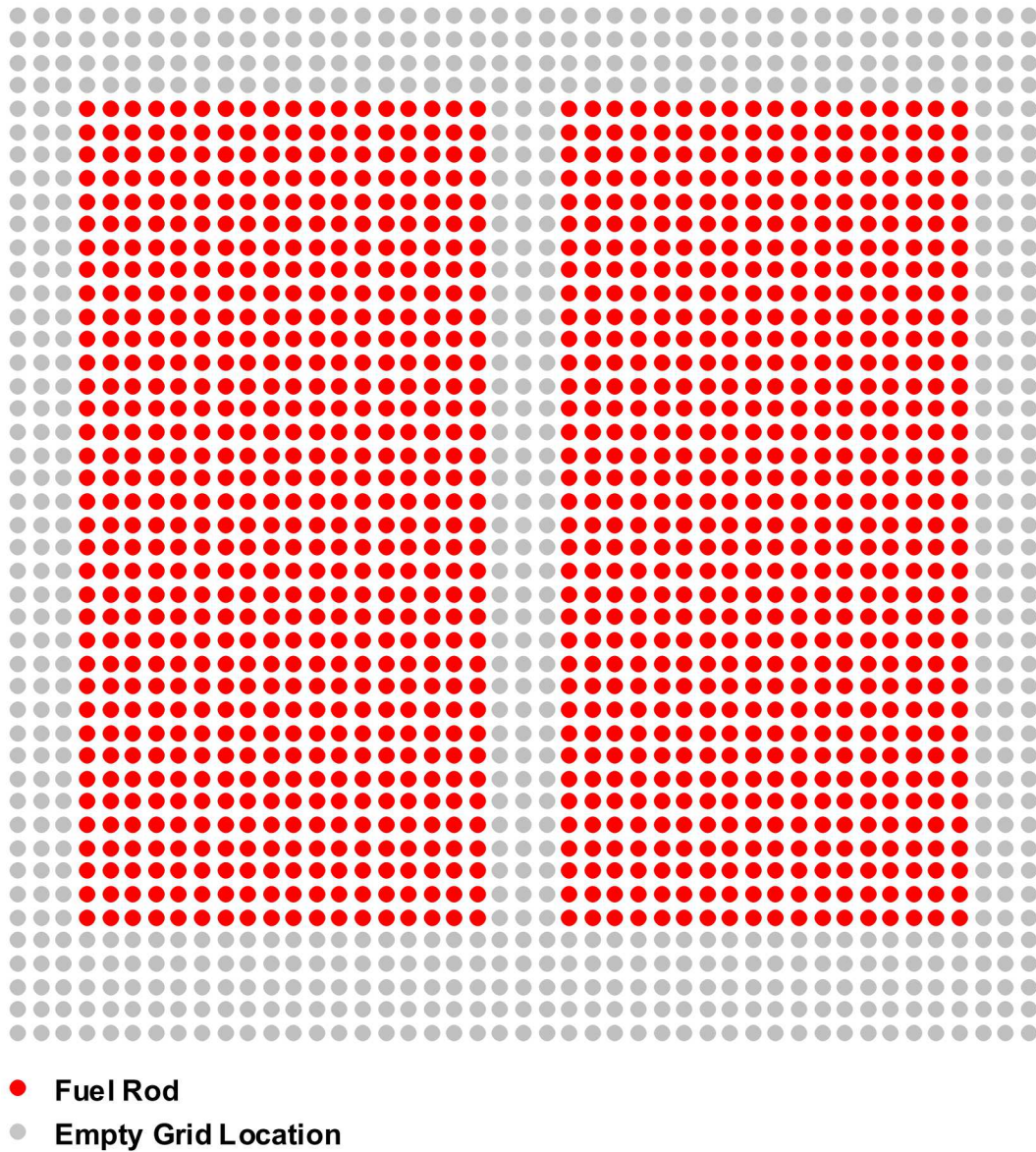


Figure 54. Fuel Rod Layout for Case 14 (1296 fuel rods).

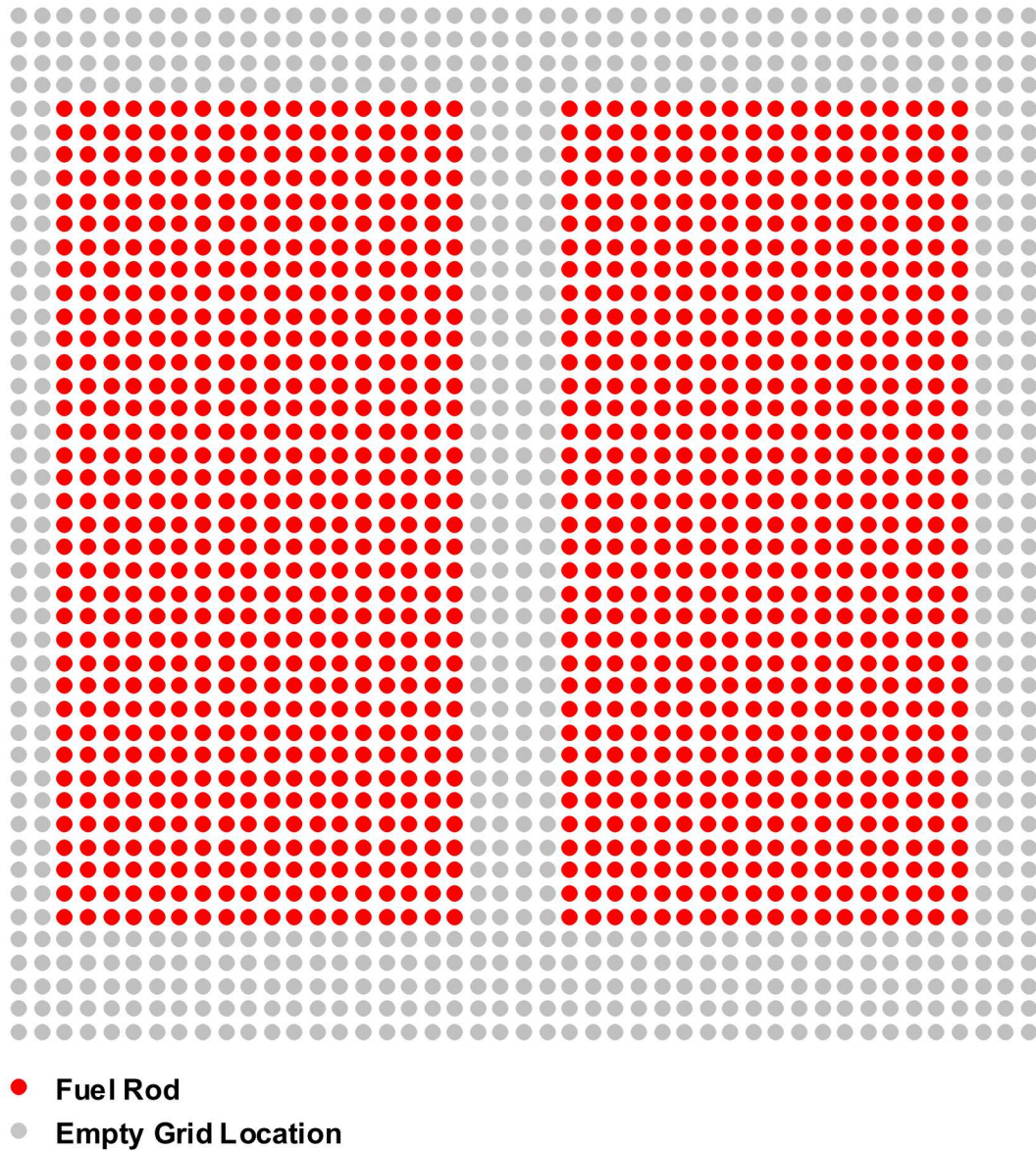


Figure 55. Fuel Rod Layout for Case 15 (1296 fuel rods).

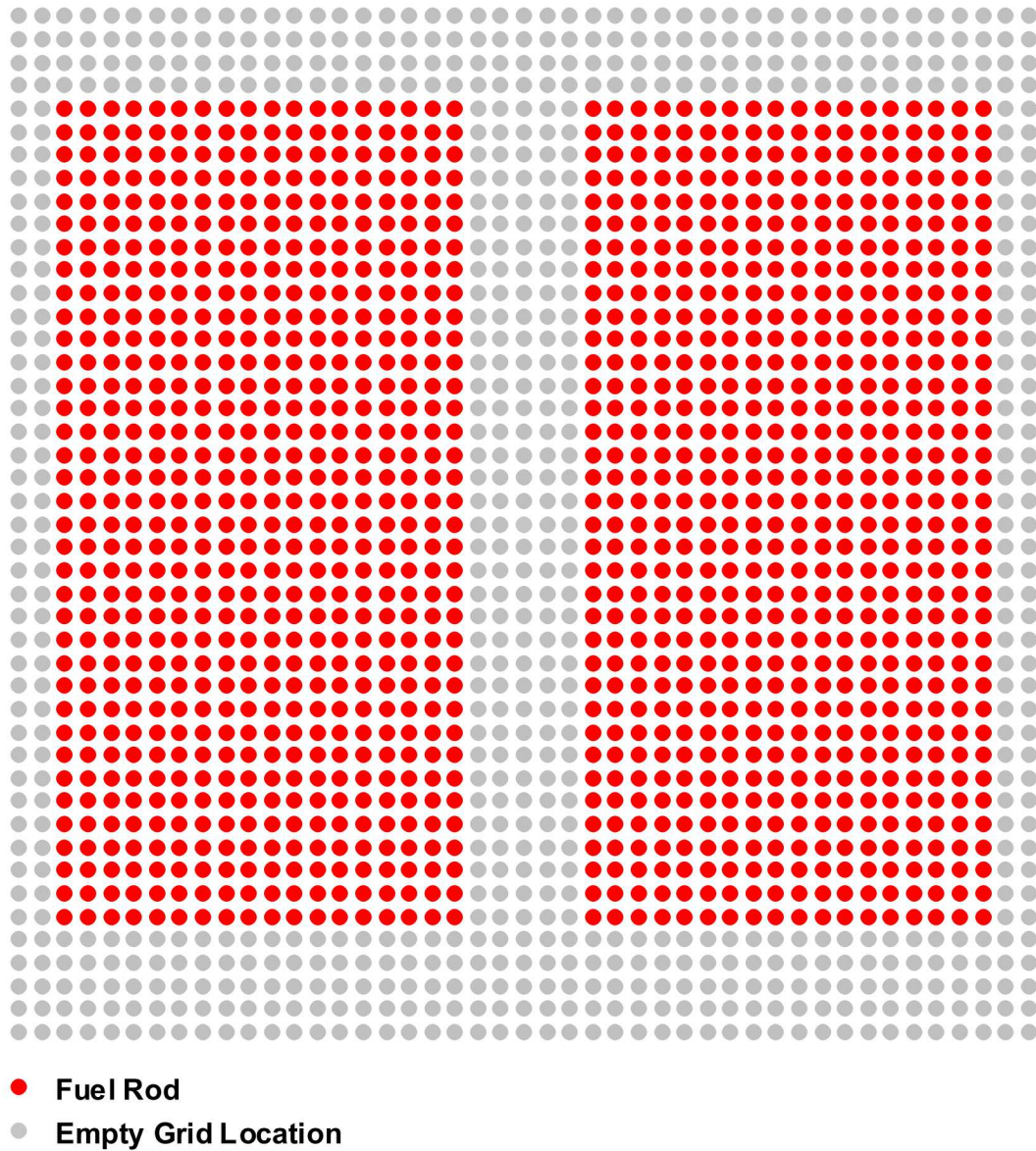


Figure 56. Fuel Rod Layout for Case 16 (1296 fuel rods).

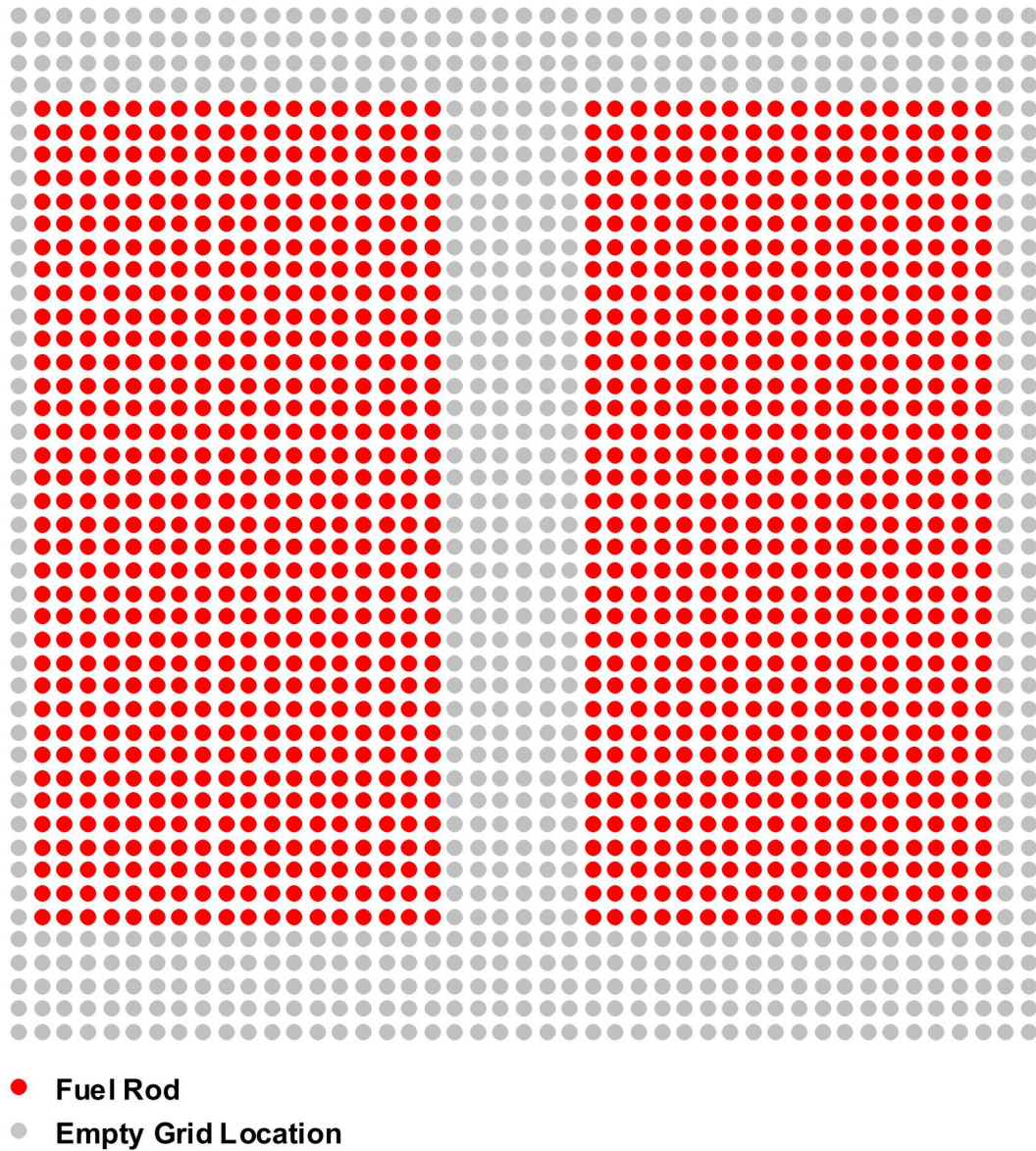


Figure 57. Fuel Rod Layout for Case 17 (1296 fuel rods).

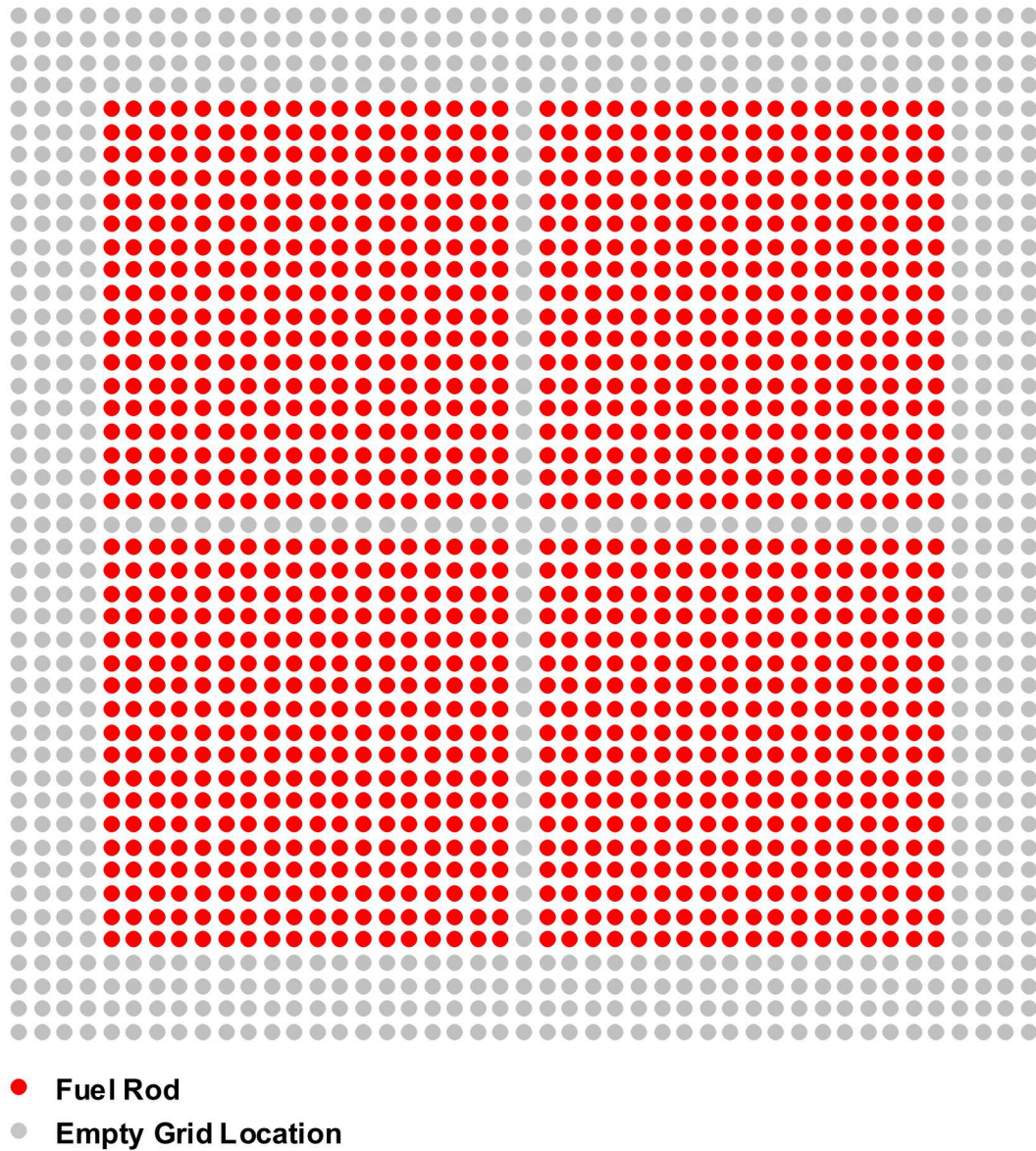


Figure 58. Fuel Rod Layout for Case 18 (1296 fuel rods).

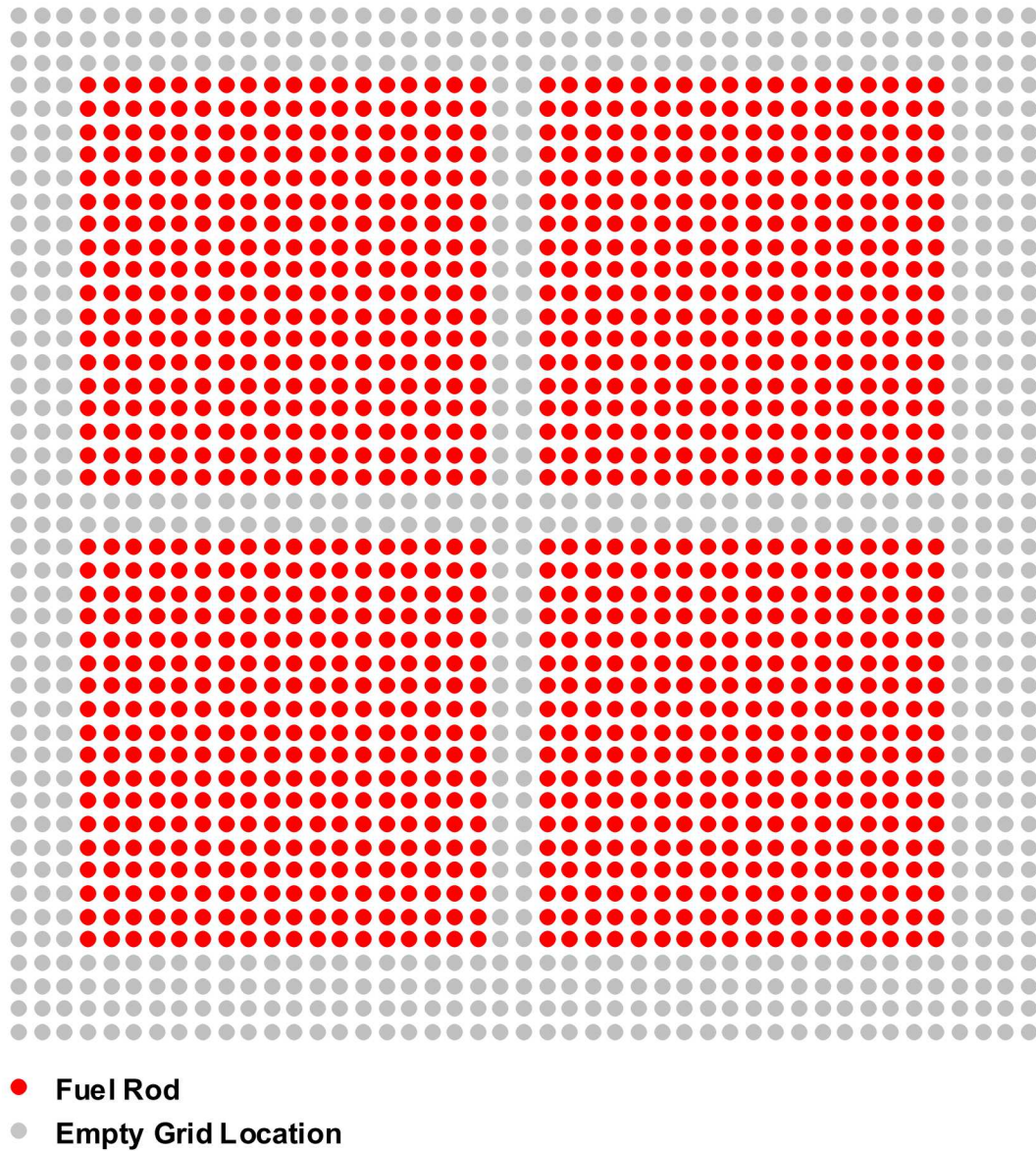


Figure 59. Fuel Rod Layout for Case 19 (1296 fuel rods).

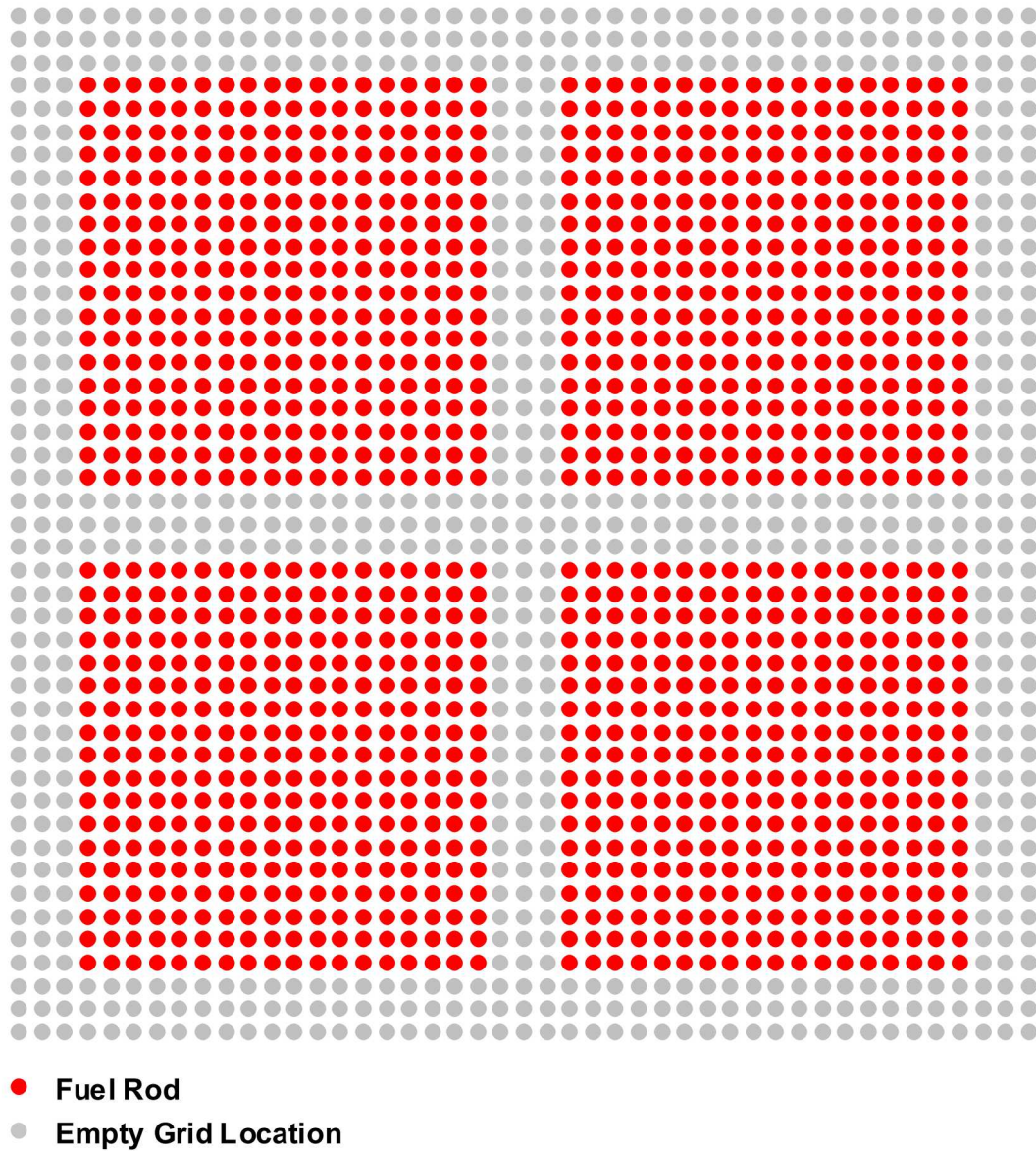


Figure 60. Fuel Rod Layout for Case 20 (1296 fuel rods).

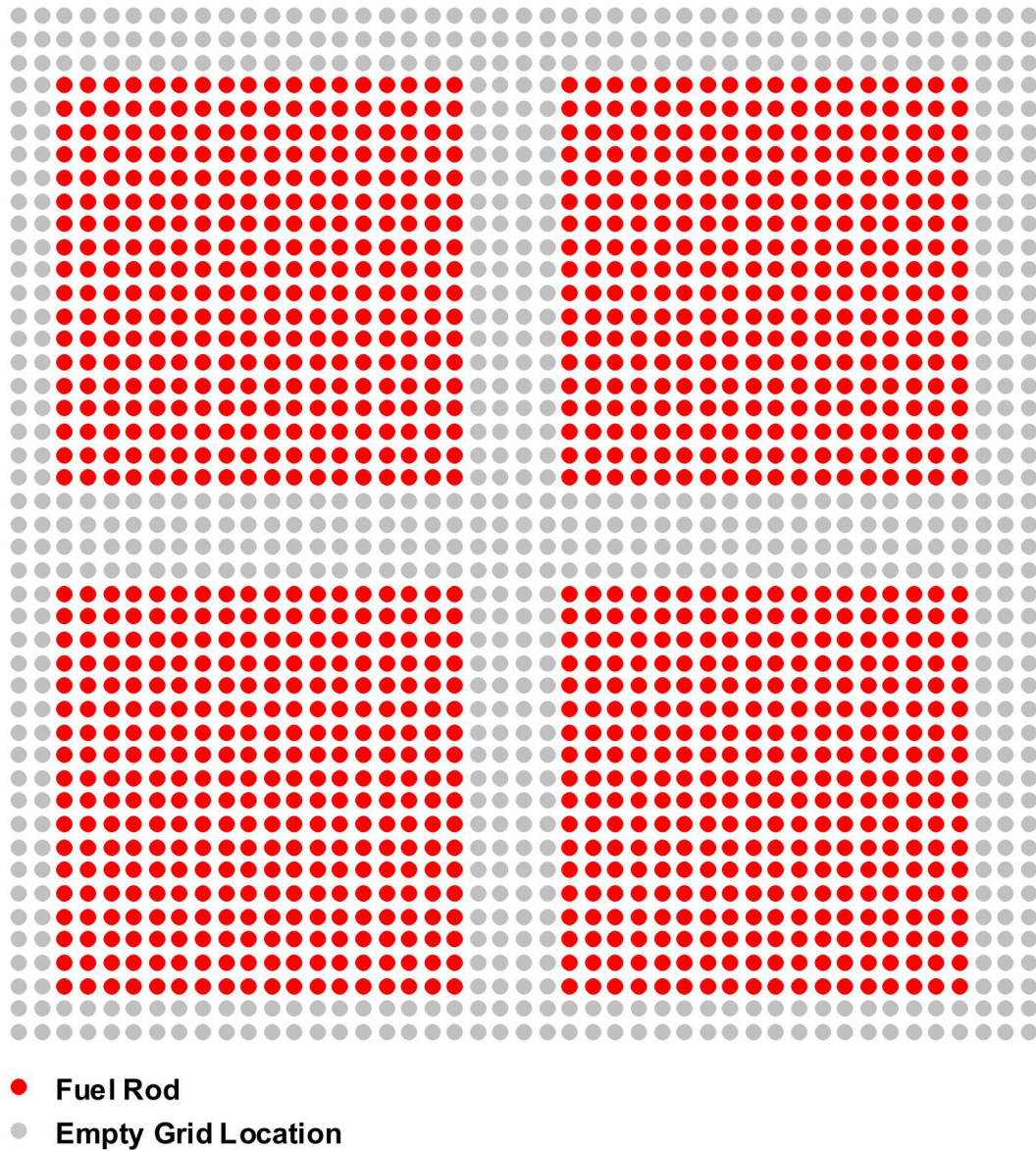


Figure 61. Fuel Rod Layout for Case 21 (1296 fuel rods).

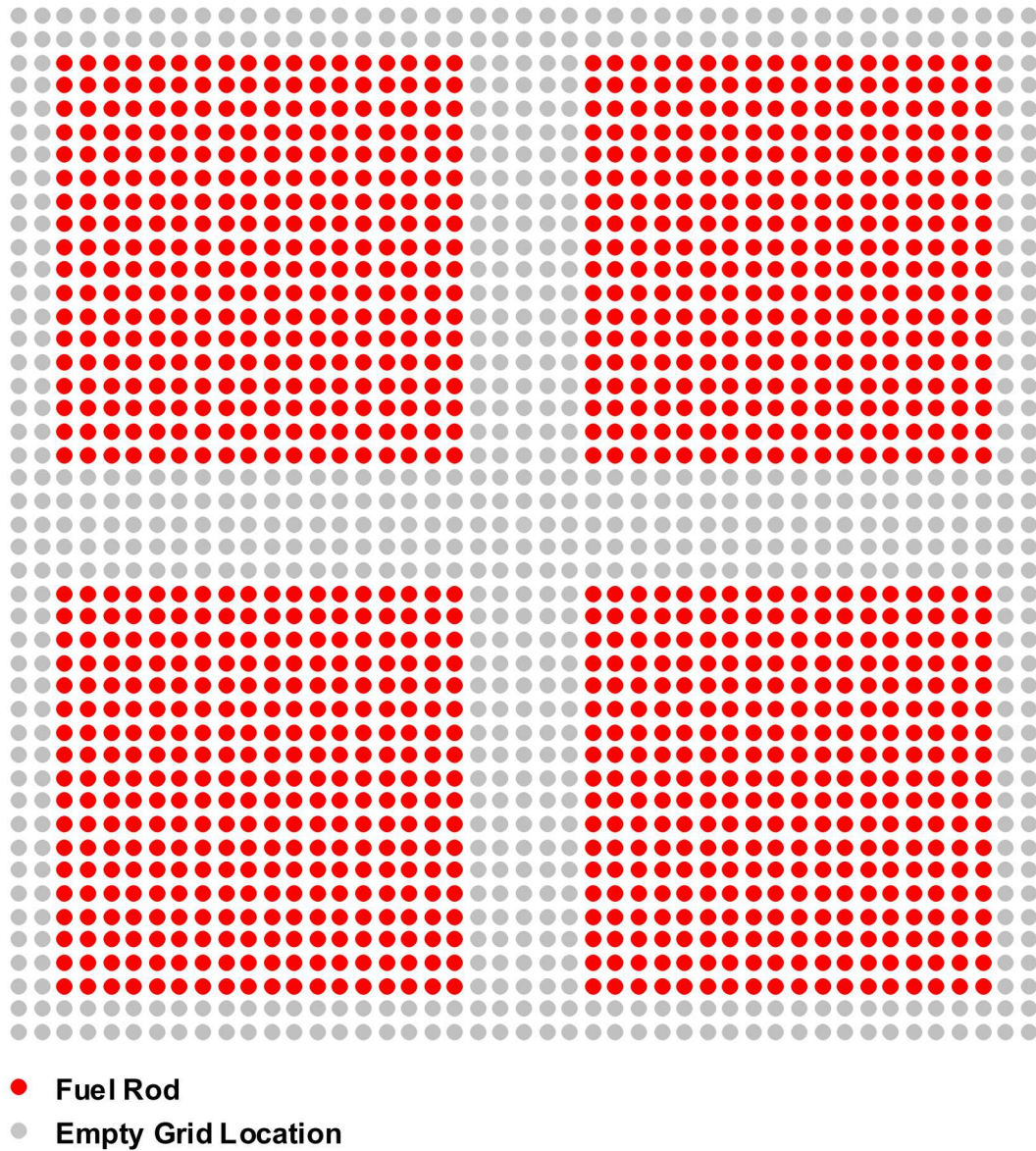


Figure 62. Fuel Rod Layout for Case 22 (1296 fuel rods).

3.3 Material Data

The atom densities for the materials in the benchmark models are listed in Table 54.

Table 54. Composition of the Materials in the Benchmark Models.

Material	Element or Isotope	Atom Number Density (barn ⁻¹ cm ⁻¹)
UO ₂ Fuel (108.7165 g of fuel [UO _{2.00} + impurities] in a cylinder 0.525628 cm diameter, 48.780 cm long)	²³⁴ U	6.5539E-06
	²³⁵ U	1.6010E-03
	²³⁶ U	1.4632E-05
	²³⁸ U	2.1296E-02
	O	4.5837E-02
	Ag	9.2319E-09
	B	2.3858E-07
	Cd	1.2380E-08
	Co	2.1620E-08
	Cr	2.5100E-06
	Cu	2.1316E-07
	Fe	1.0311E-05
	Mn	2.8372E-07
	Mo	1.2443E-07
	Ni	3.4989E-06
	V	1.4813E-08
	W	3.5998E-09
3003 Aluminum Cladding (2.73 g/cm ³) ^(a)	Al	5.9668E-02
	Si	1.7561E-04
	Fe	1.0303E-04
	Cu	3.2339E-05
	Mn	3.7407E-04
	Zn	1.2571E-05
Water (0.99705 g/cm ³) ^(b)	H	6.6659E-02
	O	3.3329E-02
6061 Aluminum Grid Plates (2.70 g/cm ³) ^(c) Also Used in Dry Well Tubes	Al	5.8376E-02
	Si	4.1683E-04
	Fe	1.8051E-04
	Cu	7.9320E-05
	Mn	2.6637E-05
	Mg	6.9574E-04
	Cr	6.2542E-05
	Zn	2.9839E-05
	Ti	6.7918E-06
	V	3.1918E-06

(a) Density from

<http://matweb.com/search/DataSheet.aspx?MatGUID=fd4a40f87d3f4912925e5e6ea5b1fbc40> accessed on May 29, 2012.

(b) This density is from the National Institute of Standards and Technology Chemistry WebBook, <http://webbook.nist.gov/chemistry/>.

(c) Density from

<http://matweb.com/search/DataSheet.aspx?MatGUID=1b8c06d0ca7c456694c7777d9e10be5b> accessed on May 29, 2012.

Table 54. Composition of the Materials in the Benchmark Models (continued).

Material	Element or Isotope	Atom Number Density (barn ⁻¹ cm ⁻¹)
304 Stainless Steel Springs (0.1923 g in an annulus 0.35052 cm ID, 0.45720 cm OD and 1.7152 cm tall)	Fe	1.2527E-02
	Cr	3.6455E-03
	Ni	1.5724E-03
	Mn	1.8160E-04
	C	3.3225E-05
	P	7.2471E-06
	S	4.6663E-06
	Si	1.7761E-04
Polyethylene in Fuel Rods (4.454 g in a cylinder 0.52578 cm OD and 21.2852 cm long) Also used in Dry Well Annuli	N	3.5613E-05
	H	8.2755E-02
	C	4.1377E-02

3.4 Temperature Data

The temperature of the moderator was maintained near 25°C. The critical data were corrected to 25°C as noted above. The model temperature is therefore 25°C.

3.5 Experimental and Benchmark-Model k_{eff}

The approach-to-critical experiments were done by varying the height of the moderator/reflector in the critical assembly. The projected critical moderator height was determined by extrapolation of inverse detector count rates from two moderator heights within a few millimeters of critical to zero. The experimental k_{eff} under the conditions of the experiment was thus 1.0000.

Several simplifications were made to the benchmark model. These simplifications resulted in a small reactivity bias in the benchmark model that is listed in Table 48. The reactivity bias in the benchmark model caused by the difference between the experiment temperatures listed in Table 8 and the benchmark model temperature of 25°C is listed in Table 49. The experiment uncertainties were estimated in Section 2.3. Table 55 summarizes these data and lists the benchmark model k_{eff} and its uncertainty.

Table 55. Simplification Bias, Temperature Correction, Experiment Uncertainty, and Benchmark-Model k_{eff} and Uncertainty for the Twenty Two Cases.

Case	Simplified Model Reactivity Bias ^(a)		Temperature Correction Reactivity ^(b)		Experiment Uncertainty ^(c)	Benchmark Model k_{eff}	
	Value	σ	Value	σ		Value ^(d)	σ ^(e)
1	-0.00041	0.00002	-0.00001	0.00000	0.00130	0.99958	0.00130
2	-0.00032	0.00002	0.00002	0.00000	0.00111	0.99970	0.00111
3	-0.00030	0.00002	-0.00010	0.00000	0.00116	0.99960	0.00116
4	-0.00020	0.00002	0.00000	0.00000	0.00116	0.99980	0.00116
5	-0.00015	0.00002	-0.00009	0.00000	0.00107	0.99976	0.00107
6	-0.00013	0.00002	-0.00003	0.00000	0.00105	0.99984	0.00105
7	-0.00008	0.00002	0.00000	0.00000	0.00103	0.99992	0.00103
8	-0.00008	0.00002	-0.00005	0.00000	0.00103	0.99987	0.00103
9	-0.00021	0.00002	-0.00010	0.00000	0.00117	0.99969	0.00117
10	-0.00013	0.00002	-0.00005	0.00000	0.00107	0.99982	0.00107
11	-0.00012	0.00002	-0.00004	0.00000	0.00107	0.99984	0.00107
12	-0.00002	0.00002	-0.00003	0.00000	0.00105	0.99995	0.00105
13	-0.00007	0.00002	-0.00002	0.00000	0.00095	0.99991	0.00096
14	-0.00011	0.00002	0.00000	0.00000	0.00089	0.99989	0.00089
15	-0.00009	0.00002	0.00000	0.00000	0.00081	0.99991	0.00081
16	-0.00012	0.00002	-0.00002	0.00000	0.00075	0.99986	0.00075
17	-0.00016	0.00002	0.00000	0.00000	0.00070	0.99984	0.00070
18	-0.00006	0.00002	-0.00002	0.00000	0.00103	0.99992	0.00103
19	-0.00008	0.00002	-0.00001	0.00000	0.00090	0.99991	0.00090
20	-0.00016	0.00002	0.00002	0.00000	0.00071	0.99986	0.00071
21	-0.00015	0.00002	0.00004	0.00000	0.00060	0.99989	0.00060
22	-0.00019	0.00002	-0.00002	0.00000	0.00053	0.99979	0.00053

(a) From Table 48.

(b) From Table 49.

(c) From Table 47.

(d) The benchmark model k_{eff} is obtained from the experiment k_{eff} (1.0000) and the two biases listed in the table.

(e) The uncertainty in the benchmark model k_{eff} is the sum in quadrature of the uncertainty in the simplification bias, the uncertainty in the temperature correction, and the experiment uncertainty.

4.0 RESULTS OF SAMPLE CALCULATIONS

The results of sample calculations using KENO V.a and MCNP6 for the twenty-two cases are shown in Table 56. The input listings used in some of the calculations are shown in Appendix A.

Table 56. Sample Calculation Results (United States).

Code (Cross Section Set) → Case ↓	KENO V.a (252-group ENDF/B-VII.1 SCALE6.2 Library)		KENO V.a (Continuous-Energy ENDF/B-VII.1 SCALE6.2 Library)		MCNP 6.1.1 (Continuous-Energy ENDF/B-VII.1)	
	k _{eff}	σ	k _{eff}	σ	k _{eff}	σ
1	0.99914	0.00018	1.00017	0.00020	1.00037	0.00020
2	0.99941	0.00021	1.00027	0.00018	1.00040	0.00019
3	0.99833	0.00021	0.99925	0.00020	0.99945	0.00018
4	0.99793	0.00024	0.99924	0.00017	0.99956	0.00019
5	0.99802	0.00020	0.99944	0.00019	0.99932	0.00019
6	0.99736	0.00021	0.99909	0.00020	0.99899	0.00018
7	0.99767	0.00022	0.99919	0.00019	0.99876	0.00019
8	0.99795	0.00018	0.99873	0.00020	0.99859	0.00019
9	0.99806	0.00020	0.99945	0.00020	0.99920	0.00020
10	0.99792	0.00023	0.99921	0.00019	0.99931	0.00018
11	0.99665	0.00018	0.99894	0.00021	0.99806	0.00018
12	0.99799	0.00020	0.99899	0.00020	0.99870	0.00018
13	0.99809	0.00020	0.99950	0.00027	0.99922	0.00020
14	0.99849	0.00018	0.99947	0.00022	0.99914	0.00019
15	0.99810	0.00020	0.99877	0.00021	0.99853	0.00018
16	0.99804	0.00022	0.99859	0.00020	0.99823	0.00019
17	0.99769	0.00021	0.99838	0.00019	0.99780	0.00018
18	0.99872	0.00020	0.99954	0.00019	0.99949	0.00019
19	0.99872	0.00021	0.99943	0.00020	0.99913	0.00019
20	0.99940	0.00019	0.99940	0.00019	0.99923	0.00018
21	0.99864	0.00018	0.99878	0.00020	0.99806	0.00018
22	0.99814	0.00019	0.99815	0.00021	0.99761	0.00017

Figure 63 shows the reactivity offset ρ of the multigroup KENO V.a calculations, defined as

$$\rho = \frac{k_c - k_b}{k_c k_b},$$

where k_c is the calculated k_{eff} for the benchmark model of a given configuration and k_b is the evaluated benchmark model k_{eff} for the same configuration. The red error bars shown in the figure represent the uncertainty in the evaluated benchmark model k_{eff} . The smaller black error bars shown in the figure represent the stochastic uncertainties in the Monte Carlo calculations. Three of the twenty-two reactivity offsets fall within the uncertainty in the benchmark model k_{eff} of zero. The remaining nineteen fall below zero by more than the uncertainty in the benchmark model k_{eff} . The unweighted average reactivity offset for all cases is -0.0016.

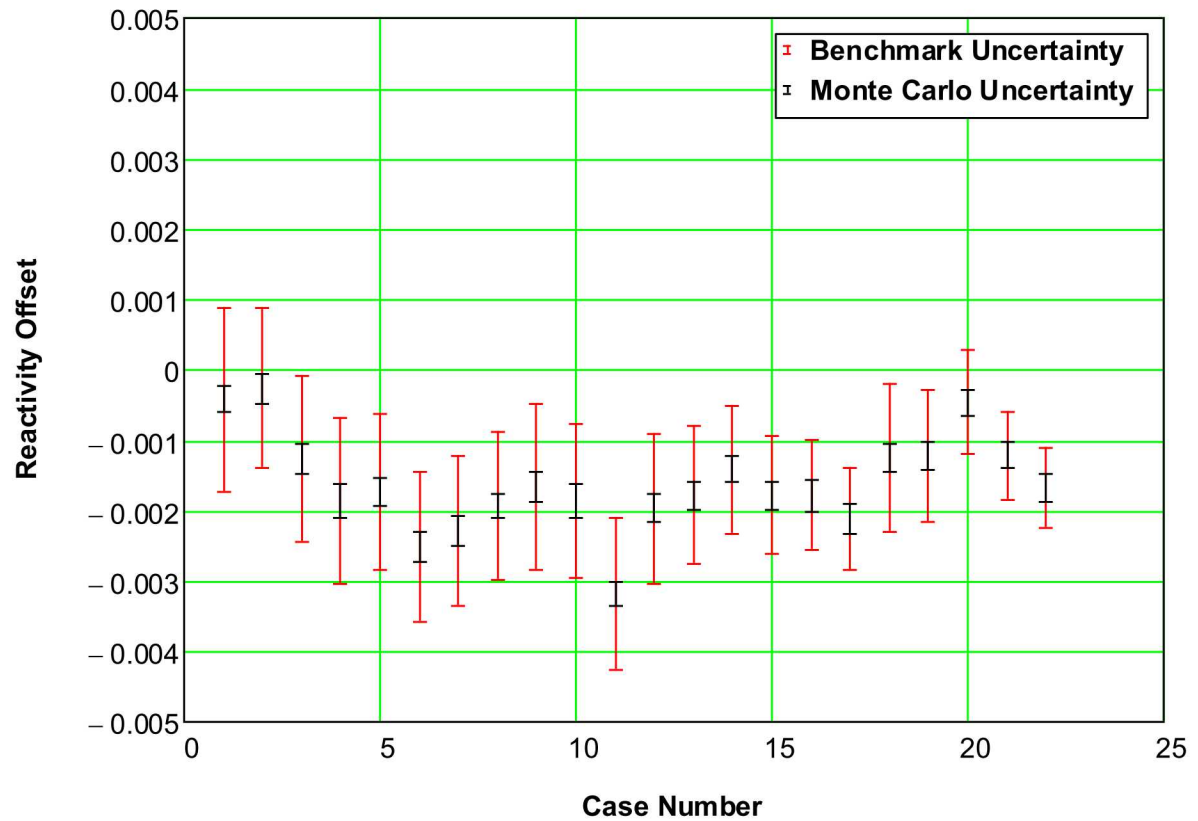


Figure 63. Reactivity Offset for KENO V.a Calculations Using Cross Sections from the 252-Group ENDF/B-VII.1 SCALE6.2 Library.

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Figure 64 shows the reactivity offset for the continuous-energy KENO V.a calculations. Sixteen of the twenty-two reactivity offsets fall within the uncertainty in the benchmark model k_{eff} of zero. The remaining six fall below zero by more than the uncertainty in the benchmark model k_{eff} . The unweighted average reactivity offset for all cases is -0.0006.

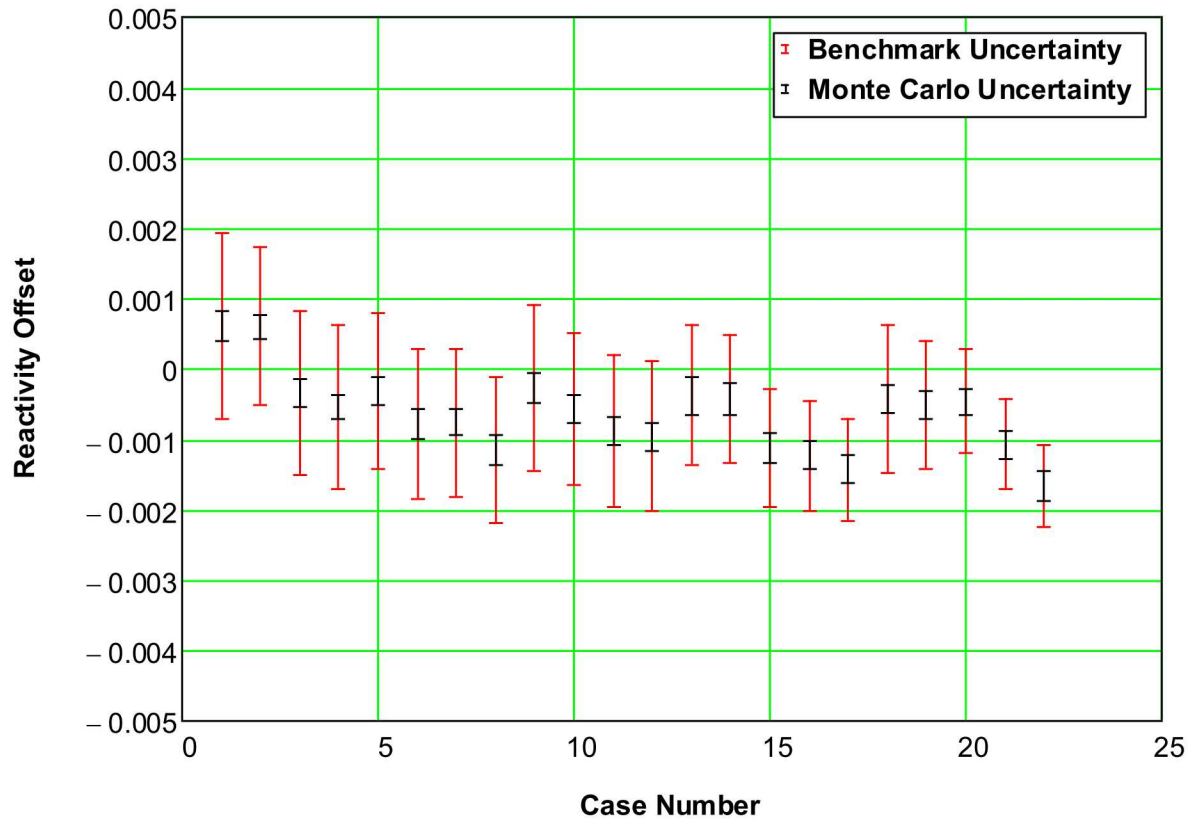


Figure 64. Reactivity Offset for KENO V.a Calculations Using Cross Sections from the Continuous-Energy ENDF/B-VII.1 SCALE6.2 Library.

Figure 65 shows the relative reactivity offset for the continuous-energy MCNP6.1.1 calculations. Thirteen of the twenty-two reactivity offsets fall within the uncertainty in the benchmark model k_{eff} of zero. The remaining nine fall below zero by more than the uncertainty in the benchmark model k_{eff} . The unweighted average reactivity offset for all cases is -0.0009.

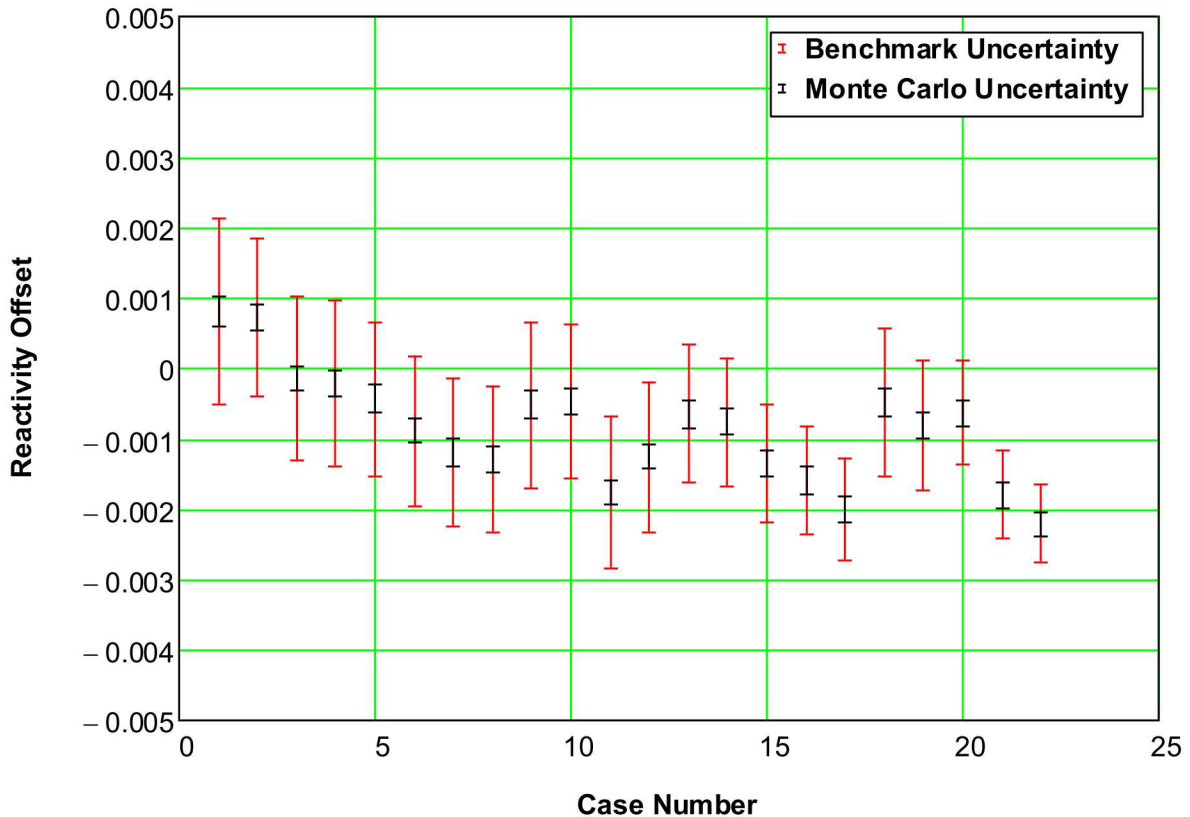


Figure 65. Reactivity Offset for MCNP6.1.1 Calculations using Continuous-Energy ENDF/B-VII.1 Cross Sections.

The results of MORET 5 calculations for the twenty-two cases are shown in Table 57. The MORET 5.D.1 calculations are run in one step. The input listings used in some of the calculations are shown in Appendix A.3 (MORET 5).

MORET 5 can be used in two calculation routes:

- Either coupled with the APOLLO2 deterministic code in a multi-group APOLLO2-MORET 5 route. It uses macroscopic cross sections from APOLLO2 and calculates k_{eff} through a 3D simulation,
- Or in a Monte Carlo MORET 5 continuous energy code. MORET uses cross sections in the ACE format processed with the GAIA code (based on NJOY 99.259 JEFF-3.1.1 and ENDF/B-VII.1 evaluations, and NJOY 2016.35 for the JEFF-3.3 and ENDF/B-VIII.0 evaluations) and performs the 3D simulation to determine k_{eff} .

The reported results are run with the continuous-energy MORET 5 code using various cross section libraries. The calculations were run with a minimum of 100 batches and a targeted Monte Carlo standard deviation of 0.00020.

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An example of input listing for Case 1 using the ENDF/B-VII.1 cross section set is provided in Appendix A. The number of batches is 5218 and the number of neutrons per batch is 4050.

A general good agreement with the benchmark k_{eff} is obtained since no significant tendency can be identified given the level of the experimental uncertainties. Similarly, no significant tendency versus cross sections library can be put forward.

Table 57. Sample Calculation Results (France).

Code (Cross Section Set) → Case ↓	Continuous Energy MORET 5.D.1 (ENDF/B-VII.1) ^(a)	Continuous Energy MORET 5.D.1 (ENDF/B-VIII.0) ^(a)	Continuous Energy MORET 5.D.1 (JEFF-3.1.1) ^(a)	Continuous Energy MORET 5.D.1 (JEFF-3.3) ^(a)
1	1.00082	0.99922	1.00094	1.00264
2	1.00203	1.00064	1.00185	1.00286
3	1.00048	0.99944	1.00072	1.00208
4	1.00040	0.99931	1.00065	1.00241
5	1.00006	0.99891	1.00004	1.00122
6	1.00020	0.99807	0.99978	1.00107
7	0.99940	0.99824	0.99925	1.00047
8	0.99928	0.99859	0.99913	1.00029
9	1.00001	0.99939	1.00007	1.00150
10	0.99961	0.99837	0.99930	1.00083
11	0.99854	0.99799	0.99840	1.00001
12	0.99963	0.99868	0.99930	1.00024
13	0.99946	0.99895	0.99935	1.00020
14	0.99935	0.99895	0.99915	1.00050
15	0.99891	0.99826	0.99873	0.99918
16	0.99828	0.99814	0.99679	0.99830
17	0.99755	0.99761	0.99633	0.99738
18	1.00000	0.99922	1.00013	1.00087
19	1.00000	0.99922	1.00025	1.00131
20	0.99977	0.99953	0.99888	1.00019
21	0.99852	0.99870	0.99748	0.99756
22	0.99751	0.99770	0.99561	0.99543

(a) Results provided by Nicolas Leclaire (France).

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Figure 66 shows the relative reactivity offset for the continuous-energy MORET 5.D.1 calculations using continuous-energy ENDF/B-VII.1 cross sections. Fifteen of the twenty-two reactivity offsets fall within the uncertainty in the benchmark model k_{eff} of zero. The remaining seven fall away from zero by more than the uncertainty in the benchmark model k_{eff} . The unweighted average reactivity offset for all cases is -0.0003.

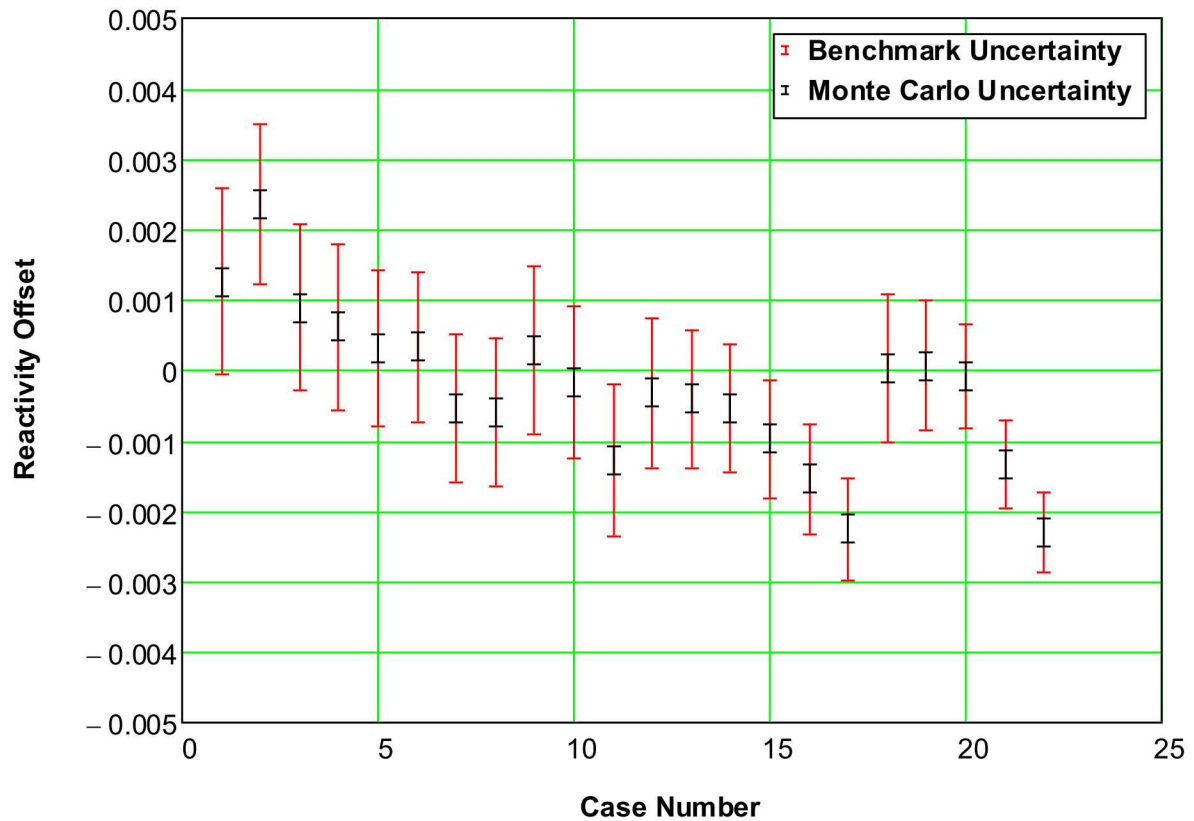


Figure 66. Reactivity Offset for MORET 5.D.1 Calculations using Continuous-Energy ENDF/B-VII.1 Cross Sections.

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Figure 67 shows the relative reactivity offset for the continuous-energy MORET 5.D.1 calculations using continuous-energy ENDF/B-VIII.0 cross sections. Ten of the twenty-two reactivity offsets fall within the uncertainty in the benchmark model k_{eff} of zero. The remaining twelve fall below zero by more than the uncertainty in the benchmark model k_{eff} . The unweighted average reactivity offset for all cases is -0.0010.

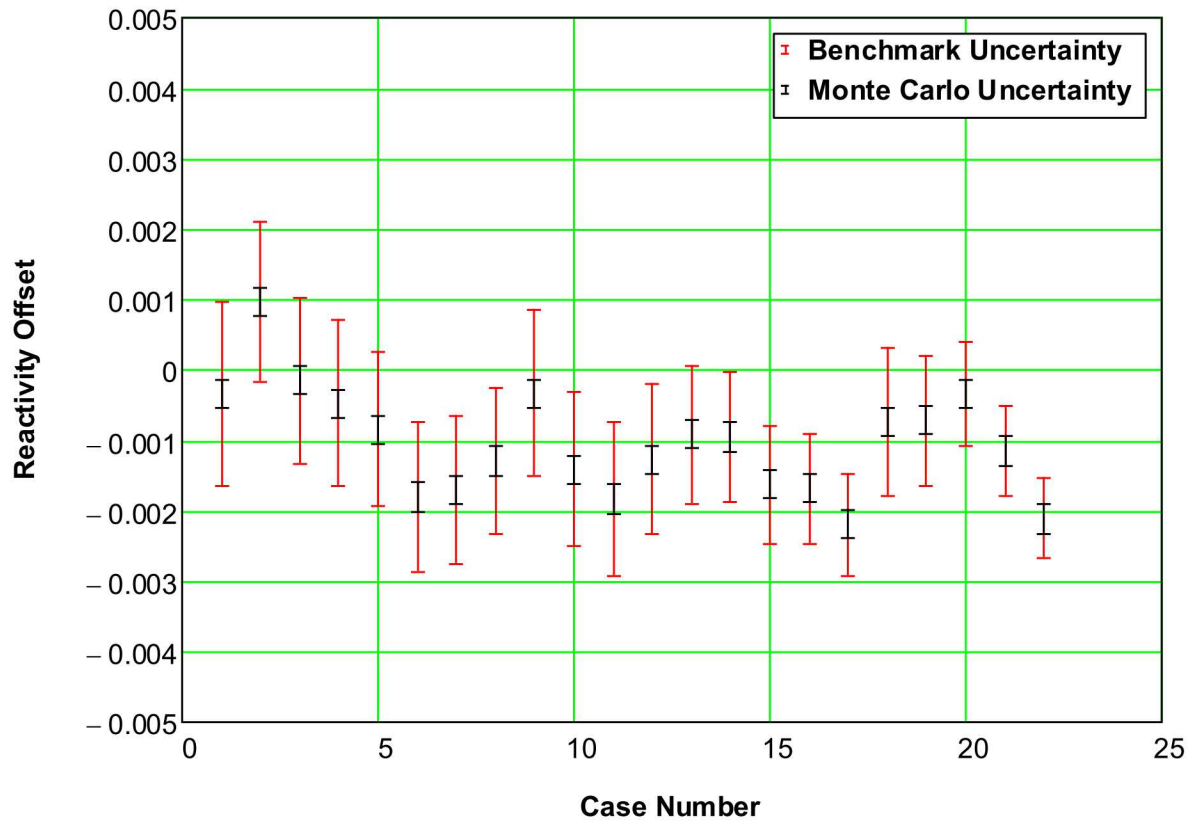


Figure 67. Reactivity Offset for MORET 5.D.1 Calculations using Continuous-Energy ENDF/B-VIII.0 Cross Sections.

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Figure 68 shows the relative reactivity offset for the continuous-energy MORET 5.D.1 calculations using continuous-energy JEFF-3.1.1 cross sections. Thirteen of the twenty-two reactivity offsets fall within the uncertainty in the benchmark model k_{eff} of zero. The remaining nine fall away from zero by more than the uncertainty in the benchmark model k_{eff} . The unweighted average reactivity offset for all cases is -0.0006.

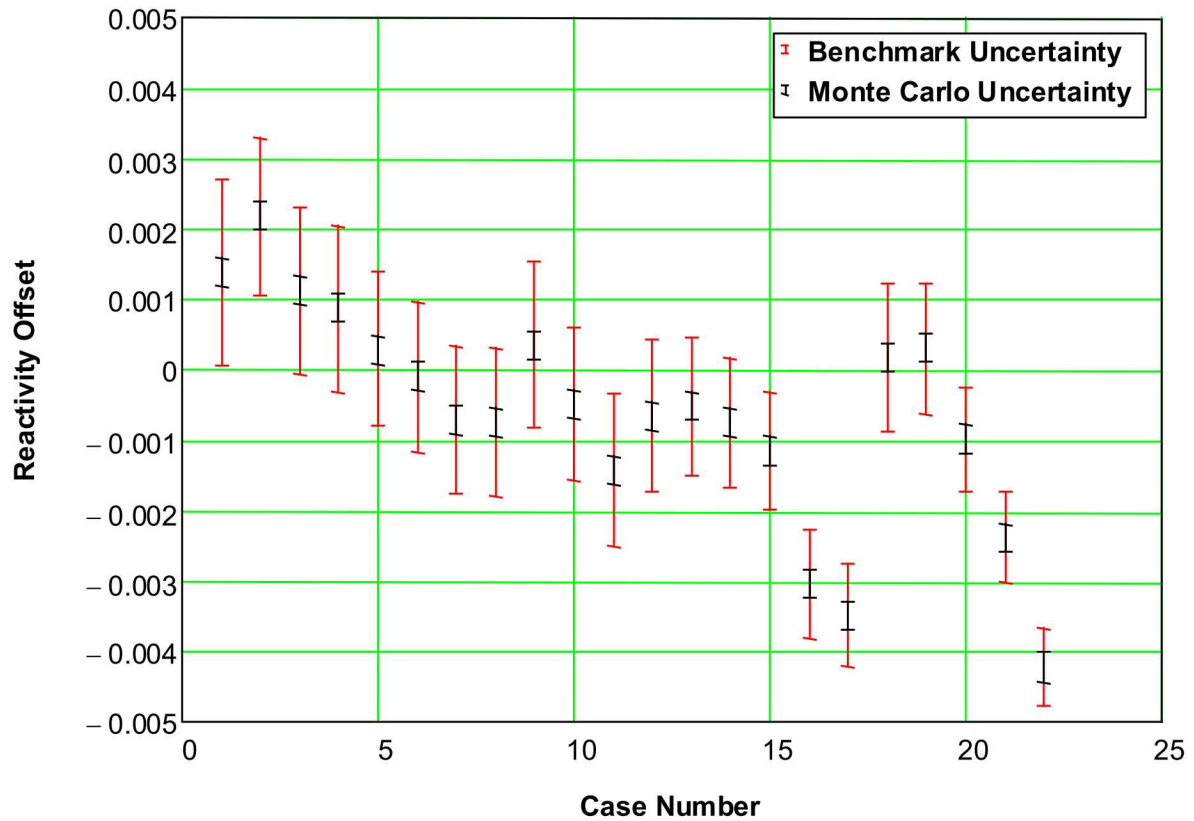


Figure 68. Reactivity Offset for MORET 5.D.1 Calculations using Continuous-Energy JEFF-3.1.1 Cross Sections.

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Figure 69 shows the relative reactivity offset for the continuous-energy MORET 5.D.1 calculations using continuous-energy JEFF-3.2 cross sections. Ten of the twenty-two reactivity offsets fall within the uncertainty in the benchmark model k_{eff} of zero. The remaining twelve fall away from zero by more than the uncertainty in the benchmark model k_{eff} . The unweighted average reactivity offset for all cases is 0.0005.

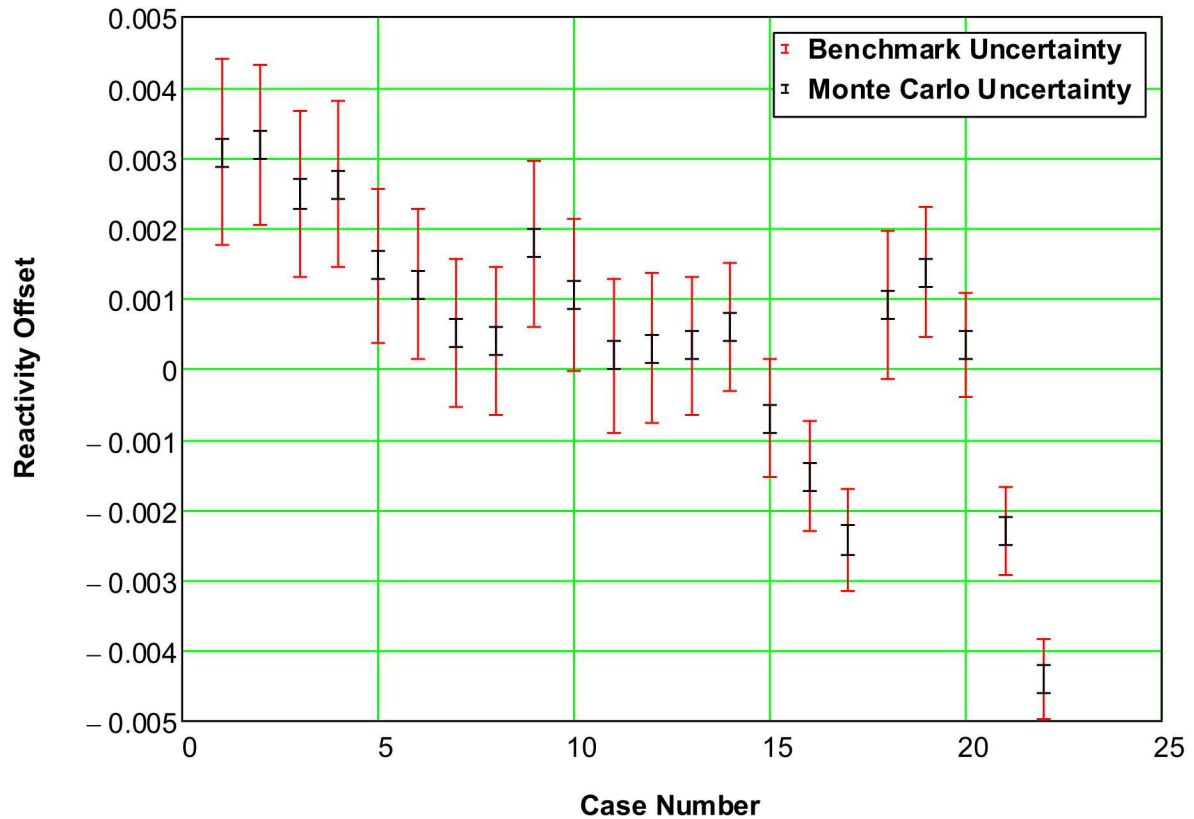


Figure 69. Reactivity Offset for MORET 5.D.1 Calculations using Continuous-Energy JEFF-3.2 Cross Sections.

5.0 REFERENCES

There are no published references.

APPENDIX A: TYPICAL INPUT LISTINGS

A.1 KENO INPUT LISTINGS

KENO V.a and the 252-group ENDF/B-VII.1 cross section set from SCALE 6.2 were used. A total of 550 batches of 40,000 neutrons were run. The first 50 batches were skipped.

KENO V.a input for Case 1

```
=csas25
LCT101 case 01, 2025 rods
v7-252
read comp
'
' UO2 fuel
'
U-234 1 0 6.5539E-06 298.15 end
U-235 1 0 1.6010E-03 298.15 end
U-236 1 0 1.4632E-05 298.15 end
U-238 1 0 2.1296E-02 298.15 end
O 1 0 4.5837E-02 298.15 end
Ag 1 0 9.2319E-09 298.15 end
B 1 0 2.3858E-07 298.15 end
Cd 1 0 1.2380E-08 298.15 end
Co 1 0 2.1620E-08 298.15 end
Cr 1 0 2.5100E-06 298.15 end
Cu 1 0 2.1316E-07 298.15 end
Fe 1 0 1.0311E-05 298.15 end
Mn 1 0 2.8372E-07 298.15 end
Mo 1 0 1.2443E-07 298.15 end
Ni 1 0 3.4989E-06 298.15 end
V 1 0 1.4813E-08 298.15 end
' W 1 0 3.5998E-09 298.15 end
' Neither natural W nor W-180 are in the SCALE 238-group ENDF/B-VII.0 set
' Source for Isotopic Atom Fractions: Chart of the Nuclides 16th ed.
' W-180 1 0 4.31976e-12 298.15 end
W-182 1 0 9.53947e-10 298.15 end
W-183 1 0 5.15131e-10 298.15 end
W-184 1 0 1.10298e-09 298.15 end
W-186 1 0 1.02342e-09 298.15 end
'
' 3003 aluminum
'
Al 2 0 5.9668E-02 298.15 end
Si 2 0 1.7561E-04 298.15 end
Fe 2 0 1.0303E-04 298.15 end
Cu 2 0 3.2339E-05 298.15 end
Mn 2 0 3.7407E-04 298.15 end
Zn 2 0 1.2571E-05 298.15 end
'
' water @ 25 C in core
'
H 3 0 6.6659E-02 298.15 end
O 3 0 3.3329E-02 298.15 end
'
' 6061 aluminum
'
Al 5 0 5.8376E-02 298.15 end
Si 5 0 4.1683E-04 298.15 end
Fe 5 0 1.8051E-04 298.15 end
Cu 5 0 7.9320E-05 298.15 end
Mn 5 0 2.6637E-05 298.15 end
Mg 5 0 6.9574E-04 298.15 end
Cr 5 0 6.2542E-05 298.15 end
Zn 5 0 2.9839E-05 298.15 end
Ti 5 0 6.7918E-06 298.15 end
V 5 0 3.1918E-06 298.15 end
'
```


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```
' polyethylene
,
H-POLY 6 0 8.2755E-02 298.15 end
C 6 0 4.1377E-02 298.15 end
,
' SS-304 for springs
,
Fe 8 0 1.2527E-02 298.15 end
Cr 8 0 3.6455E-03 298.15 end
Ni 8 0 1.5724E-03 298.15 end
Mn 8 0 1.8160E-04 298.15 end
C 8 0 3.3225E-05 298.15 end
P 8 0 7.2471E-06 298.15 end
S 8 0 4.6663E-06 298.15 end
Si 8 0 1.7761E-04 298.15 end
N 8 0 3.5613E-05 298.15 end
,
' water for reflector
,
H 10 0 6.6659E-02 298.15 end
O 10 0 3.3329E-02 298.15 end
,
' UO2 fuel
,
U-234 11 0 6.5539E-06 298.15 end
U-235 11 0 1.6010E-03 298.15 end
U-236 11 0 1.4632E-05 298.15 end
U-238 11 0 2.1296E-02 298.15 end
O 11 0 4.5837E-02 298.15 end
Ag 11 0 9.2319E-09 298.15 end
B 11 0 2.3858E-07 298.15 end
Cd 11 0 1.2380E-08 298.15 end
Co 11 0 2.1620E-08 298.15 end
Cr 11 0 2.5100E-06 298.15 end
Cu 11 0 2.1316E-07 298.15 end
Fe 11 0 1.0311E-05 298.15 end
Mn 11 0 2.8372E-07 298.15 end
Mo 11 0 1.2443E-07 298.15 end
Ni 11 0 3.4989E-06 298.15 end
V 11 0 1.4813E-08 298.15 end
' W 11 0 3.5998E-09 298.15 end
' Neither natural W nor W-180 are in the SCALE 238-group ENDF/B-VII.0 set
' Source for Isotopic Atom Fractions: Chart of the Nuclides 16th ed.
' W-180 11 0 4.31976e-12 298.15 end
W-182 11 0 9.53947e-10 298.15 end
W-183 11 0 5.15131e-10 298.15 end
W-184 11 0 1.10298e-09 298.15 end
W-186 11 0 1.02342e-09 298.15 end
,
' 3003 aluminum
,
Al 12 0 5.9668E-02 298.15 end
Si 12 0 1.7561E-04 298.15 end
Fe 12 0 1.0303E-04 298.15 end
Cu 12 0 3.2339E-05 298.15 end
Mn 12 0 3.7407E-04 298.15 end
Zn 12 0 1.2571E-05 298.15 end
end comp
read celldata
latticecell squarepitch fuelr=0.262814 1 gapr=0.284519 0 cladr=0.317474 2 hpitch=0.427482 3 end
latticecell squarepitch fuelr=0.262814 11 gapr=0.284519 0 cladr=0.317474 12 hpitch=0.427482 0 end
end celldata
read param
npg=40000 gen=550 tme=500 htm=no
nsk=50 run=yes flx=yes plt=no
wrs=35 res=10000
end param
read geom
unit 1
com=' bottom of driver rod in grid plate '
cylinder 2 1 0.317474 0.0 -1.27
```

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```

cylinder 3 1 0.333375 0.0 -1.27
cuboid 5 1 4p0.427482 0.0 -2.54
unit 2
com=' submerged fueled section of driver rod '
cylinder 1 1 0.262814 28.031 0.0
cylinder 0 1 0.284519 28.031 0.0
cylinder 2 1 0.317474 28.031 0.0
cuboid 3 1 4p0.427482 28.031 0.0
unit 301
com=' dry fueled section of driver rod '
cylinder 11 1 0.262814 48.780 28.031
cylinder 0 1 0.284519 48.780 28.031
cylinder 12 1 0.317474 48.780 28.031
cuboid 0 1 4p0.427482 48.780 28.031
unit 302
com=' driver rod spring '
cylinder 0 1 0.17526 50.4952 48.780
cylinder 8 1 0.22860 50.4952 48.780
cylinder 0 1 0.284519 50.4952 48.780
cylinder 2 1 0.317474 50.4952 48.780
cuboid 0 1 4p0.427482 50.4952 48.780
unit 3
com=' dry fueled section and spring '
array 301 -0.427482 -0.427482 28.031
cuboid 3 1 4p0.427482 50.4952 28.031
unit 4
com=' top of driver rod in grid plate '
cylinder 5 1 0.26289 53.0352 50.4952
cylinder 0 1 0.284519 53.0352 50.4952
cylinder 2 1 0.317474 53.0352 50.4952
cylinder 0 1 0.333375 53.0352 50.4952
cuboid 5 1 4p0.427482 53.0352 50.4952
unit 5
com=' poly section of fuel rod in reflector '
cylinder 6 1 0.26289 68.2752 53.0352
cylinder 0 1 0.284519 68.2752 53.0352
cylinder 2 1 0.317474 68.2752 53.0352
cuboid 0 1 4p0.427482 68.2752 53.0352
unit 11
com=' bottom grid plate without rod'
cylinder 3 1 0.333375 0.0 -1.27
cuboid 5 1 4p0.427482 0.0 -2.54
unit 12
com=' submerged fueled section without rod '
cuboid 3 1 4p0.427482 28.031 0.0
unit 13
com=' dry fueled section without rod '
cuboid 0 1 4p0.427482 50.4952 28.031
unit 14
com=' grid plate without rod'
cylinder 0 1 0.333375 53.0352 50.4952
cuboid 5 1 4p0.427482 53.0352 50.4952
unit 15
com=' poly section without rod '
cuboid 0 1 4p0.427482 68.2752 53.0352
unit 51
com=' bottom grid plate without rod'
cylinder 10 1 0.333375 0.0 -1.27
cuboid 5 1 4p0.427482 0.0 -2.54
unit 52
com=' submerged fueled section without rod '
cuboid 10 1 4p0.427482 28.031 0.0
unit 53
com=' dry fueled section without rod '
cuboid 0 1 4p0.427482 50.4952 28.031
unit 54
com=' grid plate without rod'
cylinder 0 1 0.333375 53.0352 50.4952
cuboid 5 1 4p0.427482 53.0352 50.4952
unit 55
com=' poly section without rod '

```

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```

cuboid    0 1 4p0.427482 68.2752    53.0352
unit 210
com=' water under lower grid plate '
cylinder 10 1 46.8376    16.51    0.0
cuboid    0 1 46.9 -46.9 46.9 -46.9    16.51    0.0
unit 211
com=' lower grid plate with rod ends '
array    11    -18.00225 -18.00225    0.0
cylinder  5 1 46.355    2.54    0.0
cylinder 10 1 46.8376    2.54    0.0
cuboid    0 1 46.9 -46.9 46.9 -46.9    2.54    0.0
unit 151
com=' bottom section of detector tube '
cylinder  0 1 2.8575    0.762    0.635
cylinder  5 1 3.175    0.762    0.0
unit 152
com=' submerged poly section of detector tube '
cylinder  0 1 2.875    28.031    0.762
cylinder  5 1 3.175    28.031    0.762
cylinder 10 1 3.30581 28.031    0.762
cylinder  6 1 5.75945 28.031    0.762
unit 212
com=' model above lower GP underwater '
array    12    -18.00225 -18.00225    0.0
cylinder 10 1 46.8376    28.031    0.0
hole     151    28.94    6.4122    0.0
hole     152    28.94    6.4122    0.0
hole     151   -28.94   -6.4122    0.0
hole     152   -28.94   -6.4122    0.0
cuboid    0 1 46.9 -46.9 46.9 -46.9    28.031    0.0
unit 153
com=' dry poly section of detector tube '
cylinder  0 1 2.875    30.7848    28.031
cylinder  5 1 3.175    30.7848    28.031
cylinder 10 1 3.30581 30.7848    28.031
cylinder  6 1 5.75945 30.7848    28.031
unit 154
com=' dry section of detector tube above poly in fuel '
cylinder  0 1 2.875    50.4952    30.7848
cylinder  5 1 3.175    50.4952    30.7848
unit 213
com=' model below upper GP above water level '
array    13    -18.00225 -18.00225    28.031
cylinder  0 1 46.8376    50.4952    28.031
hole     153    28.94    6.4122    0.0
hole     154    28.94    6.4122    0.0
hole     153   -28.94   -6.4122    0.0
hole     154   -28.94   -6.4122    0.0
cuboid    0 1 46.9 -46.9 46.9 -46.9    50.4952    28.031
unit 155
com=' section of detector tube at grid plate '
cylinder  0 1 2.875    53.0352    50.4952
cylinder  5 1 3.175    53.0352    50.4952
unit 214
com=' model at upper grid plate '
array    14    -18.00225 -18.00225    50.4952
cuboid    5 1 4p20.955 53.0352    50.4952
cylinder  0 1 46.8376    53.0352    50.4952
hole     155    28.94    6.4122    0.0
hole     155   -28.94   -6.4122    0.0
cuboid    0 1 46.9 -46.9 46.9 -46.9    53.0352    50.4952
unit 156
com=' top section of detector tube '
cylinder  0 1 2.875    68.2752    53.0352
cylinder  5 1 3.175    68.2752    53.0352
unit 215
com=' model above upper grid plate '
array    15    -18.00225 -18.00225    53.0352
cylinder  0 1 46.8376    68.2752    53.0352
hole     156    28.94    6.4122    0.0
hole     156   -28.94   -6.4122    0.0

```

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```

udn=0    vdn=-1    wdn=0
nax=600  ndn=600
end plt0
ttl='central "element"'
xul=-7.7 yul=7.7   zul=24.39
xlr= 7.7 ylr=-7.7  zlr=24.39
uax=1    vax=0     wax=0
udn=0    vdn=-1    wdn=0
nax=600  ndn=600
end plt1
ttl='whole core - midplane'
xul=-22  yul= 22   zul=24.39
xlr= 22  ylr=-22   zlr=24.39
uax=1    vax=0     wax=0
udn=0    vdn=-1    wdn=0
nax=600  ndn=600
end plt2
ttl='whole core - bottom gridplate'
xul=-22  yul= 22   zul=-1.2
xlr= 22  ylr=-22   zlr=-1.2
uax=1    vax=0     wax=0
udn=0    vdn=-1    wdn=0
nax=600  ndn=600
end plt3
ttl='whole core - top gridplate'
xul=-22  yul= 22   zul=51.7
xlr= 22  ylr=-22   zlr=51.7
uax=1    vax=0     wax=0
udn=0    vdn=-1    wdn=0
nax=600  ndn=600
end plt4
ttl='big look - midplane'
xul=-50  yul= 50   zul=24.39
xlr= 50  ylr=-50   zlr=24.39
uax=1    vax=0     wax=0
udn=0    vdn=-1    wdn=0
nax=600  ndn=600
end plt5
ttl='big look - bottom gridplate'
xul=-50  yul= 50   zul=-1.2
xlr= 50  ylr=-50   zlr=-1.2
uax=1    vax=0     wax=0
udn=0    vdn=-1    wdn=0
nax=600  ndn=600
end plt6
ttl='big look - top gridplate'
xul=-50  yul= 50   zul=51.7
xlr= 50  ylr=-50   zlr=51.7
uax=1    vax=0     wax=0
udn=0    vdn=-1    wdn=0
nax=600  ndn=600
end plt7
ttl='central few rods'
xul=-2.   yul=0     zul= 26.7
xlr= 2.   ylr=0     zlr= 22.7
uax=1    vax=0     wax=0
udn=0    vdn=0     wdn=-1
nax=600  ndn=600
end plt8
ttl='central few rods - top'
xul=-4.   yul=0     zul= 53.7
xlr= 4.   ylr=0     zlr= 45.7
uax=1    vax=0     wax=0
udn=0    vdn=0     wdn=-1
nax=600  ndn=600
end plt9
ttl='central few rods - bottom'
xul=-4.   yul=0     zul= 4.7
xlr= 4.   ylr=0     zlr=-3.3
uax=1    vax=0     wax=0
udn=0    vdn=0     wdn=-1

```

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```
nax=600 ndn=600
end plt10
ttl='central "element"'
xul=-7.7 yul= 0.    zul=32.4
xlr= 7.7 ylr= 0.    zlr=17.0
end plt11
ttl='big look'
xul=-50. yul=0    zul= 75.
xlr= 50. ylr=0    zlr= -25.
uax=1    vax=0    wax=0
udn=0    vdn=0    wdn=-1
nax=600 ndn=600
end plt12
ttl='top of core'
xul=-25. yul=0    zul= 70.
xlr= 25. ylr=0    zlr= 20.
uax=1    vax=0    wax=0
udn=0    vdn=0    wdn=-1
nax=600 ndn=600
end plt13
ttl='left detector y=6.4'
xul=-50. yul= 6.4 zul= 75.
xlr= 50. ylr= 6.4 zlr=-25.
uax=1    vax=0    wax=0
udn=0    vdn=0    wdn=-1
nax=600 ndn=600
end plt14
ttl='right detector y=-6.4'
xul=-50. yul=-6.4 zul= 75.
xlr= 50. ylr=-6.4 zlr=-25.
uax=1    vax=0    wax=0
udn=0    vdn=0    wdn=-1
nax=600 ndn=600
end plt15
end plot
end data
end
```


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LEU-COMP-THERM-101

```

1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 7
1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 7
1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 7
1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 7
1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 7
c
c
1000  4  9.9988E-02 921  -101   913  -914   915  -916 $ bounds on upper array
      fill=10
1002  2  5.9877E-02 10  -12  -932          $ bottom grid plate
      (-921 : 912 : -913 : 914 : -915 : 916) $ the array
1003  2  5.9877E-02 961 -962 963 -964 14  -15 $ top grid plate
      (-921 : 912 : -913 : 914 : -915 : 916) $ the array
1007  4  9.9988E-02 921 -922 -923 -100      $ reflector below water level
      (-921 : 912 : -913 : 914 : -915 : 916) $ the array
      (-10 : 12 : 932)          $ bottom grid plate
      (-961 : 962 : -963 : 964 : -14 : 15) $ top grid plate
      (-803 : 804)          $-x+y detector tube
      (-803 : 806)          $+x+y detector tube
      (810 : -811 : 812 : -814) $-x+y detector poly
      (810 : -811 : 813 : -815) $+x+y detector poly
1008  0          921 -922 -923 100 -101      $ reflector above water level
      (-921 : 912 : -913 : 914 : -915 : 916) $ the array
      (-10 : 12 : 932)          $ bottom grid plate
      (-961 : 962 : -963 : 964 : -14 : 15) $ top grid plate
      (-803 : 804)          $-x+y detector tube
      (-803 : 806)          $+x+y detector tube
      (810 : -811 : 812 : -814) $-x+y detector poly
      (810 : -811 : 813 : -815) $+x+y detector poly
1030  0          -101  802 -805          $ -x+y detector well
1031  2  5.9877E-02 -101  803 -804          $ -x+y detector tube
      (-802 : 805)          $-x+y well
1032  7  1.2236E-01 -810  811 -812 814      $ -x+y detector poly
1033  0          -101  802 -807          $ +x+y detector well
1034  2  5.9877E-02 -101  803 -806          $ +x+y detector tube
      (-802 : 807)          $+x+y well
1035  7  1.2236E-01 -810  811 -813 815      $ +x+y detector poly
1100  0          $ external void
      (-921 : 101 : 923)      $ water in upper tank

c
c fuel rod surfaces
c
1  cz  0.262814 $ fuel OD
2  cz  0.284519 $ clad ID
3  cz  0.317474 $ clad OD
4  cz  0.333375 $ ID of hole in grid plate at fuel
5  cz  0.17526  $ ID of spring
6  cz  0.22860  $ OD of spring
7  cz  0.26289  $ intermediate plug OD
8  cz  0.26289  $ poly OD
10 pz -2.54     $ bottom of bottom grid plate
11 pz -1.27     $ bottom of rod
12 pz  0.0      $ bottom of fuel
13 pz 48.780    $ top of fuel
14 pz 50.4952   $ bottom of upper grid plate
15 pz 53.0352   $ top of upper grid plate
c
c water level
c
100 pz 28.031    $ top of the water
c
c top of the model
101 pz 68.2752   $ top of the model - 68.2752 gives 6" above grid plate
c
c detector wells
c
802 pz 0.635    $ bottom inside of tube
803 pz 0.0      $ bottom of tube
804 c/z 28.94   6.4122 3.175 $ OD tube outside

```

LEU-COMP-THERM-101

```

805  c/z   28.94      6.4122  2.8575 $ ID of tube
806  c/z  -28.94     -6.4122  3.175  $ OD tube
807  c/z  -28.94     -6.4122  2.8575 $ ID of tube
810  pz   30.7848                $ top of poly
811  pz    0.762                $ bottom of poly
812  c/z   28.94      6.4122  5.75945 $ OD poly
813  c/z  -28.94     -6.4122  5.75945 $ OD poly
814  c/z   28.94      6.4122  3.30581 $ ID poly
815  c/z  -28.94     -6.4122  3.30581 $ ID poly
c
c cell boundaries
c
901  px   -0.42748
902  px    0.42748
903  py   -0.42748
904  py    0.42748
c
c array boundaries
c
911  pz  -16.00001
912  pz  145.00001
913  px  -19.2366
914  px   19.2366
915  py  -19.2366
916  py   19.2366
c
c the water
c
921  pz  -19.05      $ bottom of reflector
922  pz   82.55      $ top of reflector
923  cz   46.8376    $ outside of reflector
932  cz   46.355     $ outside curve of lower grid plate
c
c upper grid plate
c
961  px  -20.955
962  px   20.955
963  py  -20.955
964  py   20.955

c Source for Isotopic Atom Fractions: Chart of the Nuclides 16th ed.
c
c UO2 fuel
c
ml
    92234.80c  6.5539E-06
    92235.80c  1.6010E-03
    92236.80c  1.4632E-05
    92238.80c  2.1296E-02
    8016.80c  4.5837E-02
c    47000.xxc  9.2319E-09  $Ag
    47107.80c  4.78572e-09
    47109.80c  4.44618e-09
c    5000.xxc  2.3858E-07  $B
    5010.80c  4.74774e-08
    5011.80c  1.91103e-07
c    48000.xxc  1.2380E-08  $Cd
    48106.80c  1.54750e-10
    48108.80c  1.10182e-10
    48110.80c  1.54626e-09
    48111.80c  1.58464e-09
    48112.80c  2.98729e-09
    48113.80c  1.51284e-09
    48114.80c  3.55677e-09
    48116.80c  9.27262e-10
    27059.80c  2.1620E-08  $Co
c    24000.xxc  2.5100E-06  $Cr
    24050.80c  1.0906e-07
    24052.80c  2.1031e-06
    24053.80c  2.38475e-07
    24054.80c  5.93615e-08

```

LEU-COMP-THERM-101

```

c      29000.xx c  2.1316E-07  $Cu
      29063.80 c  1.47443e-07
      29065.80 c  6.57172e-08
c      26000.xx c  1.0311E-05  $Fe
      26054.80 c  6.02678e-07
      26056.80 c  9.46075e-06
      26057.80 c  2.18490e-07
      26058.80 c  2.90770e-08
      25055.80 c  2.8372E-07  $Mn
c Molybdenum 1.2443E-07
      42092.80 c  1.84654e-08
      42094.80 c  1.15098e-08
      42095.80 c  1.98093e-08
      42096.80 c  2.07549e-08
      42097.80 c  1.18831e-08
      42098.80 c  3.00250e-08
      42100.80 c  1.19826e-08
c      28000.xx c  3.4989E-06  $Ni
      28058.80 c  2.38194e-06
      28060.80 c  9.17520e-07
      28061.80 c  3.98840e-08
      28062.80 c  1.27168e-07
      28064.80 c  3.23858e-08
c      23000.XXX 1.4813E-08  $V
      23050.80 c  3.70325E-11
      23051.80 c  1.4776E-08
c      74000.xx c  3.5998E-09  $W
      74180.80 c  4.31976e-12
      74182.80 c  9.53947e-10
      74183.80 c  5.15131e-10
      74184.80 c  1.10298e-09
      74186.80 c  1.02342e-09

c
c      6061 aluminum
c
m2 13027.80 c  5.8376E-02
c      14000.xxx 4.1683E-04
      14028.80 c  3.84441e-04
      14029.80 c  1.95210e-05
      14030.80 c  1.28684e-05
c      26000.xxx 1.8051E-04
      26054.80 c  1.05508e-05
      26056.80 c  1.65625e-04
      26057.80 c  3.82501e-06
      26058.80 c  5.09038e-07
c      29000.xxx 7.9320E-05
      29063.80 c  5.48656e-05
      29065.80 c  2.44544e-05
      25055.80 c  2.6637E-05
c Magnesium 6.9574E-04
      12024.80 c  5.49565e-04
      12025.80 c  6.9574e-05
      12026.80 c  7.6601e-05
c      24000.xxx 6.2542E-05
      24050.80 c  2.71745e-06
      24052.80 c  5.24033e-05
      24053.80 c  5.94212e-06
      24054.80 c  1.47912e-06
c      30000.XXX 2.9839e-05
      30064.80 c  1.45107E-05
      30066.80 c  8.32508E-06
      30067.80 c  1.2234E-06
      30068.80 c  5.59481E-06
      30070.80 c  1.85002E-07
c Titanium 6.7918e-006
      22046.80 c  5.60324e-07
      22047.80 c  5.05310e-07
      22048.80 c  5.00691e-06
      22049.80 c  3.67436e-07
      22050.80 c  3.51815e-07
c      23000.XXX 3.1918E-06

```


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```

23050.80c 7.9795E-09
23051.80c 3.18382E-06
c
c 3003 aluminum
c
m3 13027.80c 5.9668E-02
c 14000.xxx 1.7561E-04
14028.80c 1.61965e-04
14029.80c 8.22417e-06
14030.80c 5.42143e-06
c 26000.xxx 1.0303E-04
26054.80c 6.02210e-06
26056.80c 9.45341e-05
26057.80c 2.18321e-06
26058.80c 2.90545e-07
c 29000.xxx 3.2339E-05
29063.80c 2.23689e-05
29065.80c 9.97011e-06
25055.80c 3.7407E-04
c 30000.XXX 1.2571e-05
30064.80c 6.11328E-06
30066.80c 3.50731E-06
30067.80c 5.15411E-07
30068.80c 2.35706E-06
30070.80c 7.79402E-08
c
c water
c
m4 1001.80c 6.6659E-02
8016.80c 3.3329E-02
mt4 lwtr.20t
c
c stainless steel 304
c
m5
c Iron 1.2527e-02
26054.80c 7.32203e-04
26056.80c 1.14940e-02
26057.80c 2.65447e-04
26058.80c 3.53261e-05
c Chromium 3.6455E-03
24050.80c 1.58397e-04
24052.80c 3.05453e-03
24053.80c 3.46359e-04
24054.80c 8.62161e-05
c Nickel 1.5724E-03
28058.80c 1.07044e-03
28060.80c 4.12332e-04
28061.80c 1.79238e-05
28062.80c 5.71489e-05
28064.80c 1.45541e-05
25055.80c 1.8160E-04 $Mn
6000.80c 3.3225E-05 $C
15031.80c 7.2471E-06 $P
c Sulfur 4.6663e-006
16032.80c 4.42972e-06
16033.80c 3.54639e-08
16034.80c 2.00184e-07
16036.80c 9.33260e-10
c Silicon 1.7761e-04
14028.80c 1.63809e-04
14029.80c 8.31783e-06
14030.80c 5.48318e-06
c Nitrogen 3.5613e-005
7014.80c 3.54819e-05
7015.80c 1.31056e-07
c
c polyethylene (CH2)
c
m7
1001.80c 8.2755E-02

```

LEU-COMP-THERM-101

```
        6000.80c  4.1377E-02
mt7  poly.20t
c
c
imp:n    1 38r 0
mode     n
kcode    40000 1 50 550
ksrc     0 0 17.55
prdmp    0 0 0 1
print    -128
lost     1000 10
kopts    kinetics=yes
```

LEU-COMP-THERM-101

A.3 MORET 5 INPUT LISTING

The MORET 5.D.1 code and the continuous-energy cross section set based on ENDF/B-VII.1 were used. A total of 5218 batches of 4050 neutrons were run. The first 3 batches were skipped.

MORET5 Input for Case 1

DEBUT_MORET
LEU-COMP-THERM-101-001

ARRE
KEFF SIGM 0.00020
FARR

CHIM
PONC
BIBL endf71.xml
TEMP 294

COMP UO2_Fuel CONC
U234 6.5539E-06
U235 1.6010E-03
U236 1.4632E-05
U238 2.1296E-02
O16 4.5837E-02
AG 9.2319E-09
B 2.3858E-07
CD 1.2380E-08
CO 2.1620E-08
CR 2.5100E-06
CU 2.1316E-07
FE 1.0311E-05
MN 2.8372E-07
MO 1.2443E-07
NI 3.4989E-06
V 1.4813E-08
W182 9.53947e-10
W183 5.15131e-10
W184 1.10298e-09
W186 1.02342e-09

FINC

COMP 3003_Al CONC
AL 5.9668E-02
SI 1.7561E-04
FE 1.0303E-04
CU 3.2339E-05
MN 3.7407E-04
ZN 1.2571E-05

FINC

COMP Eau CONC
H1-H2O 6.6659E-02
O16 3.3329E-02
FINC

COMP 6061_Al CONC
AL 5.8376E-02
SI 4.1683E-04
FE 1.8051E-04
CU 7.9320E-05
MN 2.6637E-05
MG 6.9574E-04
CR 6.2542E-05
ZN 2.9839E-05
TI 6.7918E-06
V 3.1918E-06

LEU-COMP-THERM-101

FINC

COMP POLYETHYLENE CONC

H1-CH2 8.2755E-02
C 4.1377E-02

FINC

COMP SS-304 CONC

FE 1.2527E-02
CR 3.6455E-03
NI 1.5724E-03
MN 1.8160E-04
C 3.3225E-05
P 7.2471E-06
S 4.6663E-06
SI 1.7761E-04
N 3.5613E-05

FINC

COMP Air CONC

N 4.1985E-10
O16 1.1263E-10

FINC

FINChimie

* -----
* Matériaux
* 1 - Combustible UO2
* 2 - Aluminium 3003
* 3 - Eau
* 4 - Aluminium 6061
* 5 - Polyéthylène
* 6 - SS-304
* -----

GEOM
MODU 0

*intérieur cuve (totale)
TYPE 1 CYLZ 46.8376 46.8376
VOLUME 1 0 1 7 0. 0. 46.8376

*intérieur cuve immergé
*HAUTEUR D'EAU*****
TYPE 2 CYLZ 46.8376 23.5405
VOLUME 2 1 2 3 0. 0. 23.5405

*Réflecteur bas
TYPE 3 CYLZ 46.8376 8.255
VOLUME 3 2 3 3 0. 0. 8.255

*Plaque inférieure
TYPE 4 CYLZ 46.355 1.27
VOLUME 4 2 4 4 0. 0. 17.78

*Plaque supérieure
TYPE 5 BOITE 20.955 20.955 1.27
VOLUME 5 1 5 4 0. 0. 70.8152

*détecteurs
TYPE 6 CYLZ 5.75945 15.0114
TYPE 7 CYLZ 3.30581 15.0114
TYPE 8 CYLZ 3.175 34.0741
TYPE 9 CYLZ 2.8575 33.7566

VOLUME 6 1 6 5 6.4 -28.94 34.6964 ECRASE 1 2
VOLUME 7 6 7 7 6.4 -28.94 34.6964
VOLUME 8 1 8 4 6.4 -28.94 53.1241 ECRASE 3 2 6 7
VOLUME 9 8 9 7 6.4 -28.94 53.4416

LEU-COMP-THERM-101

VOLU 10 1 6 5 -6.4 28.94 34.6964 ECRASE 1 2
VOLU 11 10 7 7 -6.4 28.94 34.6964
VOLU 12 1 8 4 -6.4 28.94 53.1241 ECRASE 3 2 10 11
VOLU 13 12 9 7 -6.4 28.94 53.4416

*Crayons combustibles

TYPE 14 BOIT 19.23669 19.23669 35.4076
TROU 1 1 14 1 0.0 0.0 51.9176 ECRASE 4 3 4 2 5

FINM

MODU 1

* universe

TYPE 1 BOITE 19.23669 19.23669 35.4076
VOLU 1 0 1 7 0. 0. 35.4076

*Volume Maille

TYPE 2 BOITE 0.427482 0.427482 35.4076
VOLU 2 1 2 7 -18.809208 -18.809208 35.4076

*Zone 1

TYPE 3 BOITE 0.427482 0.427482 0.635
VOLU 3 2 3 4 -18.809208 -18.809208 0.635

*Zone 2

*ALU

TYPE 4 BOITE 0.427482 0.427482 0.635
VOLU 4 2 4 4 -18.809208 -18.809208 1.905

*EAU

TYPE 5 CYLZ 0.333375 0.635
VOLU 5 4 5 3 -18.809208 -18.809208 1.905

*ALU3003

TYPE 6 CYLZ 0.317474 0.635
VOLU 6 5 6 2 -18.809208 -18.809208 1.905

*Zone 3

*AIR

TYPE 7 BOITE 0.427482 0.427482 24.39
VOLU 7 2 7 7 -18.809208 -18.809208 26.93

*EAU*****

TYPE 71 BOITE 0.427482 0.427482 14.0155
VOLU 71 7 71 3 -18.809208 -18.809208 16.5555

*3003 ALU

TYPE 8 CYLZ 0.317474 24.39
VOLU 8 7 8 2 -18.809208 -18.809208 26.93 ECRASE 1 71

*VIDE

TYPE 9 CYLZ 0.284519 24.39
VOLU 9 8 9 7 -18.809208 -18.809208 26.93

*UO2

TYPE 10 CYLZ 0.262814 24.39
VOLU 10 9 10 1 -18.809208 -18.809208 26.93

*Zone 4

*VIDE

TYPE 11 BOITE 0.427482 0.427482 0.8576
VOLU 11 2 11 7 -18.809208 -18.809208 52.1776

*3003 ALU

TYPE 12 CYLZ 0.317474 0.8576
VOLU 12 11 12 2 -18.809208 -18.809208 52.1776

*VIDE

TYPE 13 CYLZ 0.284519 0.8576
VOLU 13 12 13 7 -18.809208 -18.809208 52.1776

*303 SS

TYPE 14 CYLZ 0.2286 0.8576
VOLU 14 13 14 6 -18.809208 -18.809208 52.1776

*VIDE

TYPE 15 CYLZ 0.17526 0.8576
VOLU 15 14 15 7 -18.809208 -18.809208 52.1776

*zone 5

LEU-COMP-THERM-101

*6061 AL
TYPE 16 BOITE 0.427482 0.427482 1.27
VOLU 16 2 16 4 -18.809208 -18.809208 54.3052
*VIDE
TYPE 17 CYLZ 0.333375 1.27
VOLU 17 16 17 7 -18.809208 -18.809208 54.3052
*3003 AL
TYPE 18 CYLZ 0.317474 1.27
VOLU 18 17 18 2 -18.809208 -18.809208 54.3052
*VIDE
TYPE 19 CYLZ 0.284519 1.27
VOLU 19 18 19 7 -18.809208 -18.809208 54.3052
*6061 AL
TYPE 20 CYLZ 0.26289 1.27
VOLU 20 19 20 4 -18.809208 -18.809208 54.3052

*zone 6
*VIDE
TYPE 21 BOITE 0.427482 0.427482 7.62
VOLU 21 2 21 7 -18.809208 -18.809208 63.1952
*3003 AL
TYPE 22 CYLZ 0.317474 7.62
VOLU 22 21 22 2 -18.809208 -18.809208 63.1952
*VIDE
TYPE 23 CYLZ 0.284519 7.62
VOLU 23 22 23 7 -18.809208 -18.809208 63.1952
*CH2
TYPE 24 CYLZ 0.26289 7.62
VOLU 24 23 24 5 -18.809208 -18.809208 63.1952

RESC
MPRI 2
DIMR 45 45 1
FINR

FINM

FING

GRAP X 0.44 FGRA
PEIN X 0.44 FGRA
GRAP Y 6.4 FGRA
PEIN Y 6.4 FGRA
GRAP Y -6.4 FGRA
PEIN Y -6.4 FGRA
GRAP Z 30 FGRA
PEIN Z 30 FGRA

SORTies
SCORes
ANNUle TOUS

ACTI SEUL 2 BILAN_2G
CARA
FSCORes

FSORTies

SOUR
UNIF 2 MODU 1 VOLU 10 FUNI
FINS

FIND

FIN_MORET