6.0 CRITICALITY EVALUATION

6.1 DESCRIPTION OF CRITICALITY DESIGN

A criticality safety analysis is performed to demonstrate the RAJ-II shipping container safety. The RAJ-II meets applicable IAEA and 10 CFR 71 requirements for a Type B fissile material-shipping container, transporting heterogeneous UO_2 enriched to a maximum of 5.00 wt. percent U-235.

The RAJ-II shipping container design features a stainless steel inner container positioned inside an outer stainless steel container by four evenly spaced stainless steel fixture assemblies. The fixture assemblies cradle the inner container and prevent horizontal or vertical movement. The inner container has two fuel assembly transport compartments, aligned side-by-side and separated by a stainless steel divider. Each transport compartment is lined with polyethylene foam in which the fuel assemblies rest. Additional container details are described in Section 1.2, Package Description. Material manufacturing tolerances are presented in the general arrangement drawings in Section 1.4.1.

The uranium transported in the RAJ-II container is UO_2 pellets enclosed in zirconium alloy cladding. The fuel rods are arranged in 8x8, 9x9, or 10x10 square lattice arrays at fixed center-to-center spacing. Fuel rods may also be transported loose with no fixed center-to-center spacing, bundled together in a close packed configuration, or inside a 5-inch diameter stainless steel pipe or protective case.

Water exclusion from the inner container is not required for this package design. The inner container is analyzed in both undamaged and damaged package arrays under optimal moderation conditions and is demonstrated to be safe under Normal Conditions of Transport (NCT) and Hypothetical Accident Condition (HAC) testing.

The criticality analysis for the RAJ-II container is performed at a maximum enrichment of 5.00 wt. percent U-235 for UO_2 fuel pellets contained in zirconium alloy clad cylindrical rods. The cylindrical fuel rods are arranged in 8x8, 9x9, or 10x10 square lattice arrays at fixed center-to-center spacing. Sensitivity analyses are performed by varying fuel parameters (rod pitch, clad ID, clad OD, pellet OD, fuel orientation, polyethylene spacer quantity, and moderator density) to obtain the most reactive configuration. The most reactive configuration is modeled for each authorized payload to demonstrate safety and to validate the fuel parameter ranges specified as loading criteria.

Table 6-1 RAJ-II Fuel Assembly Loading Criteria summarizes the fuel loading criteria for the RAJ-II shipping container.

Table 6-1 RAJ-II Fuel Assembly Loading Criteria

Parameter	Units	Type	Type	Type	Type
Fuel Assembly Type	Rods	8x8	9x9	FANP 10x10	GNF 10x10
UO_2 Density		≤ 98% Theoretical	≤ 98% Theoretical	≤ 98% Theoretical	≤ 98% Theoretical
Number of water rods	#	0, 2x2	0, 2-2x2 off-center diagonal, 3x3	0, 2-2x2 off-center diagonal, 3x3	0, 2-2x2 off-center diagonal, 3x3
Number of fuel rods	#	60 - 64	72 - 81	91 - 100	91 - 100
Fuel Rod OD	cm	≥ 1.176	≥ 1.093	≥ 1.000	≥ 1.010
Fuel Pellet OD	cm	≤ 1.05	≤ 0.96	≤ 0.895	≤ 0.895
Cladding Type		Zirconium Alloy	Zirconium Alloy	Zirconium Alloy	Zirconium Alloy
Cladding ID	cm	≤ 1.10	≤ 1.02	≤ 0.933	≤ 0.934
Cladding Thickness	cm	≥ 0.038	≥ 0.036	≥ 0.033	≥ 0.038
Active fuel length	cm	≤ 381	≤ 381	≤ 385	≤ 385
Fuel Rod Pitch	cm	≤ 1.692	≤ 1.51	≤ 1.350	≤ 1.350
U-235 Pellet Enrichment	wt%	≤ 5.0	≤ 5.0	≤ 5.0	≤ 5.0
Maximum Lattice Average Enrichment	wt%	≤ 5.0	≤ 5.0	≤ 5.0	≤ 5.0
Channel Thickness[a]	cm	0.17 – 0.3048	0.17 – 0.3048	0.17 – 0.3048	0.17 – 0.3048
Part Length Fuel Rods (1/3 through 2/3 normal length)	Max #	None	12	14	14
Gadolinia Requirements Lattice Average Enrichment[b]	# @ wt% Gd_2O_3				
≤ 5.0 wt % U-235		7 @ 2 wt %	10 @ 2 wt %	12 @ 2 wt %	12 @ 2 wt %
≤ 4.7 wt % U-235		6 @ 2 wt %	8 @ 2 wt %	12 @ 2 wt %	12 @ 2 wt %
≤ 4.6 wt % U-235		6 @ 2 wt %	8 @ 2 wt %	10 @ 2 wt %	10 @ 2 wt %
≤ 4.3 wt % U-235		6 @ 2 wt %	8 @ 2 wt %	9 @ 2 wt %	9 @ 2 wt %
≤ 4.2 wt % U-235		6 @ 2 wt %	6 @ 2 wt %	8 @ 2 wt %	8 @ 2 wt %
≤ 4.1 wt % U-235		4 @ 2 wt %	6 @ 2 wt %	8 @ 2 wt %	8 @ 2 wt %
≤ 3.9 wt % U-235		4 @ 2 wt %	6 @ 2 wt %	6 @ 2 wt %	6 @ 2 wt %
≤ 3.8 wt % U-235		4 @ 2 wt %	4 @ 2 wt %	6 @ 2 wt %	6 @ 2 wt %
≤ 3.7 wt % U-235		2 @ 2 wt %	4 @ 2 wt %	6 @ 2 wt %	6 @ 2 wt %
≤ 3.6 wt % U-235		2 @ 2 wt %	4 @ 2 wt %	4 @ 2 wt %	4 @ 2 wt %
≤ 3.5 wt % U-235		2 @ 2 wt %	2 @ 2 wt %	4 @ 2 wt %	4 @ 2 wt %
≤ 3.3 wt % U-235		2 @ 2 wt %	2 @ 2 wt %	2 @ 2 wt %	2 @ 2 wt %
≤ 3.1 wt % U-235		None	2 @ 2 wt %	2 @ 2 wt %	2 @ 2 wt %
≤ 3.0 wt % U-235		None	None	2 @ 2 wt %	2 @ 2 wt %
≤ 2.9 wt % U-235		None	None	None	None
Polyethylene Equivalent Mass (Maximum per Assembly)[c]	kg	11	11	10.2	10.2

a. Transport with or without channels is acceptable
b. Required gadolinia rods must be distributed symmetrically about the major diagonal
c. Polyethylene equivalent mass (refer to 6.3.2.2)

Cylindrical fuel rods containing UO_2, enriched to 5 wt. percent U-235, are analyzed within the RAJ-II inner container in a 5-inch stainless steel pipe, loose, in a protective case, or bundled together. The fuel rod loading criteria, determined from the criticality evaluation for the RAJ-II shipping container, are shown in Table 6-2 RAJ-II Fuel Rod Loading Criteria.

Table 6-2 RAJ-II Fuel Rod Loading Criteria

Parameter	Units	Type	Type	Type
Fuel Assembly Type		8x8	9x9	10x10
UO_2 Density		≤ 98% Theoretical	≤ 98% Theoretical	≤ 98% Theoretical
Allowable number of fuel rods per container compartment Configured loose Configured in 5-inch SS Pipe/Protective Case Configured strapped together	# 	 ≤ 25 ≤ 22 ≤ 25	 ≤ 25 ≤ 26 ≤ 25	 ≤ 25 ≤ 30 ≤ 25
Fuel Rod OD	cm	≥ 1.10	≥ 1.02	≥ 1.00
Fuel Pellet OD	cm	≤ 1.05	≤ 0.96	≤ 0.90
Cladding Type		Zirc Alloy	Zirc Alloy	Zirc Alloy
Cladding ID	cm	≤ 1.10	≤ 1.02	≤ 1.00
Cladding Thickness	cm	≥ 0.00	≥ 0.00	≥ 0.00
Active fuel length	cm	≤ 381	≤ 381	≤ 385
Maximum U-235 Pellet Enrichment	wt%	≤ 5.0	≤ 5.0	≤ 5.0
Maximum Average Fuel Rod Enrichment	wt%	≤ 5.0	≤ 5.0	≤ 5.0

6.1.1 Design Features

6.1.1.1 Packaging

A general discussion of the RAJ-II container design is provided in Section 1.2, Package Description. A detailed set of licensing drawings for the RAJ-II container is provided in Appendix 1.4.1 RAJ-II General Arrangement Drawings. Components important to criticality safety are described below.

The RAJ-II is comprised of two primary components: 1) an inner stainless steel container, and 2) an outer stainless steel container.

The inner stainless steel container is 468.6 cm (184.49 in) in length, 45.9 cm (18.07 in) in width, and 28.6 cm (11.26 in) in height, and provides containment for the uranium inside the cylindrical zirconium alloy tubes. The fuel rods are located inside one of two compartments within the inner container. The compartments are fabricated from 18-gauge (0.122 cm thick) stainless steel, 456.7 cm (179.8 in) in length, 17.6 cm (6.93in) in width and height. Each compartment is lined with 1.8 cm (0.71 in) thick polyethylene foam and separated from each other by the compartment walls. A 5 cm (1.97 in) thick Alumina Silicate fiber surrounds the compartments to provide thermal insulation, and a 16-gauge (0.15 cm thick) stainless steel sheet surrounds the insulator. The inner container lid consists of an Alumina Silicate layer encased in a 16-gauge (0.15 cm

thick) stainless steel sheet. The lid width and length are consistent with the inner container and the overall height is 5.25 cm (2.07 in).

The outer container is 506.8 cm (199.53 in) in length, 72.0 cm (28.35 in) in width, and 64.2 cm (25.28 in) in height (with the skids attached the height is 74.2 cm (29.21 in)). The inner container is held rigidly within the outer stainless steel container by four evenly spaced stainless steel fixture assemblies. Shock absorbers, fabricated from a phenol impregnated cardboard material, are placed at six locations above and below the inner container, and twelve locations on either side of the inner container. The wall for the outer container is fabricated from 14-gauge (0.2 cm thick) stainless steel.

6.1.2 Summary Table of Criticality Evaluation

Table 6-3 Criticality Evaluation Summary, lists the bounding cases evaluated for a given set of conditions. The cases include: fuel assembly transport single package normal and Hypothetical Accident Conditions (HAC), fuel assembly transport package array normal conditions of transport, fuel assembly transport package array HAC, fuel rod transport single package normal and hypothetical accident conditions, fuel rod transport package array normal conditions of transport, and fuel rod transport package array HAC.

Table 6-3 Criticality Evaluation Summary

Case	Bounding Fuel Type	k_{eff}	σ	$k_{eff} + 2\sigma$	USL
Fuel Assembly Single Package Normal	GNF 10x10 with worst case fuel parameters, 12, 2.0 wt % Gd_2O_3 fuel rods, and 12 part length fuel rods	0.6673	0.0008	0.6689	0.94254
Fuel Assembly Single Package HAC	GNF 10x10 with worst case fuel parameters, 12, 2.0 wt % Gd_2O_3 fuel rods, and 12 part length fuel rods	0.6931	0.0010	0.6951	0.94254
Fuel Assembly Package Array Normal	GNF 10x10 with worst case fuel parameters, 12, 2.0 wt % Gd_2O_3 fuel rods, and 12 part length fuel rods	0.8519	0.0008	0.8535	0.94254
Fuel Assembly Package Array HAC	GNF 10x10 with worst case fuel parameters, 12, 2.0 wt % Gd_2O_3 fuel rods, and 12 part length fuel rods	0.9378	0.0009	0.9396	0.94254
Fuel Rod Single Package Normal	25 GNF 8x8 fuel rods per container with worst case fuel parameters	0.6365	0.0008	0.6381	0.94254
Fuel Rod Single Package HAC	25 GNF 8x8 fuel rods per container with worst case fuel parameters	0.6532	0.0008	0.6548	0.94254
Fuel Rod Package Array Normal	25 GNF 8x8 fuel rods per container with worst case fuel parameters	0.6365	0.0008	0.6381	0.94254
Fuel Rod Package Array HAC	25 GNF 8x8 fuel rods per container with worst case fuel parameters	0.8731	0.0007	0.8745	0.94254

A comparison between the nominal fuel parameters and the worst case fuel parameters used in the criticality evaluation is shown in Table 6-4 Nominal vs. Worst Case Fuel Parameters for the RAJ-II Criticality Analysis.

Table 6-4 Nominal vs. Worst Case Fuel Parameters for the RAJ-II Criticality Analysis

Case	Fuel Rod Pitch (cm)	Clad Outer Diameter (cm)	Clad Inner Diameter (cm)	Pellet Outer Diameter (cm)	Pellet Theoretical Density
FANP 10x10					
Nominal	1.284, 1.2954	1.010, 1.033	0.9020, 0.9217	0.8682, 0.8882	< 98%
Worst Case Modeled for Fuel Assembly Transport	1.350	1.000	0.9330	0.895	98%
Worst Case Modeled for Fuel Rod Transport	1.350	1.000	1.000	0.900	98%
GNF 10x10					
Nominal	1.2954	1.019	0.9322	0.8941	< 98%
Worst Case Modeled for Fuel Assembly Transport	1.350	1.010	0.9338	0.895	98%
Worst Case Modeled for Fuel Rod Transport	1.350	1.000	1.000	0.900	98%
FANP 9x9					
Nominal	1.4478	1.095, 1.0998	0.968, 0.9601	0.94, 0.9398	< 98%
Worst Case Modeled for Fuel Assembly Transport	1.510	1.093	1.020	0.960	98%
Worst Case Modeled for Fuel Rod Transport	1.510	1.020	1.020	0.960	98%
GNF 9x9					
Nominal	1.438	1.110	0.983	0.955	< 98%
Worst Case Modeled for Fuel Assembly Transport	1.510	1.093	1.020	0.960	98%
Worst Case Modeled for Fuel Rod Transport	1.510	1.020	1.020	0.960	98%
GNF 8x8					
Nominal	1.6256	1.2192	1.072	1.044	< 98%
Worst Case Modeled for Fuel Assembly Transport	1.6923	1.176	1.100	1.050	98%
Worst Case Modeled for Fuel Rod Transport	1.6923	1.100	1.100	1.050	98%

6.1.3 Criticality Safety Index

For the RAJ-II, undamaged packages have been analyzed in 21x3x24 arrays and damaged packages have been analyzed in 10x1x10 arrays. Pursuant to 10 CFR 71.59, the number of

packages "N" in a 2N array that are subjected to the tests specified in 10 CFR 71.73, or in a 5N array for undamaged packages is used to determine the Criticality Safety Index (CSI). The CSI is determined by dividing the number 50 by the most limiting value of "N" as specified in 10 CFR 71.59.

The RAJ-II criticality analysis demonstrates safety for 5N=1,512 (undamaged) and 2N=100 (damaged) packages. The corresponding Criticality Safety Index (CSI) for criticality control is given by CSI = 50/N. Since 5N=1,512 and 2N = 100, it follows that the more restrictive N = 50 and CSI = 50/50 = 1.0. Therefore the maximum allowable number of packages per shipment is 50/1.0 = 50.

6.2 FISSILE MATERIAL CONTENTS

The RAJ-II shall be used to transport UO_2 conforming to the requirements stated in Section 6.1, Table 6-1 and Table 6-2. The uranium isotopic distribution considered in the models used for the criticality safety demonstration is shown in Table 6-5 Uranium Isotopic Distribution.

Table 6-5 Uranium Isotopic Distribution

Isotope	Modeled wt. %
U-235	5.00
U-238	95.00

The criticality analysis conservatively demonstrates safety for UO_2 pellets within cylindrical zirconium alloy tubes, arranged in 8x8, 9x9, or 10x10 square assembly lattices. Cylindrical fuel rods containing UO_2, enriched up to 5 wt. percent U-235, are also conservatively demonstrated safe within the RAJ-II container in a 5-inch stainless steel pipe, loose, in a protective case, or bundled together. The fuel loadings demonstrated safe in the RAJ-II are specified in Table 6-1 and Table 6-2.

6.3 GENERAL CONSIDERATIONS

Models are generated for single package and package arrays under normal conditions and Hypothetical Accident Conditions (HAC).

6.3.1 Model Configuration

6.3.1.1 RAJ-II Shipping Container Single Package Model

The RAJ-II single package models are constructed for both normal conditions of transport and hypothetical accident conditions. The single package models are enveloped with a 30.48 cm layer of full density water for reflection.

6.3.1.1.1 Single Package Normal Conditions of Transport Model

The RAJ-II is comprised of an inner and outer container fabricated from Stainless Steel. The inner container dimensions are shown in

Figure 6-4 RAJ-II Inner Container Normal Conditions of Transport Model and Figure 6-5 RAJ-II Container Cross-Section Normal Conditions of Transport Model. It is lined with polyethylene foam having a density of up to 0.080 g/cm^3. The fuel assemblies rest against the polyethylene foam in a fixed position, and the inner container is positioned within the outer container as shown in Figure 6-5. The inner container has Alumina Silicate thermal insulation between the inner and outer walls. The Alumina Silicate density is approximately 0.25 g/cm^3. The outer container dimensions are contained in Figure 6-3 and Figure 6-5. The outer container provides protection for the inner container and additional separation between fuel assemblies in adjacent containers. No credit is taken for any of the structural steel between the inner and outer containers. The honeycomb shock absorbers, located between the inner and outer containers, are not explicitly modeled. Instead, water is placed in the space between the inner and outer containers, and its density is varied from 0.0 – 1.0 g/cm^3. The honeycomb shock absorbers have a density between 0.04 and 0.08 g/cm^3. The hydrogen number densities for water (1.0 g/cm^3) and for the honeycomb shock absorber (0.08 g/cm^3) are 6.677x10^{-2} and 2.973x10^{-3} atoms/b*cm, respectively. As a result, water is more effective at thermalizing neutrons than the honeycomb shock absorbers. Therefore, the use of water at 1.0 g/cm^3 between the inner and outer containers is considered a conservative replacement for the honeycomb shock absorbers.

The fuel assemblies are modeled inside the inner container, flush with the polyethylene foam. No fuel assembly structures outside the active length of the rod are represented in the models, with the exception of the fuel assembly channel. The fuel assembly structures outside the active fuel length, other than the fuel assembly channel, are composed of materials that absorb neutrons by radiative capture, therefore, neglecting them is conservative. In addition, no grids within the rod active length are represented. The internal grid structure displaces water from between the fuel rods, decreasing the H/X ratio. Since the fuel assemblies are undermoderated, decreasing the H/X ratio decreases system reactivity. Therefore, it is conservative to neglect the internal grid structure in modeling the RAJ-II container. The maximum pellet enrichment and maximum fuel lattice average enrichment is 5.0 wt% U-235. Only 75% credit is taken for gadolinia present in the fuel rods.

Calculations performed with the package array HAC model determine the fuel assembly modeling for the single package Normal Conditions of Transport (NCT) model. A fuel parameter sensitivity study is conducted and a worst case fuel assembly is developed for each fuel design. The sensitivity study results determine the fuel parameter ranges for the fuel assembly loading criteria shown in Table 6-1 and Table 6-2. The ranges are broad enough to accommodate future fuel assembly design changes. The fuel rod pitch, fuel pellet outer diameter, fuel rod clad inner and outer diameters, fuel rod number, and part length fuel rod number are varied independently in the package array HAC calculations. Reactivity effects are investigated, and the worst case is identified for each parameter perturbation. To validate the ranges for worst case fuel parameter combinations (e.g., worst case pellet OD, clad OD, clad ID, etc.) within the same assembly, a worst case fuel assembly is created for each fuel design considered for transport in the RAJ-II container, by choosing each parameter value that provides the highest system reactivity. Calculations performed with the worst case fuel assemblies validate the parameter ranges to be used as fuel acceptance criteria. Both un-channeled (Figure 6-9 through Figure 6-15) and channeled fuel assemblies, Figure 6-16, are considered in the worst case orientation, subjected to the worst case fuel damage, and the most reactive configuration is chosen for subsequent calculations.

The GNF 10x10 worst case fuel assembly is used for the RAJ-II single package NCT model since it is determined to be the most reactive assembly type in the package array HAC fuel parameter studies. The worst case fuel parameters for the GNF 10x10 assembly are presented in Table 6-11.

Polyethylene inserts or cluster separators are positioned between fuel rods at various locations along the axis of the fuel assembly to avoid stressing the axial grids during transportation. Two types of inserts, shown in Figure 6-1 and Figure 6-2, are considered for use with the RAJ-II container. Since the polyethylene cluster separators provide a higher volume average density polyethylene inventory, they are chosen for the RAJ-II criticality analysis. Other types of inserts are acceptable provided that their polyethylene inventory is within the limits established using the cluster separators.

The normal condition model utilizes the maximum allowable polyethylene mass and applies it over the full axial length of the fuel. The polyethylene is smeared into the water region surrounding the fuel rods as well as the water region surrounding the fuel assembly normally occupied by the cluster holder.

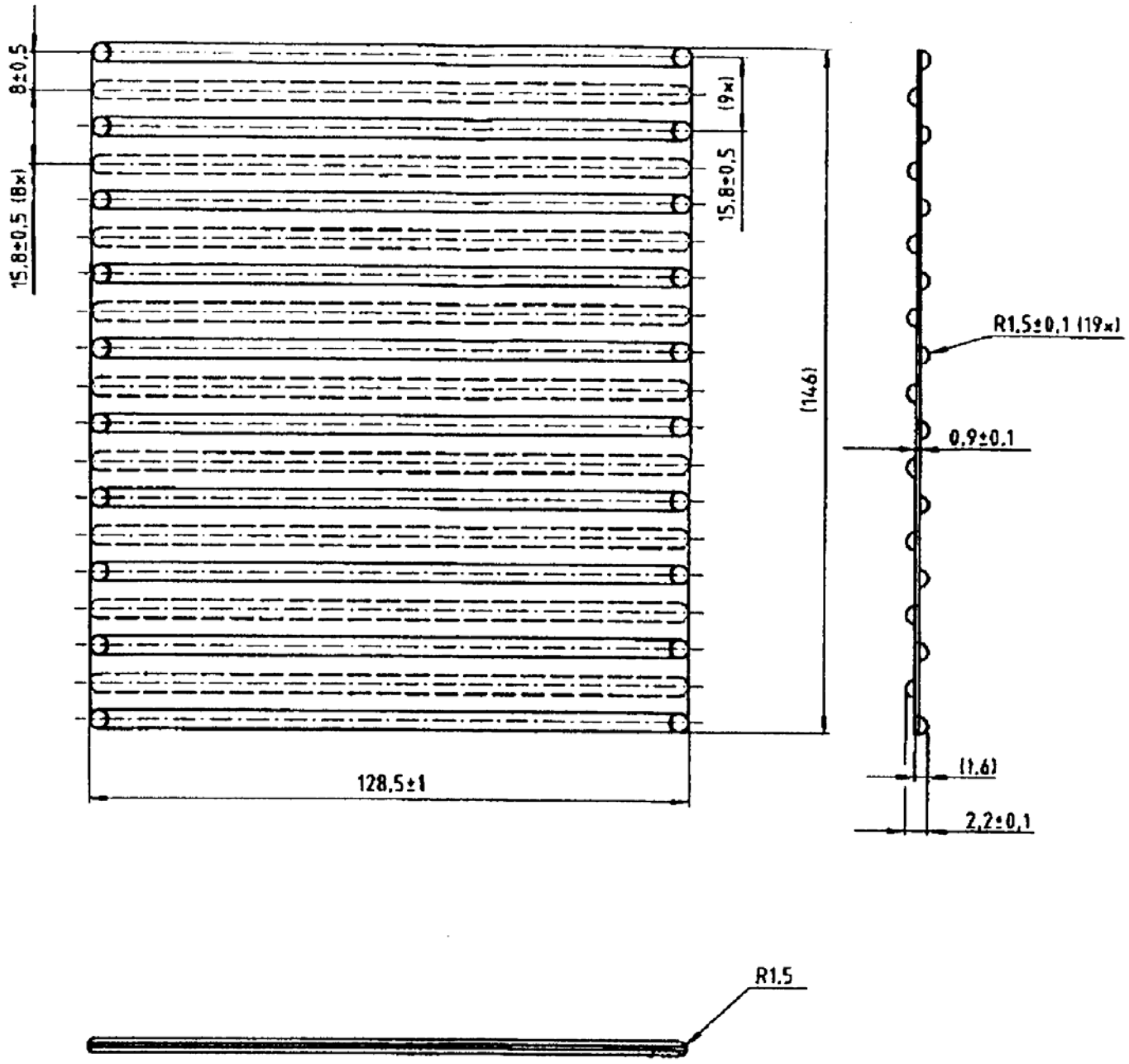


Figure 6-1 Polyethylene Insert (FANP Design)

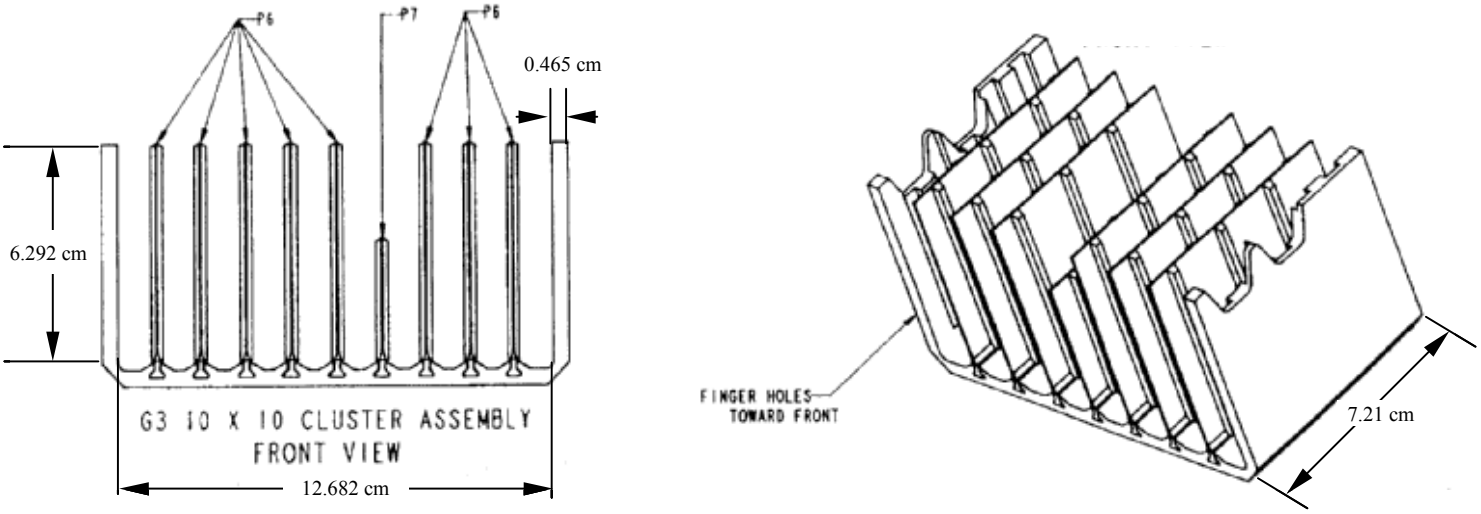


Figure 6-2 Polyethylene Cluster Separator Assembly (GNF Design)

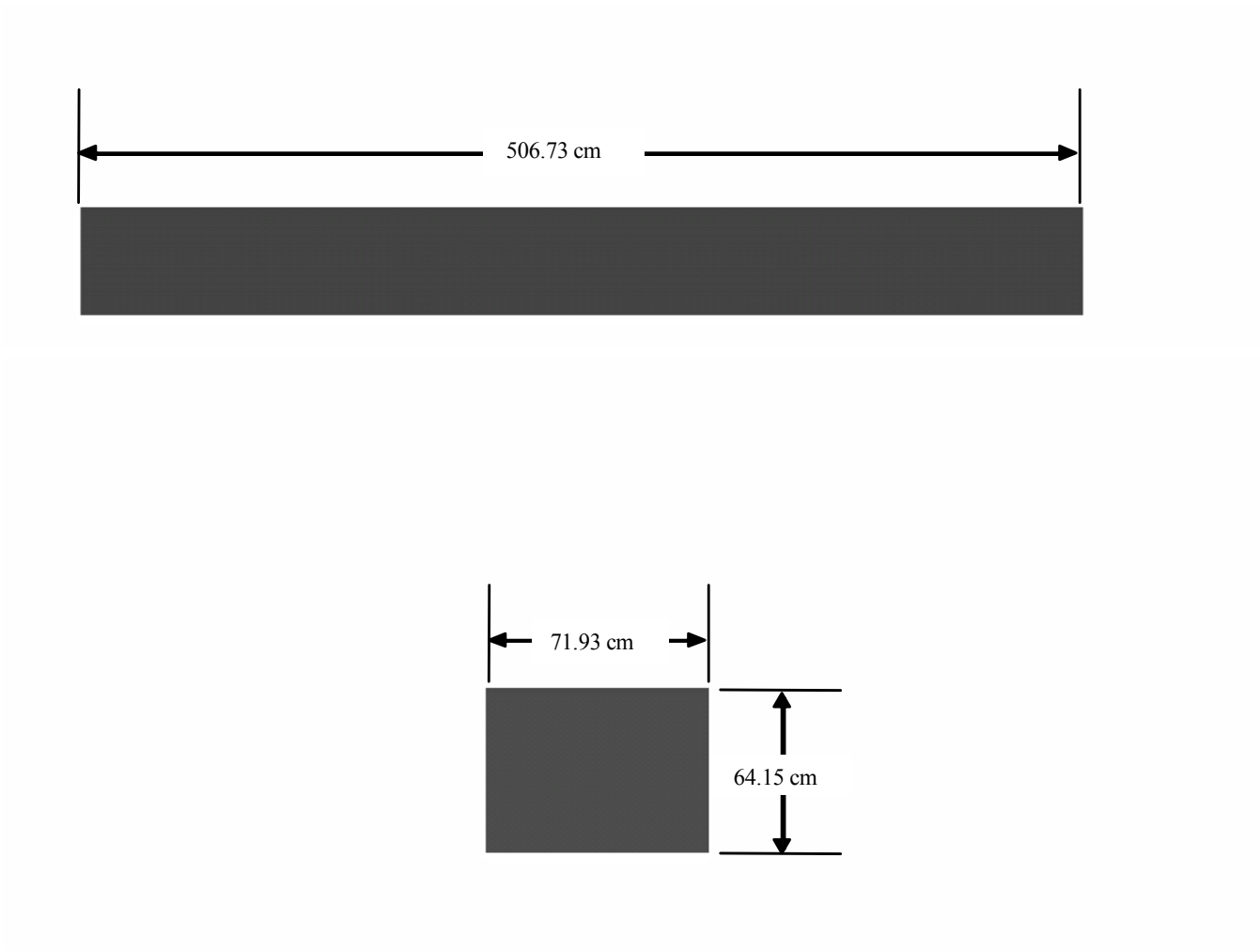


Figure 6-3 RAJ-II Outer Container Normal Conditions of Transport Model

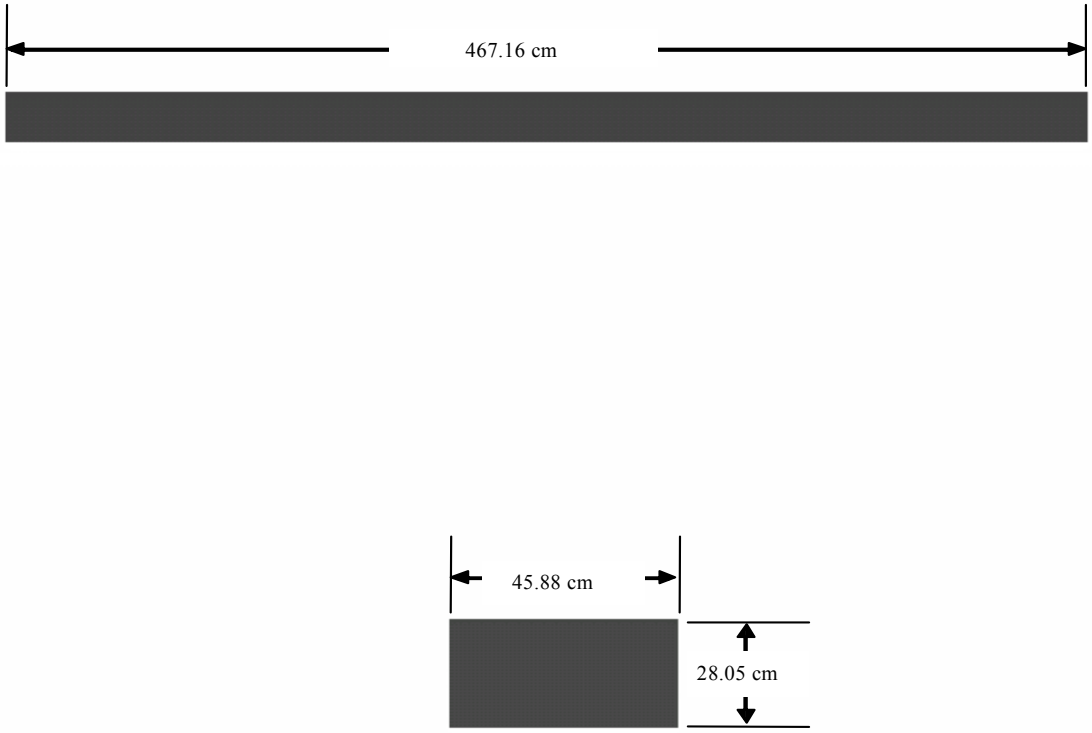


Figure 6-4 RAJ-II Inner Container Normal Conditions of Transport Model

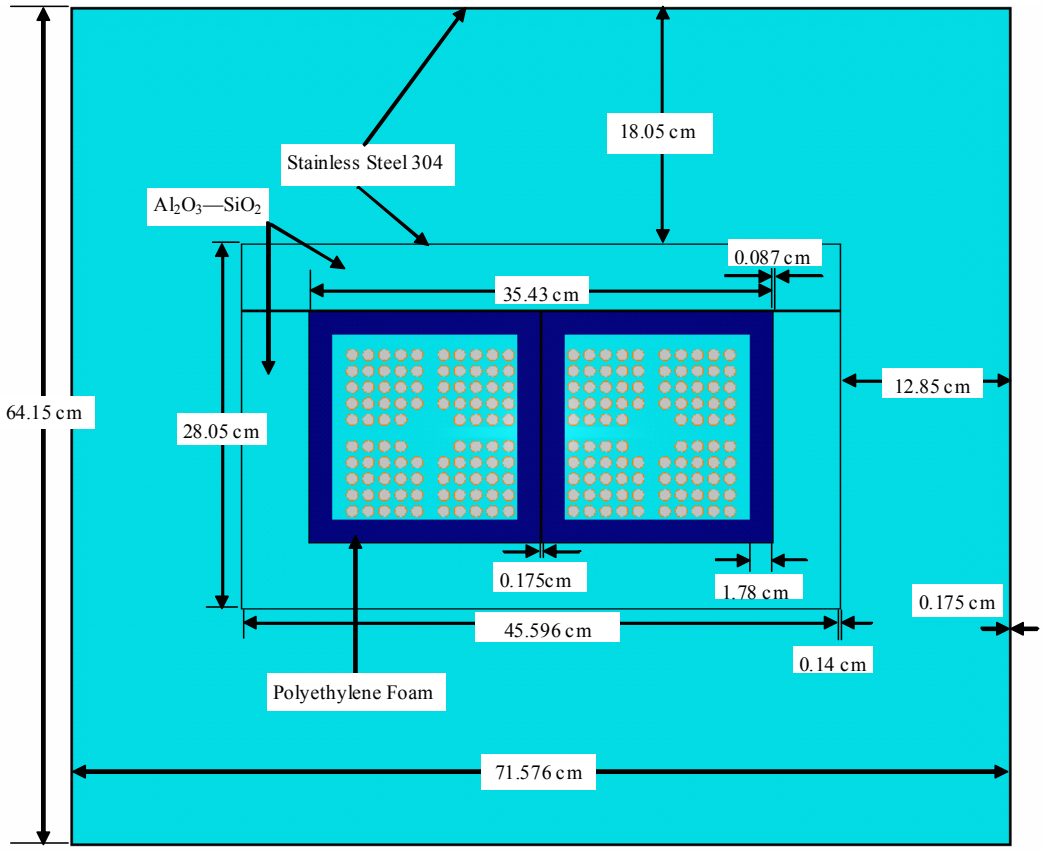


Figure 6-5 RAJ-II Container Cross-Section Normal Conditions of Transport Model

6.3.1.1.2 Single Package Hypothetical Accident Condition Model

The RAJ-II HAC model inner container dimensions are shown in Figure 6-7 and Figure 6-8. The container deformation modeled for the RAJ-II HAC model includes the damage incurred from the 9-meter drop onto an unyielding surface as well as conservative factors. The RAJ-II inner container length is conservatively reduced by 8.1 cm to bound the damage incurred from the 9-meter drop onto an unyielding surface. The polyethylene foam is assumed to burn away for the HAC single package model. Full density water that provides more reflection capability is assumed to flood the RAJ-II inner container fuel compartment. The Alumina Silicate insulation is assumed to remain in place, since scoping calculations proved it to provide a more reactive configuration. The fuel assemblies are assumed to freely move within the respective compartment resulting in a worst case orientation. The rubber vibro-isolating devices are also assumed to melt when exposed to an external fire, allowing the inner container to shift downward about 2.54 cm. However, scoping calculations reveal no increase in reactivity by moving the inner container; therefore, the inner container is positioned within the outer container as shown in Figure 6-8. The inner container horizontal position within the outer container remains the same as the normal condition model, since the stainless steel fixture assemblies remained intact following the 9-meter drop. The outer container dimensions are shown in Figure 6-6 RAJ-II Outer Container Hypothetical Accident Condition Model and Figure 6-8. The outer

container length is reduced by 4.7 cm to bound the damage sustained from a 9-meter drop onto an unyielding surface. In addition, the outer container height is reduced by 2.4 cm to bound the damage sustained during the 9-meter drop (Reference 1). No credit is taken for the structural steel between the inner and outer containers. The honeycomb shock absorbers, located between the inner and outer containers, are not explicitly modeled. Instead, water is placed in the space between the inner and outer containers, and its density is varied from 0.0 – 1.0 g/cm^3. The honeycomb shock absorbers have a density between 0.04 and 0.08 g/cm^3. The hydrogen number densities for water (1.0 g/cm^3) and for the honeycomb shock absorber (0.08 g/cm^3) are 6.677×10^{-2} and 2.973×10^{-3} atoms/b*cm, respectively. As a result, water is more effective at thermalizing neutrons than the honeycomb shock absorbers. Therefore, the use of water at 1.0 g/cm^3 between the inner and outer containers is considered a conservative replacement for the honeycomb shock absorbers. The reduction in length for the inner and outer containers, the reduction in height for the outer container, the absence of polyethylene foam, the presence of the insulation, and the fuel assembly freedom of movement are consistent with the physical condition of the RAJ-II shipping container after being subjected to the tests specified in 10 CFR Part 71.

Calculations performed with the package array HAC model determine the fuel assembly modeling for the single package HAC model. No fuel assembly structures outside the active length of the rod are represented in the models, with the exception of the fuel assembly channel. The fuel assembly structures outside the active fuel length, other than the fuel assembly channel, are composed of materials that absorb neutrons by radiative capture, therefore, neglecting them is conservative. In addition, no grids within the rod active length are represented. The internal grid structure displaces water from between the fuel rods, decreasing the H/X ratio. Since the fuel assemblies are undermoderated, decreasing the H/X ratio decreases system reactivity. Therefore, it is conservative to neglect the internal grid structure in modeling the RAJ-II container. The maximum pellet enrichment and maximum fuel lattice average enrichment is 5.0 wt% U-235. The gadolinia content of any gadolinia-urania fuel rods is taken to be 75% of the minimum value specified in Table 6-1. The fuel assemblies are modeled inside the inner container, in one of seven orientations shown in Figure 6-9 RAJ-II Hypothetical Accident Condition Model with Fuel Assembly Orientation 1 through Figure 6-15 RAJ-II Hypothetical Accident Condition Model with Fuel Assembly Orientation 7. The worst case orientation is chosen for each fuel assembly design considered for transport and used in subsequent calculations. Fuel damage sustained during the 9-meter (30 foot) drop test is simulated as a change in fuel rod pitch along the full axial length of each fuel assembly considered for transport. Based on the fuel damage sustained in the RAJ-II shipping container drop test (Reference 1), a 10% reduction in fuel rod pitch over the full length of each fuel assembly, or a 4.1% increase in fuel rod pitch over the full length of each fuel assembly, is determined to be conservative. Both un-channeled (Figure 6-9 through Figure 6-15) and channeled fuel assemblies (Figure 6-16) are considered in the worst case orientation, subjected to the worst case fuel damage, and the most reactive configuration is chosen for subsequent calculations.

The fuel damage sustained during the 9-meter drop test is bounded by performing a fuel parameter sensitivity study and creating a worst case fuel assembly for each fuel design. The sensitivity study results determine the fuel parameter ranges for the fuel assembly loading criteria shown in Table 6-1. The ranges are broad enough to accommodate future fuel assembly design changes. The fuel rod pitch, fuel pellet outer diameter, fuel rod clad inner and outer

diameters, fuel rod number, and part length fuel rod number are varied independently in the package array HAC calculations. Reactivity effects are investigated, and the worst case is identified for each parameter perturbation. To validate the ranges for worst case fuel parameter combinations (e.g. worst case pellet OD, clad OD, clad ID, etc.) within the same assembly, a worst case fuel assembly is created for each fuel design considered for transport in the RAJ-II container, by choosing each parameter value that provides the highest system reactivity. Calculations performed with the worst case fuel assemblies validate the parameter ranges to be used as fuel acceptance criteria.

The GNF 10x10 worst case fuel assembly at a 5.0 wt% U-235 enrichment, containing twelve 2 wt % gadolinia-urania fuel rods, and twelve part length fuel rods is used for the RAJ-II single package HAC model since it is determined to be the most reactive assembly in the package array HAC fuel parameter studies. The worst case fuel parameters for the 10x10 assembly are presented in Table 6-11.

Polyethylene inserts (cluster separators) are positioned between fuel rods at various locations along the axis of the fuel assembly to avoid stressing the axial grids during transportation. Two types of inserts, shown in Figure 6-1 and Figure 6-2, are considered for use with the RAJ-II container. Since the polyethylene cluster separators provide a higher volume averaged density polyethylene inventory, they are chosen for the RAJ-II criticality analysis. Other types of inserts are acceptable provided that their polyethylene inventory is within the limits established using the cluster separators.

In the hypothetical accident condition model, the polyethylene inserts are assumed to melt when subjected to the tests specified in 10 CFR Part 71. The polyethylene is assumed to uniformly coat the fuel rods in each fuel assembly forming a cylindrical layer of polyethylene around each fuel rod. Different coating thicknesses are investigated in the package array HAC calculations, and a polyethylene mass limit is developed for each fuel assembly type considered for transport. The RAJ-II single package model contains 10x10 worst case fuel assemblies with 10.2 kg of polyethylene per assembly. The polyethylene is smeared into the fuel rod cladding to accommodate the limitations in the lattice cell modeling for cross-section processing in SCALE. A visual representation of the smeared clad/polyethylene mixture compared to a discrete treatment is shown in Figure 6-21 Visual Representation of the Clad/Polyethylene Smeared Mixture versus Discrete Modeling. The polyethylene mass and the volume fractions of polyethylene and zirconium clad for each fuel assembly analyzed are shown in Table 6-13 Polyethylene Mass and Volume Fraction Calculations. The volume fractions in Table 6-13 are entered into the model input standard composition specification area. Mixtures representing the polyethylene inserts between fuel rods are created using the compositions specified, and used in the KENO V.a calculation. The mixtures are also used in the lattice cell description to provide the lump shape and dimensions for resonance cross-section processing, the lattice corrections for cross-section processing, and the information necessary to create flux-weighted cross-sections based on the lattice cell geometry.

6.3.1.2 Package Array Models

6.3.1.2.1 Package Array Normal Condition Model

The RAJ-II container package array normal condition model consists of a 21x3x24 array of containers, surrounded by a 30.48 cm layer of full density water for reflection. The container array is fully flooded with water at a density sufficient for optimum moderation. The container and fuel model in the array are those discussed in Section 6.3.1.1.1.

6.3.1.2.2 Package Array Hypothetical Accident Condition (HAC) Model

The RAJ-II package array HAC model consists of either a 14x2x16 or 10x1x10 array of containers, surrounded by a 30.48 cm layer of full density water for reflection. The 14x2x16 array (Sections 6.4.1 – 6.4.10) is initially used under the assumption that the polyethylene foam, on which the fuel assemblies rest, completely burns away during a fire. The 10x1x10 array (Sections 6.4.11 – 6.4.13) assumes the polyethylene foam remains intact following a fire. The container array has no interspersed water between packages in the array and no water in the outer container. These moderator conditions optimize the interaction between packages in the array. Unlike the HAC single package model, the HAC package array model assumes the polyethylene foam remains in place following the tests specified in 10 CFR 71. The presence of polyethylene foam allows increased neutron leakage from the inner container fuel compartment and promotes increased neutron interaction among containers in the array. The inner container fuel compartment space not occupied by the polyethylene foam is fully flooded with water at a density sufficient for optimum moderation. The remaining HAC model container and fuel details are those discussed in Section 6.3.1.1.2.

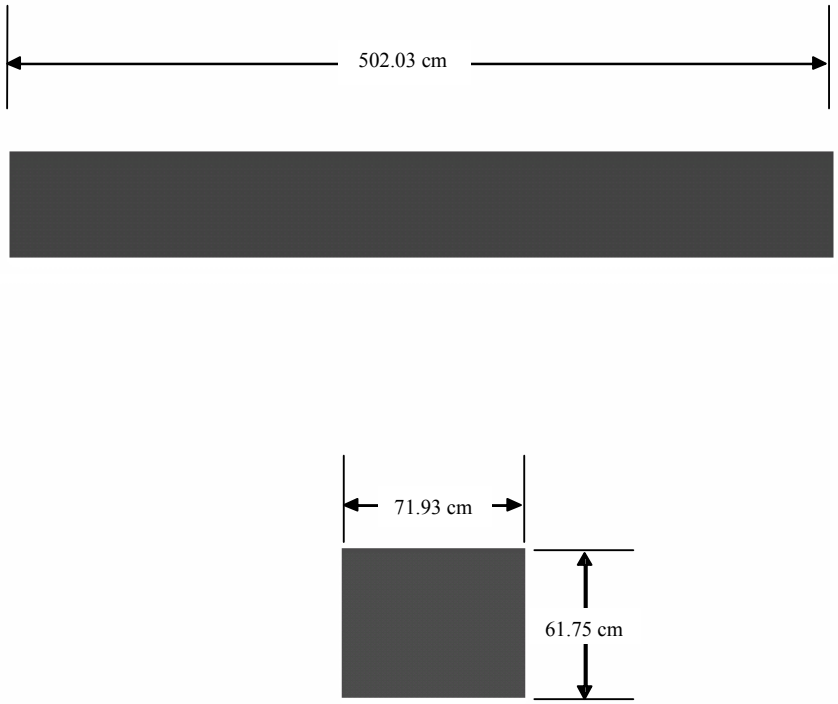


Figure 6-6 RAJ-II Outer Container Hypothetical Accident Condition Model

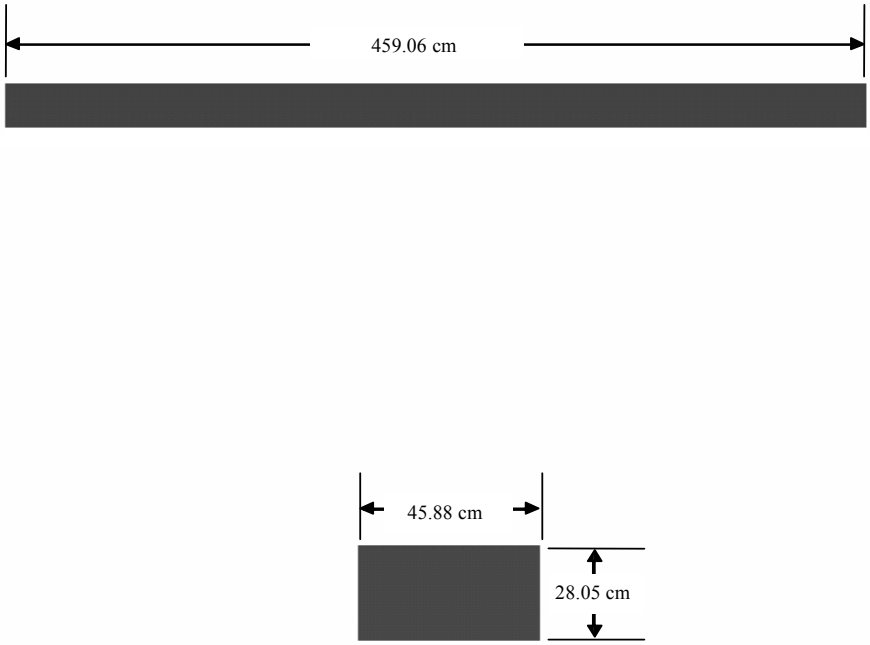


Figure 6-7 RAJ-II Inner Container Hypothetical Accident Condition Model

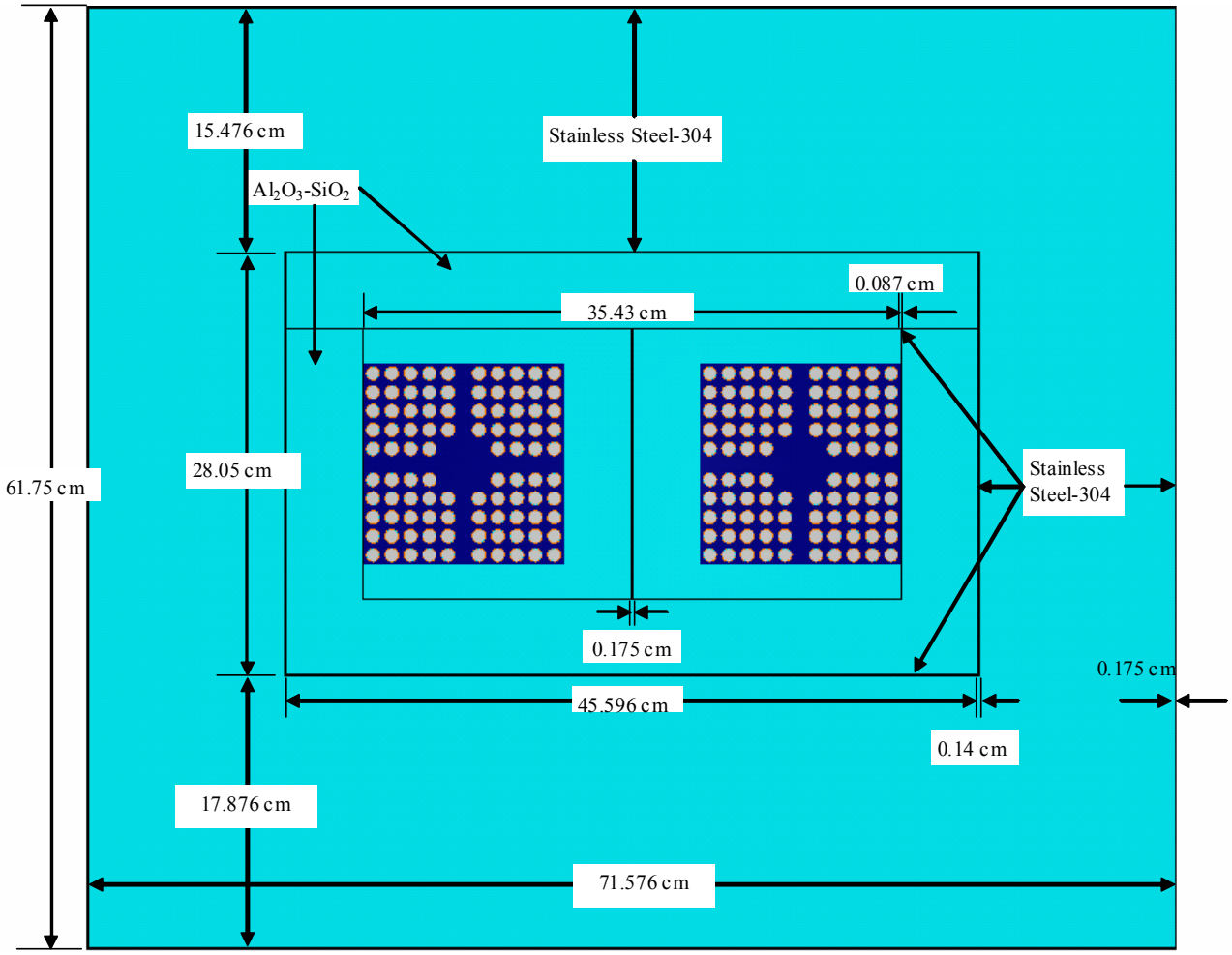


Figure 6-8 RAJ-II Cross-Section Hypothetical Accident Condition Model

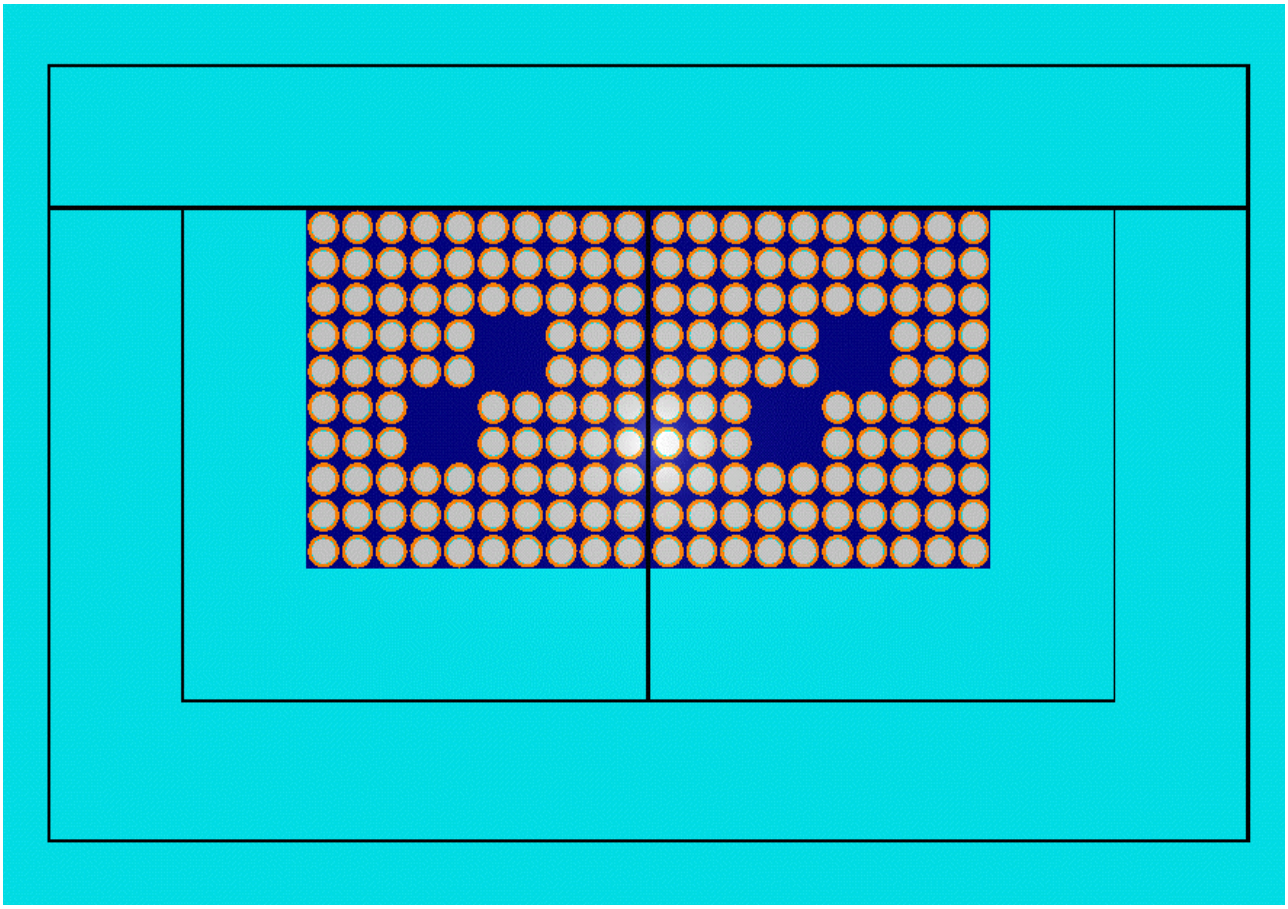


Figure 6-9 RAJ-II Hypothetical Accident Condition Model with Fuel Assembly Orientation 1

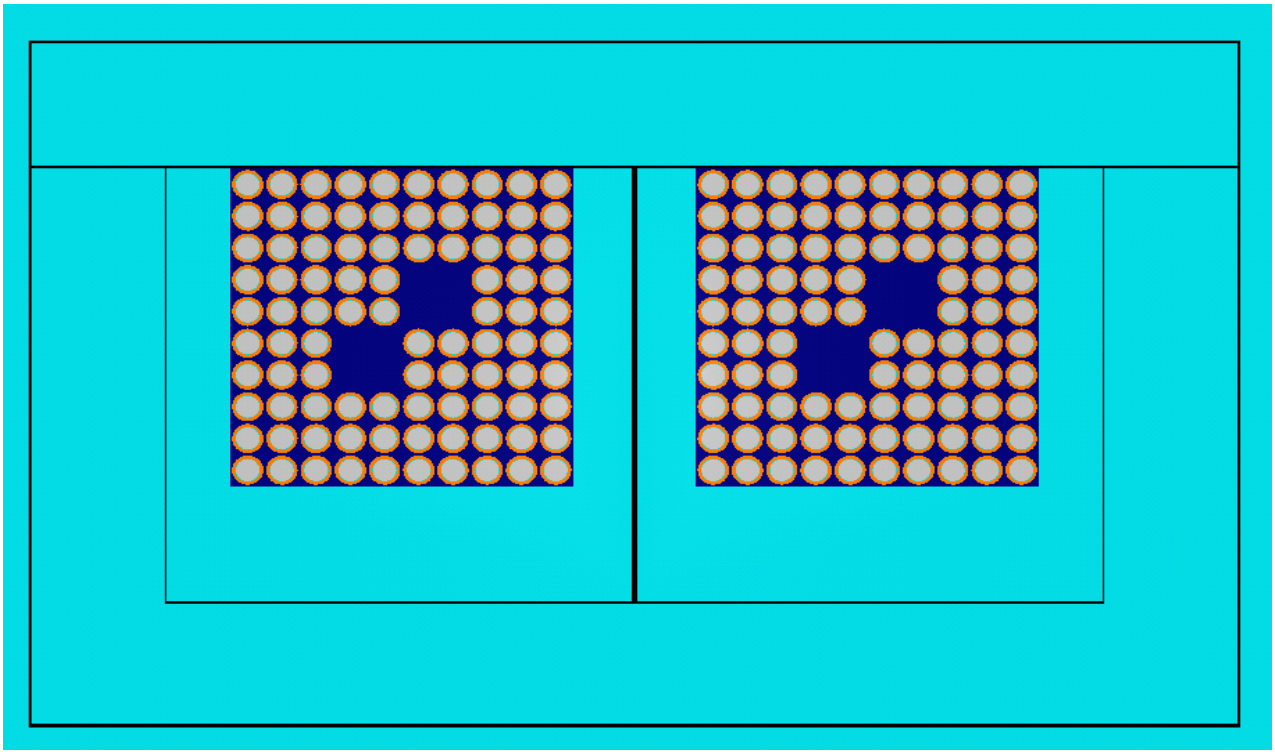


Figure 6-10 RAJ-II Hypothetical Accident Condition Model with Fuel Assembly Orientation 2

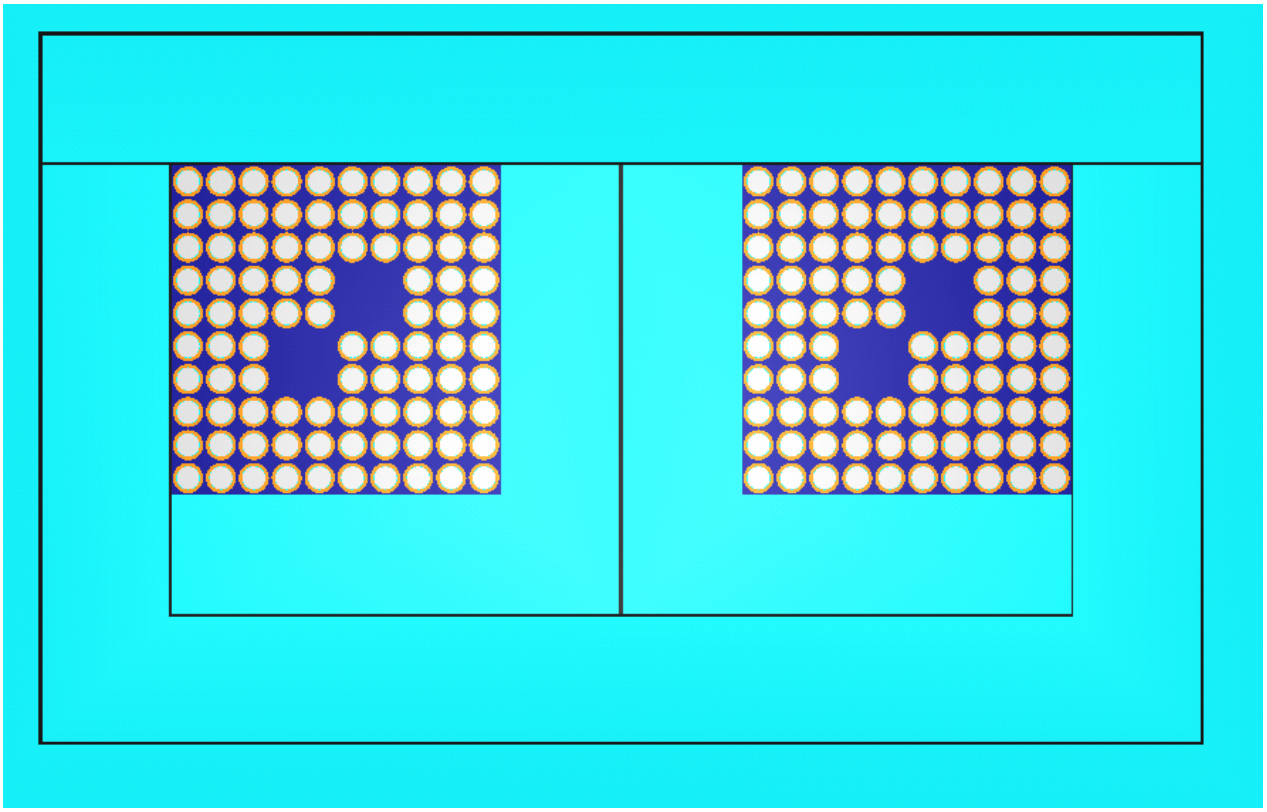


Figure 6-11 RAJ-II Hypothetical Accident Condition Model with Fuel Assembly Orientation 3

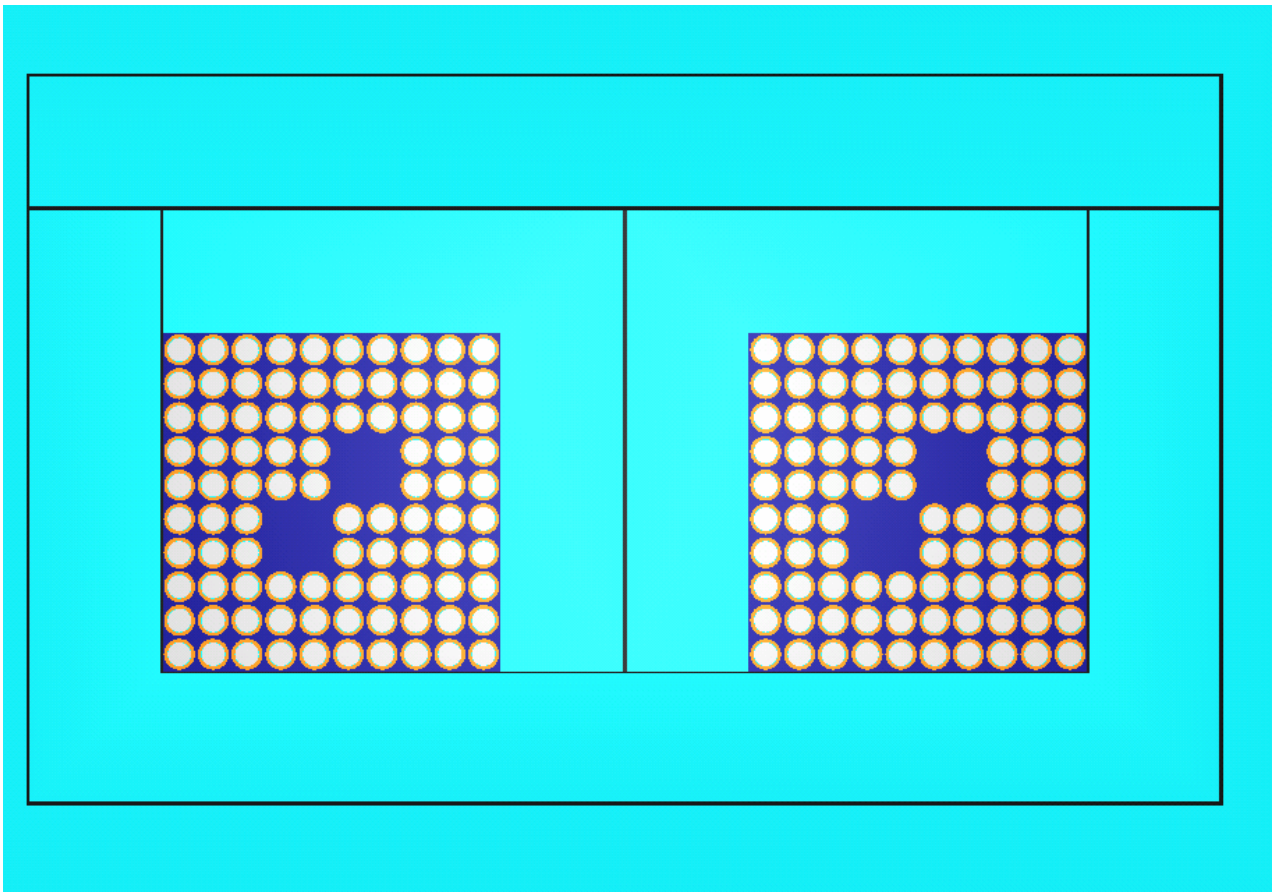


Figure 6-12 RAJ-II Hypothetical Accident Condition Model with Fuel Assembly Orientation 4

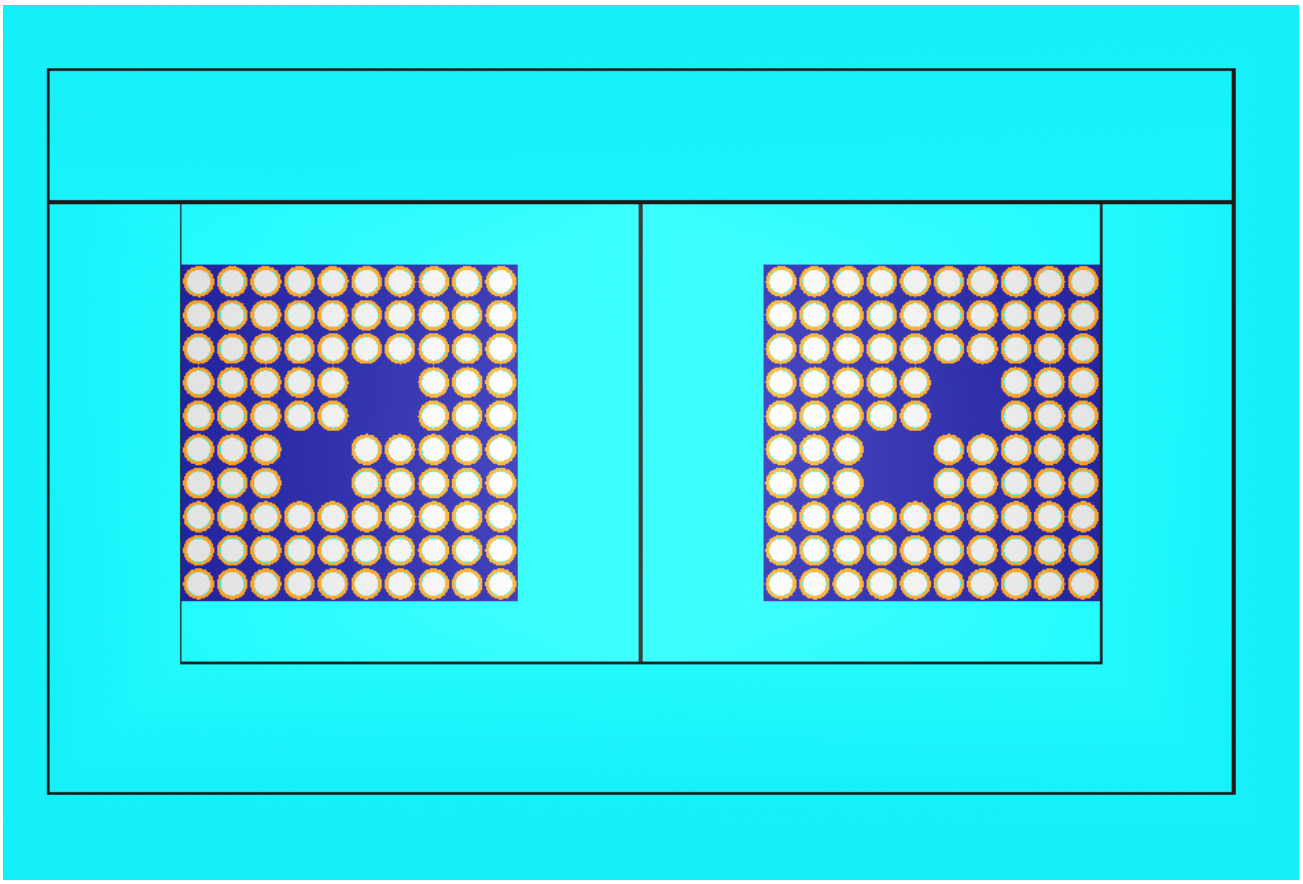


Figure 6-13 RAJ-II Hypothetical Accident Condition Model with Fuel Assembly Orientation 5

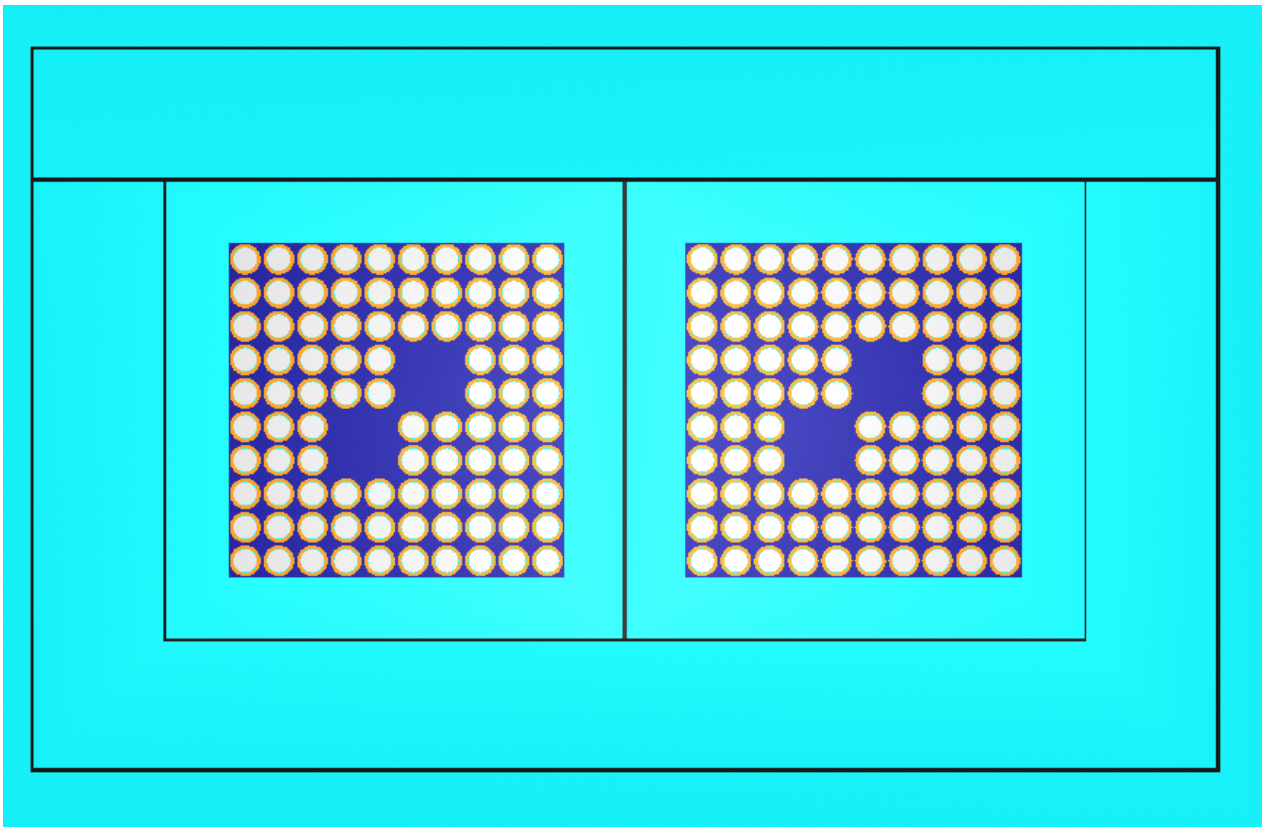


Figure 6-14 RAJ-II Hypothetical Accident Condition Model with Fuel Assembly Orientation 6

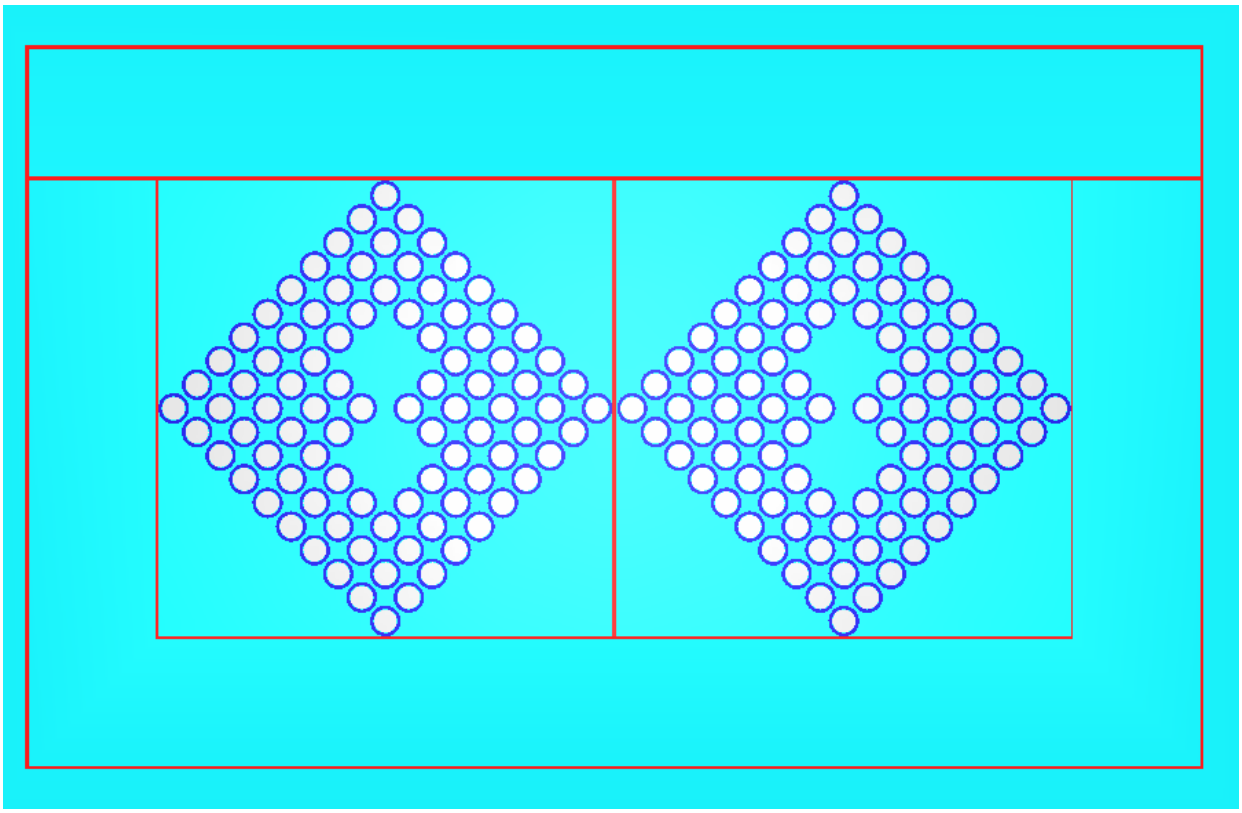


Figure 6-15 RAJ-II Hypothetical Accident Condition Model with Fuel Assembly Orientation 7

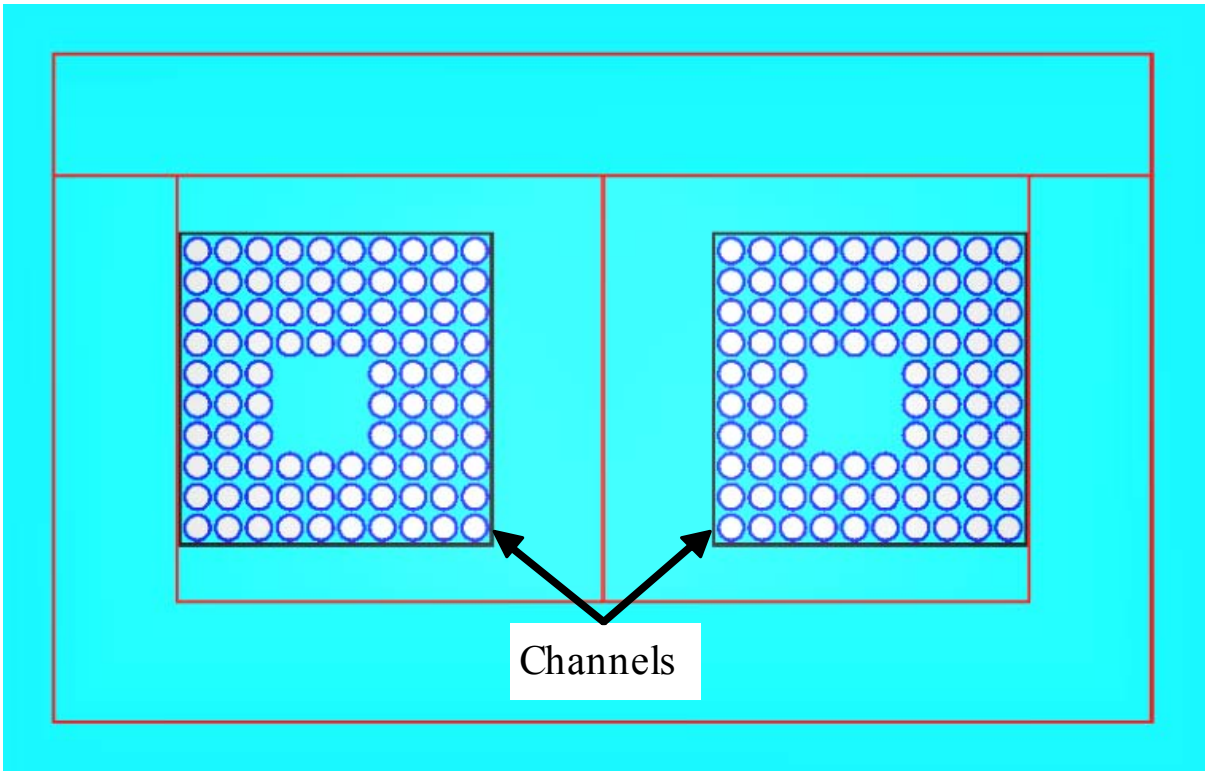


Figure 6-16 RAJ-II Hypothetical Accident Condition Model with Channels

6.3.1.3 RAJ-II Fuel Rod Transport Model

The RAJ-II fuel rod transport models are developed for single packages and package arrays under normal transport and hypothetical accident conditions. Cylindrical fuel rods containing UO_2, enriched to 5 wt. percent U-235, are modeled loose, bundled together, or in the RAJ-II inner container in 5-inch stainless steel pipe or protective case.

6.3.1.3.1 RAJ-II Single Package Fuel Rod Transport NCT Model

The RAJ-II single package normal conditions of transport described in Section 6.3.1.1.1 are used for the single package fuel rod transport models.

The fuel rods are modeled inside the inner container, flush with the polyethylene foam. A 0.0152 cm thick polyethylene layer is modeled around each fuel rod to simulate any protective material present. The worst case fuel rod parameters are shown in Table 6-6 RAJ-II Fuel Rod Transport Model Fuel Parameters.

Table 6-6 RAJ-II Fuel Rod Transport Model Fuel Parameters

Fuel Rod Type	Pellet OD (cm)	Fuel Rod ID (cm)	Fuel Rod OD (cm)	Fuel Rod Length (cm)
10x10	0.9	1.000	1.000	385
9 x 9	0.9600	1.0200	1.0200	381
8 x 8	1.05	1.1000	1.1000	381

Calculations performed with the fuel rod transport, package array, HAC model determine the fuel assembly modeling for the fuel rod transport, single package, Normal Conditions of Transport (NCT) model. The calculations investigate transporting loose fuel rods, bundled fuel rods, and fuel rods in 5-inch stainless steel pipe within each RAJ-II shipping compartment. A fuel rod pitch sensitivity study is conducted for each fuel rod type to determine the number of fuel rods that can be transported in a loose configuration within the RAJ-II fuel assembly compartment. A square pitch fuel rod array is used for the sensitivity study since scoping calculations showed no statistically significant difference in system reactivity between fuel rods in a square pitch array and those in a triangular pitch array within the container geometry. The pitch sensitivity study results in the minimum and maximum allowable fuel rod quantity for shipping in a loose configuration. The loose rod analysis is used to bound a fuel rod shipment in which fuel rods are strapped or bundled together. A fuel rod pitch sensitivity analysis is also performed to determine the fuel rod quantity that may be transported inside a 5-inch stainless steel pipe. A triangular pitch fuel rod array is used for the sensitivity study since scoping calculations showed it to result in a higher system reactivity than a square pitch rod array inside a 5-inch stainless steel pipe. The stainless steel material is conservatively neglected when performing the calculations, therefore, any container with a volume equivalent to or less than the 5-inch stainless steel pipe is acceptable for fuel rod transport, as long as the fuel rod quantity is limited to that for the pipe.

The 8x8 worst case fuel rod is used for the RAJ-II fuel rod transport, single package, NCT model since it is determined to be the most reactive rod in the fuel rod transport, package array, HAC pitch sensitivity studies. The RAJ-II fuel rod transport, single package NCT model is shown in Figure 6-17 RAJ-II Fuel Rod Transport Single Package NCT Model. The worst case fuel parameters for the 8x8 rod are presented in Table 6-6. As shown in Table 6-6, the fuel rod cladding is not modeled for the 8x8 fuel rod. Although the cladding material is removed, the fuel rod external boundary is maintained (i.e. pellet clad gap to fuel rod OD is maintained, polyethylene coating applied to fuel rod OD region).

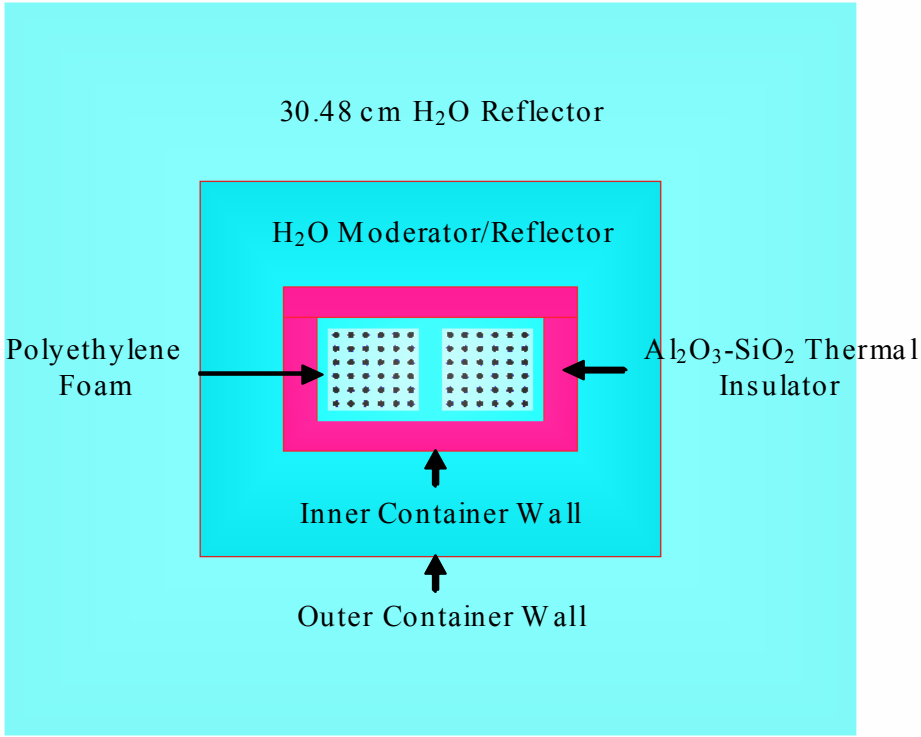


Figure 6-17 RAJ-II Fuel Rod Transport Single Package NCT Model

6.3.1.3.2 RAJ-II Single Package Fuel Rod Transport HAC Model

The RAJ-II single package hypothetical accident conditions described in Section 6.3.1.1.2 are used for the single package fuel rod transport models.

The fuel rods are modeled as filling the inner container fuel assembly compartment, since the polyethylene foam is removed due to the HAC. A 0.0152 cm thick polyethylene layer is modeled around each fuel rod to simulate any protective material present. Worst case fuel rod parameters determined from the package array HAC parameter sensitivity analyses (Section 6.3.1.1.2), are used for the fuel rod transport models. The worst case fuel rod parameters are shown in Table 6-6 RAJ-II Fuel Rod Transport Model Fuel Parameters.

Calculations performed with the fuel rod transport, package array, HAC model determine the fuel assembly modeling for the fuel rod transport, single package, HAC model. The calculations

investigate transporting loose fuel rods, bundled fuel rods, fuel rods in a 5-inch stainless steel pipe and protective case within each RAJ-II shipping compartment. A fuel rod pitch sensitivity study is conducted for each fuel rod type to determine the number of fuel rods that can be transported in a loose configuration within the RAJ-II fuel assembly compartment. A square pitch fuel rod array is used for the sensitivity study since scoping calculations showed no statistically significant difference in system reactivity between fuel rods in a square pitch array and those in a triangular pitch array within the container geometry. The pitch sensitivity study results in the minimum and maximum allowable fuel rod quantity for shipping in a loose configuration. The loose rod analysis is used to bound a fuel rod shipment in which fuel rods are strapped together. A fuel rod pitch sensitivity analysis is also performed to determine the fuel rod quantity that may be transported inside a 5-inch stainless steel, Type 304 pipe. A triangular pitch fuel rod array is used for the sensitivity study since scoping calculations showed it to result in a higher system reactivity than a square pitch rod array inside a 5-inch stainless steel pipe. The stainless steel material is conservatively neglected when performing the calculations, therefore, any container with a volume equivalent to or less than the 5-inch stainless steel pipe is acceptable for fuel rod transport, as long as the fuel rod quantity is limited to that for the pipe.

The 8x8 worst case fuel rod is used for the RAJ-II fuel rod transport, single package, HAC model since it is determined to be the most reactive rod in the fuel rod transport, package array, HAC pitch sensitivity studies. The RAJ-II fuel rod transport, single package HAC model is shown in Figure 6-18 RAJ-II Fuel Rod Transport Single Package HAC Model. The worst case fuel parameters for the 8x8 rod are presented in Table 6-6. As shown in Table 6-6, the fuel rod cladding is not modeled for the 8x8 fuel rod. Although the cladding material is removed, the fuel rod external boundary is maintained (i.e., pellet clad gap to fuel rod OD is maintained, polyethylene coating applied to fuel rod OD region).

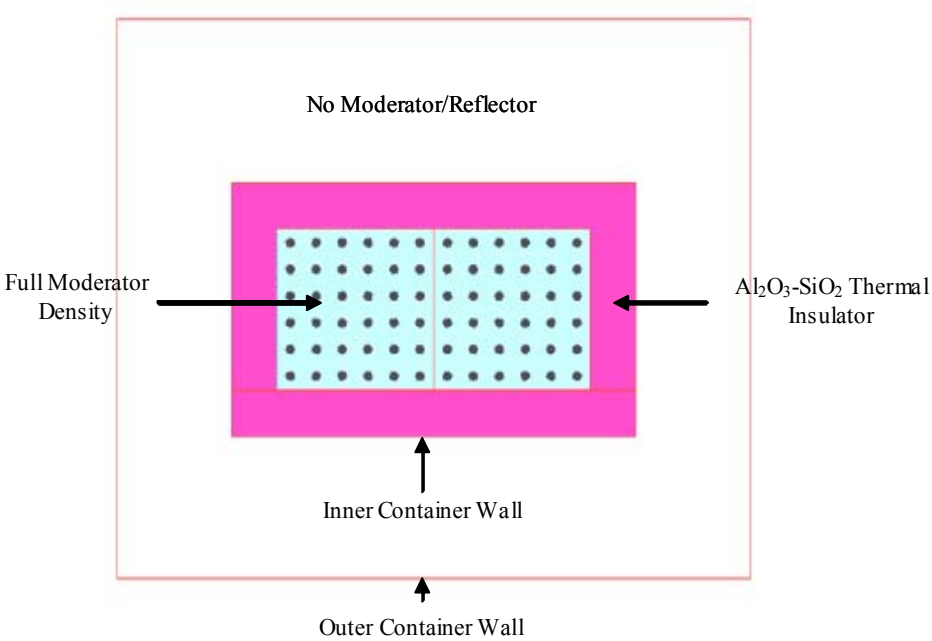


Figure 6-18 RAJ-II Fuel Rod Transport Single Package HAC Model

6.3.1.3.3 RAJ-II Package Array Fuel Rod Transport NCT Model

The RAJ-II package array normal conditions of transport described in Section 6.3.1.2.1 are used for the package array, normal conditions of transport, fuel rod transport models.

The fuel rods are modeled inside the inner container, flush with the polyethylene foam. A 0.0152 cm thick polyethylene layer is modeled around each fuel rod to simulate any protective material present. Worst case fuel rod parameters determined from the package array HAC parameter sensitivity analyses (Section 6.3.1.2.2), are used for the fuel rod transport models. The worst case fuel rod parameters are shown in Table 6-6.

Calculations performed with the fuel rod transport, package array, HAC model determine the fuel assembly modeling for the fuel rod transport, package array, Normal Conditions of Transport (NCT) model. The calculations investigate transporting loose fuel rods, bundled fuel rods, and fuel rods in 5-inch stainless steel pipe within each RAJ-II shipping compartment. A fuel rod pitch sensitivity study is conducted for each fuel rod type to determine the number of fuel rods that can be transported in a loose configuration within the RAJ-II fuel assembly compartment. A square pitch fuel rod array is used for the sensitivity study since scoping calculations showed no statistically significant difference in system reactivity between fuel rods in a square pitch array and those in a triangular pitch array within the container geometry. The pitch sensitivity study results in the minimum and maximum allowable fuel rod quantity for shipping in a loose configuration. The loose rod analysis is used to bound a fuel rod shipment in which fuel rods are strapped or bundled together.

A fuel rod pitch sensitivity analysis is also performed to determine the fuel rod quantity that may be transported inside a 5-inch stainless steel pipe. A triangular pitch fuel rod array is used for the sensitivity study since scoping calculations showed it to result in a higher system reactivity than a square pitch rod array inside a 5-inch stainless steel pipe. The stainless steel material is conservatively neglected when performing the calculations, therefore, any container with a volume equivalent to or less than the 5-inch stainless steel pipe is acceptable for fuel rod transport, as long as the fuel rod quantity is limited to that for the pipe.

The 8x8 worst case fuel rod is used for the RAJ-II fuel rod transport, package array, NCT model since it is determined to be the most reactive rod in the fuel rod transport, package array, HAC pitch sensitivity studies. A portion of the RAJ-II fuel rod transport, 21x3x24 package array, NCT model is shown in Figure 6-19. The worst case fuel parameters for the 8x8 rod are presented in Table 6-6. As shown in Table 6-6, the fuel rod cladding is not modeled for the 8x8 fuel rod. Although the cladding material is removed, the fuel rod external boundary is maintained (i.e., pellet clad gap to fuel rod OD is maintained, polyethylene coating applied to fuel rod OD region).

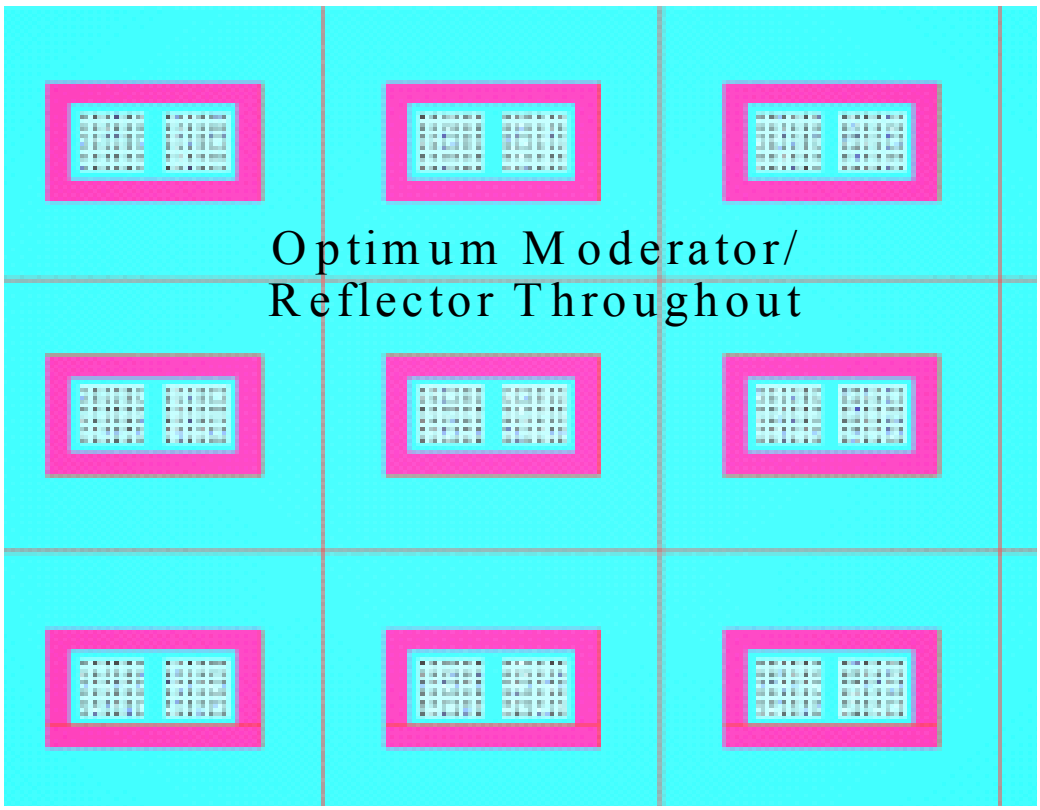


Figure 6-19 RAJ-II Fuel Rod Transport Package Array NCT Model

6.3.1.3.4 RAJ-II Package Array Fuel Rod Transport HAC Model

The RAJ-II package array hypothetical accident conditions described in Section 6.3.1.2.2 are used for the package array, HAC, fuel rod transport models.

The fuel rods are modeled filling the inner container for the hypothetical accident conditions. A 0.0152 cm thick polyethylene layer is modeled around each fuel rod to simulate any protective material present. Worst case fuel rod parameters determined from the package array HAC parameter sensitivity analyses (Section 6.3.1.2.2), are used for the fuel rod transport models. The worst case fuel rod parameters are shown in Table 6-6.

Calculations are conducted to investigate transporting loose fuel rods, bundled fuel rods, and fuel rods in 5-inch stainless steel pipe within each RAJ-II shipping compartment. A fuel rod pitch sensitivity study is conducted for each fuel rod type, to determine the number of fuel rods that can be transported in a loose configuration within the RAJ-II fuel assembly compartment. For convenience, a square pitch array is used to conduct the sensitivity study, since scoping calculations revealed little difference in the reactivity between square and triangular pitch arrays. The pitch sensitivity study results in the minimum and maximum allowable fuel rod quantity for shipping rods in a loose configuration. The loose rod analysis is used to bound a fuel rod shipment in which fuel rods are strapped or bundled together.

A fuel rod pitch sensitivity analysis is also performed to determine the fuel rod quantity that may be transported inside a 5-inch stainless steel pipe. Triangular pitch fuel rod arrays are used to

find the maximum allowable quantity. The stainless steel material is conservatively neglected when performing the calculations, therefore, any container with a volume equivalent to or less than the 5-inch stainless steel pipe is acceptable for fuel rod transport, as long as the fuel rod quantity is limited to that for the pipe.

The fuel rod type with the most reactive configuration is chosen for the RAJ-II fuel rod transport, package array, HAC model. A portion of the RAJ-II fuel rod transport package array HAC model is shown in Figure 6-20.

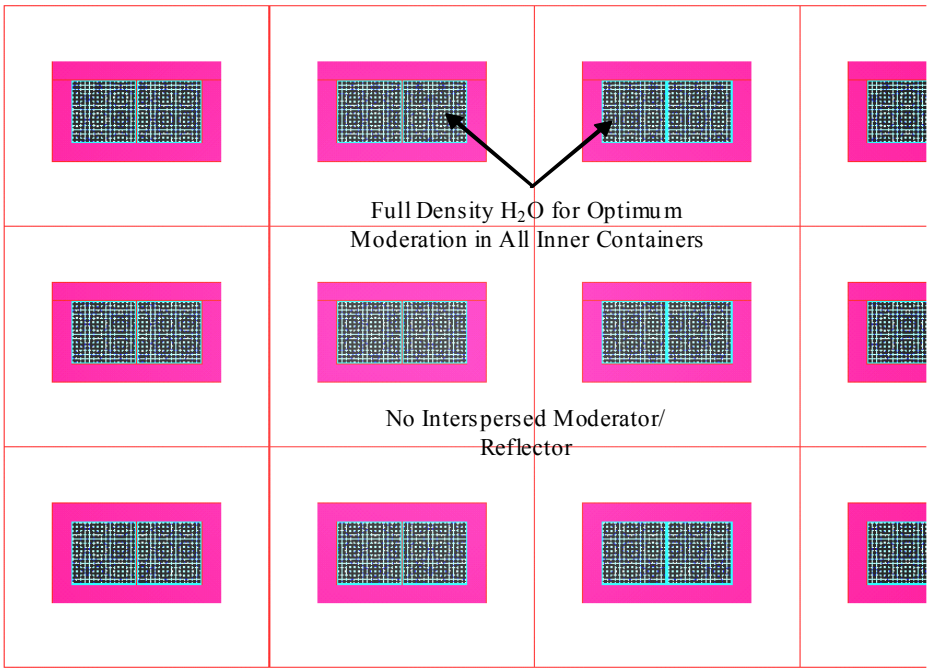


Figure 6-20 RAJ-II Fuel Rod Transport Package Array HAC Model

6.3.2 Material Properties

6.3.2.1 Material Tolerances

Table 6-7 Dimensional Tolerances provides sheet metal thickness dimensional tolerance from ASTM A240 and ASTM A480 (the former refers to the latter for specific tolerances). The table also provides the thicknesses used in the damaged and undamaged container models.

Table 6-7 Dimensional Tolerances

Stainless Steel Sheet Gauge	Nominal Thickness (mm)	Permissible Variations* (mm)	Model Thickness Used (in.) [cm] (description)
2 mm.	2.00 mm	± 0.18	0.0689 [0.175] (outer container wall)
1.5 mm	1.50 mm	± 0.15	0.0535 [0.136] (inner container wall)
1.0 mm.	1.00 mm	± 0.13	0.0344 [0.0875] (inner container fuel assembly compartments)

* ASTM-A240/A240M- 97b, Table A1.2, *Standard Specification for Heat Resisting Chromium and Chromium-Nickel Stainless Steel Plate, Sheet, and Strip for Pressure Vessels*, August 1997.

6.3.2.2 MATERIAL SPECIFICATIONS

Table 6-8 Material Specifications for the RAJ-II contains the material compositions for the RAJ-II shipping container. The UO_2 stack density is taken as 98% of theoretical. The presence of Gd_2O_3 in the UO_2-Gd_2O_3 pellet reduces the density from 10.74 to 10.67 g/cm^3.

Table 6-8 Material Specifications for the RAJ-II

Material	Density (g/cm^3)	Constituent	Atomic Density (atoms/b-cm)
$U(5.0)O_2$ 98% Theoretical Density	10.74	U-235 U-238 O	1.2128×10^{-3} 2.2753×10^{-2} 4.7931×10^{-2}
$U(5.0)O_2$-Gd_2O_3 98% Theoretical Density 2 wt% Gd_2O_3 (75% credit for Gd)	10.67	U-235 U-238 O Gd-152 Gd-154 Gd-155 Gd-156 Gd-157 Gd-158 Gd-160	1.18663×10^{-03} 2.22611×10^{-02} 4.76929×10^{-02} 1.06320×10^{-6} 1.15892×10^{-5} 7.86790×10^{-5} 1.08822×10^{-4} 8.31978×10^{-5} 1.32053×10^{-4} 1.16211×10^{-4}
Zirconium	6.49	Zr	4.2846×10^{-2}
Stainless Steel 304	7.94	Fe Cr Ni Mn Si C P	5.8545×10^{-2} 1.7473×10^{-2} 7.7402×10^{-3} 1.7407×10^{-3} 1.7025×10^{-3} 3.1877×10^{-4} 6.9468×10^{-5}

Material	Density (g/cm^3)	Constituent	Atomic Density (atoms/b-cm)
Polyethylene Foam	≤ 0.05 – 0.075	C H	3.4374×10^{-3} 6.8748×10^{-3}
Low Density Polyethylene (LDPE) Insert	0.925	C H	3.9745×10^{-2} 7.9490×10^{-2}
Polyethylene Cluster Assembly	0.949	C H	4.0776×10^{-2} 8.1552×10^{-2}
Alumina Silicate [Al_2O_3(49%)-SiO_2(51%)]	0.25	Al Si O	1.4474×10^{-3} 1.2783×10^{-3} 4.7277×10^{-3}
Paper Honeycomb $C_6H_{10}O_5$	0.04 – 0.08	C H O	1.7840×10^{-3} 2.9733×10^{-3} 1.4867×10^{-3}
Full Density Water	1.0	H O	6.6769×10^{-2} 3.3385×10^{-2}

Polyethylene inserts or polyethylene cluster separators are positioned between fuel rods at various locations along the axis of the fuel assembly to avoid stressing the axial grids during transportation. The inserts are shown in Figure 6-1 while the separators are shown in Figure 6-2. The Low Density Polyethylene (LDPE) insert has a 0.925 g/cm^3 density and an approximate volume of 25 cm^3. Therefore, a 10x10 assembly with 9 polyethylene inserts has a 225 cm^3 total LDPE volume required for one location along the fuel assembly.

The cluster separator is composed of LDPE (0.925 g/cm^3) fingers and a High Density Polyethylene (HDPE, 0.959 g/cm^3) holder (The LDPE and HDPE densities are based on accepted industry definitions). The LDPE fingers (10x10) occupy an approximate volume of 38 cm^3 while the HDPE holder has an approximate volume of 85 cm^3. A volume average density of 0.949 g/cm^3 is calculated for the polyethylene cluster assembly, i.e.

$$\left[\frac{\left(38cm^3 \times 0.925g/cm^3\right) + \left(85cm^3 \times 0.959g/cm^3\right)}{123cm^3}\right]$$

For a 10x10 assembly, two cluster separators, shown in Figure 6-2, are placed at numerous locations along the fuel assembly. A total polyethylene volume of 246 cm^3 is calculated for each location in which the cluster separators are placed. The RAJ-II criticality calculations use the 10x10 cluster separator characteristics for the fuel types investigated. However, the polyethylene characteristics are only used to establish a polyethylene mass limit so that an accurate measurement of polyethylene characteristics by the user is unnecessary. Other plastics with equivalent hydrogen mass limits are acceptable. The following equation can be used to determine plastic equivalence (e.g., ABS plastic).

$$M_{eq,i} = M_{poly} \times \frac{0.137}{(\rho_{mix,i} \times wf_{H,i})}$$

The formula for polyethylene mass equivalence is:

$$M_{eq,i} = M_{poly} \times [(rho_{mix,poly})(wf_{H,\ poly})]/[(rho_{mix,i})(wf_{H,i})]$$

$$= M_{poly} \times [(0.949\ g/cm^3)(0.144)]/[(rho_{mix,i})(wf_{H,i})]$$

$$= M_{poly} \times (0.137\ g/cm^3)/[(rho_{mix,i})(wf_{H,i})]$$

The fuel parameters used to calculate volume fractions for the water and polyethylene mixture in the RAJ-II normal condition model are shown in Table 6-9 RAJ-II Normal Condition Model Fuel Parameters. The volume fractions of polyethylene and water for the worst case fuel assembly type analyzed are shown in Table 6-10 RAJ-II Normal Condition Model Polyethylene and Water Volume Fractions and Table 6-11 Single Package Normal and HAC Model Fuel Parameters. The volume fractions in Table 6-10 are entered into the model input standard composition specification area. Mixtures representing the polyethylene inserts between fuel rods are created using the compositions specified, and used in the KENO V.a calculation. The mixtures are also used in the lattice cell description to provide the lump shape and dimensions for resonance cross-section processing, the lattice corrections for cross-section processing, and the information necessary to create cell-weighted cross-sections.

Table 6-9 RAJ-II Normal Condition Model Fuel Parameters

Fuel Assembly	Fuel Rod OR (cm)	Number of Fuel Rods	Fuel Rod Pitch (cm)	Fuel Rod Length (cm)	Cluster Separator Volume Surrounding Fuel (cm^3)	Number of Part Length Fuel Rods
GNF 10x10	0.505	92	1.350	385	10,200	12

Table 6-10 RAJ-II Normal Condition Model Polyethylene and Water Volume Fractions

Fuel Assembly	Assembly Volume (cm^3)	Fuel Rod Volume (cm^3)	Interstitial Volume (cm^3)	Polyethylene Volume (cm^3)	Vf_{poly}	Vf_{H2O}
GNF 10x10	66,676.46	26,527.22	40,149.24	10,200	0.25405	0.74595

Table 6-11 Single Package Normal and HAC Model Fuel Parameters

Fuel Assembly	Partial Fuel Rods (#)	Pitch (cm)	Pellet Diameter (cm)	Clad Inner Diameter (cm)	Clad Outer Diameter (cm)
GNF 10X10	12	1.350	0.895	0.9338	1.010

In the hypothetical accident condition model, the polyethylene inserts are assumed to melt when subjected to the tests specified in 10 CFR Part 71. The polyethylene is assumed to uniformly coat the fuel rods in each fuel assembly forming a cylindrical layer of polyethylene around each fuel rod. Different coating thicknesses are investigated, and a maximum thickness is determined to set a polyethylene mass limit for each fuel assembly type considered for transport. The fuel assembly parameters used to calculate the polyethylene mass limits are shown in Table 6-12 Fuel Assembly Parameters for Polyethylene Mass Calculations. For the fuel parameter sensitivity study and the worst case fuel assembly models, the polyethylene is smeared into the fuel rod cladding to accommodate the limitations in the lattice cell modeling for cross-section processing in SCALE. A visual representation of the smeared clad/polyethylene mixture compared to a discrete treatment is shown in Figure 6-21 Visual Representation of the Clad/Polyethylene Smeared Mixture versus Discrete Modeling. The polyethylene mass and the volume fractions of polyethylene and zirconium clad for each fuel assembly analyzed are shown in Table 6-13 Polyethylene Mass and Volume Fraction Calculations. The volume fractions in Table 6-13 are entered into the model input standard composition specification area. Mixtures representing the polyethylene inserts between fuel rods are created using the compositions specified, and used in the KENO V.a calculation. The mixtures are also used in the lattice cell description to provide the lump shape and dimensions for resonance cross-section processing, the lattice corrections for cross-section processing, and the information necessary to create cell-weighted cross-sections.

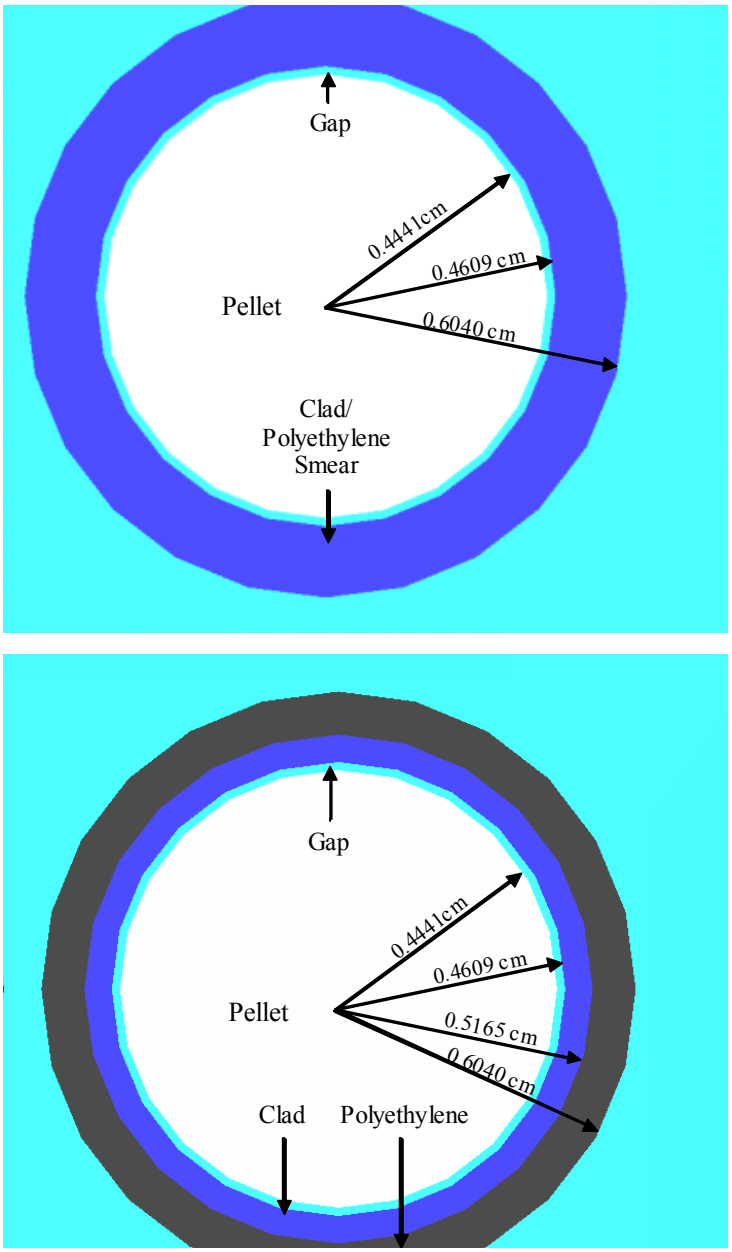


Figure 6-21 Visual Representation of the Clad/Polyethylene Smeared Mixture versus Discrete Modeling

Table 6-12 Fuel Assembly Parameters for Polyethylene Mass Calculations

Fuel Assembly Design	Fuel Rod OR (cm)	Number of Fuel Rods	Fuel Rod Pitch (cm)	Fuel Rod Length (cm)	Fuel Rod IR (cm)
ATRIUM 10x10	0.5165	91	1.284	383.54	0.4609
GNF 10x10	0.50927	92	1.2954	381	0.46609
Framatome 9x9	0.54991	72	1.4478	381	0.48006
GNF 9x9	0.55499	74	1.43764	381	0.49149
GNF 8x8	0.6096	60	1.6256	381	0.53594

Table 6-13 Polyethylene Mass and Volume Fraction Calculations

Radius (cm)	Thickness (cm)	Total Poly Volume[a] (cm^3)	Total Poly Mass[b] (g)	$Volume_{poly}$ Per Fuel Rod[c] (cm^3)	$Volume_{clad}$ Per Fuel Rod[d] (cm^3)	Vf_{clad}[e]	Vf_{poly}[f]
Two ATRIUM 10x10 Fuel Assemblies							
0.51650	0.00000	0	0	0.00	65.47985	1.00000	0.00000
0.56504	0.04854	11512.03	10924.92	63.25	65.47985	0.50865	0.49135
0.59071	0.07421	18019.18	17100.20	99.01	65.47985	0.39809	0.60191
0.60395	0.08745	21487	20391.16	118.06	65.47985	0.35676	0.64324
0.61369	0.08000	24087.04	22858.60	132.35	65.47985	0.33100	0.66900
0.62343	0.10693	26729.6	25366.39	146.87	65.47985	0.30836	0.69164
0.63317	0.11667	29414.68	27914.53	161.62	65.47985	0.28833	0.71167
Two GNF 10x10 Fuel Assemblies							
0.50927	0.00000	0	0	0.00	50.41067	1.00000	0.00000
0.55824	0.04897	11512.03	10924.92	62.57	50.41067	0.44621	0.55379
0.59086	0.08159	19768.04	18759.87	107.43	50.41067	0.31937	0.68063
0.59743	0.08816	21487	20391.16	116.78	50.41067	0.30152	0.69848
0.60723	0.09796	24087.04	22858.6	130.91	50.41067	0.27802	0.72198
0.61703	0.10776	26729.6	25366.39	145.27	50.41067	0.25762	0.74238
0.62683	0.11756	29414.68	27914.53	159.86	50.41067	0.23974	0.76026
Two Framatome 9x9 Fuel Assemblies							
0.5499	0.0000	0	0	0.00	86.11243	1.00000	0.00000
0.6470	0.0971	20021.07	19000	139.04	86.11243	0.38247	0.61753
0.6610	0.1111	23182.3	22000	160.99	86.11243	0.34849	0.65151
0.6702	0.1203	25289.78	24000	175.62	86.11243	0.32901	0.67099
0.6792	0.1293	27397.26	26000	190.26	86.11243	0.31158	0.68842
0.6882	0.1383	29504.74	28000	204.89	86.11243	0.29591	0.70409
0.6970	0.1471	31612.22	30000	219.53	86.11243	0.28174	0.71826
Two GNF 9x9 Fuel Assemblies							
0.55499	0.00000	0	0	0.00	79.53889	1.00000	0.00000
0.65344	0.09845	21074.82	20000	142.40	79.53889	0.35839	0.64161
0.66248	0.10749	23182.3	22000	156.64	79.53889	0.33678	0.66322
0.67140	0.11641	25289.78	24000	170.88	79.53889	0.31763	0.68237

Radius (cm)	Thickness (cm)	Total Poly Volume[a] (cm^3)	Total Poly Mass[b] (g)	$Volume_{poly}$ Per Fuel Rod[c] (cm^3)	$Volume_{clad}$ Per Fuel Rod[d] (cm^3)	Vf_{clad}[e]	Vf_{poly}[f]
0.68020	0.12521	27397.26	26000	185.12	79.53889	0.30054	0.69946
0.68889	0.13390	29504.74	28000	199.36	79.53889	0.28519	0.71481
0.69747	0.14248	31612.22	30000	213.60	79.53889	0.27134	0.72866
Two GNF 8x8 Fuel Assemblies							
0.60960	0.00000	0	0	0.00	100.9989	1.00000	0.00000
0.71484	0.10524	20021.07	19000	166.84	100.9989	0.37709	0.62291
0.73008	0.12048	23182.3	22000	193.19	100.9989	0.34332	0.65668
0.74006	0.13046	25289.78	24000	210.75	100.9989	0.32398	0.67602
0.74990	0.14030	27397.26	26000	228.31	100.9989	0.30670	0.69330
0.75962	0.15002	29504.74	28000	245.87	100.9989	0.29117	0.70883
0.76922	0.15962	31612.22	30000	263.44	100.9989	0.27714	0.72286

The following example calculations are for two Atrium 10x10 assemblies with a total 21,487 cm^3 polyethylene volume:

a. Total Polyethylene Volume = (Total Fuel Rod Number)x(2 Fuel Assemblies)x(Polyethylene Area)x(Fuel Rod Length)

$$Volume = (91\,fuelrods)(2\,fuelassemblies)\left\{(\pi)\left[(0.60395cm)^2 - (0.5165cm)^2\right]\right\}(383.54cm) = 21487cm^3$$

b. Total Polyethylene Mass = (Total Polyethylene Volume)x(Polyethylene Density)

$$Mass = \left(21487cm^3\right)\left(0.949\frac{g}{cm^3}\right) = 20391.16g$$

c. Polyethylene Volume per Fuel Rod = Total Polyethylene Volume/Total Fuel Rod Number

$$\frac{Volume_{Poly}}{FuelRod} = \frac{21487cm^3}{(91\,fuelrods)(2\,fuelassemblies)} = 118.06cm^3$$

d. Clad Volume per Fuel Rod = [(Fuel Rod Area to Outer Clad)-(Fuel Rod Area to Inner Clad)]x Fuel Rod Length

$$\frac{Volume_{clad}}{FuelRod} = (\pi)\left[(0.5165cm)^2 - (0.4609cm)^2\right](383.54cm) = 65.48cm^3$$

e. Clad Volume Fraction = Clad Volume/Total Clad and Polyethylene Volumes

$$VF_{clad} = 65.48cm^3 \Big/ \left[(118.06cm^3)(65.48cm^3)\right] = 0.35676$$

f. Polyethylene Volume Fraction = Polyethylene Volume/ Total Clad and Polyethylene Volumes

$$VF_{Poly} = 118.06cm^3 \Big/ \left[(118.06cm^3)(65.48cm^3)\right] = 0.64323$$

6.3.3 Computer Codes and Cross-Section Libraries

The calculational methodology employed in the analyses is based on that embodied in SCALE - PC (version 4.4a), as documented in Reference 8. The neutron cross-section library employed in the analyses and the supporting validation analyses was the 44 group ENDF/B-V library distributed with version 4.4a of the SCALE package. Each case was run using the CSAS25 sequence of codes, i.e., BONAMI, NITAWL, and KENO V.a. For each case, 400 generations with 2,500 neutrons per generation were run to ensure proper behavior about the mean value. The methodology and results of the validation of SCALE 4.4a on the PC is outlined in Section 6.10, and results in an Upper Safety Limit (USL) that is the basis for comparison to ensure subcriticality.

6.3.4 Demonstration of Maximum Reactivity

The objectives for the RAJ-II shipping container analysis are to demonstrate package criticality safety and determine fuel loading criteria. To accomplish these objectives, calculations are performed to determine the most reactive fuel configuration inside the RAJ-II assembly compartments. Once the fuel configuration is determined, moderator and reflector conditions are investigated. Finally, package orientation (for arrays) is examined. When the worst case fuel configuration, moderator/reflector conditions, and package orientation are found, the single package and package array calculations under both normal and hypothetical accident conditions are performed.

6.3.4.1 Fuel Assembly Orientation Study (2N=448)

The package array dimensions for the fuel assembly orientation are 14x2x16 (width x depth x height). Initial calculations are performed to find the worst case fuel assembly orientation inside each RAJ-II fuel compartment. Nominal fuel assembly dimensions are used for these initial calculations (Table 6-4). Note that in all cases with cladding, zirconium is used to conservatively represent any zirconium alloy. The package array HAC model described in Section 6.3.1.2.2 is used and the fuel assembly orientations depicted in Figure 6-9 through Figure 6-15 are applied. In addition, a polyethylene coating covers each fuel rod in the assembly, the fuel assembly is un-channeled, and the moderator density is 1.0 g/cm^3 in the RAJ-II inner container fuel region. The polyethylene foam is assumed to burn away, Alumina Silicate thermal insulator envelopes the inner container, and no water is in either the outer container or between packages in the array. The results of the calculations are shown in Table 6-14 RAJ-II Array HAC Fuel Assembly Orientation. Based on the results in Table 6-14, assembly orientation 6, is bounding for all designs. Therefore, orientation 6 with the assembly centered in each fuel compartment is used in the remaining design calculations. It is also noted that most results in Table 6-14 exceed the 0.94254 USL. For this reason, gadolinia-urania fuel rods are added to the fuel assemblies to provide reactivity hold-down.

Table 6-14 RAJ-II Array HAC Fuel Assembly Orientation

Fuel Assembly	Interspersed Moderator Density (g/cm^3)	Polyethylene Mass Per Assembly (kg)	Assembly Orientation	k_{eff}	σ	$k_{eff} + 2\sigma$
FANP 10x10	0.0	10.2	1	0.9375	0.0010	0.9395
FANP 10x10	0.0	10.2	2	0.9529	0.0008	0.9545
FANP 10x10	0.0	10.2	3	0.8973	0.0008	0.8989
FANP 10x10	0.0	10.2	4	0.8965	0.0010	0.8985
FANP 10x10	0.0	10.2	5	0.9248	0.0010	0.9268
FANP 10x10	0.0	10.2	6	0.9741	0.0009	**0.9759**
FANP 10x10	0.0	10.2	7	0.9486	0.0009	0.9504
GNF 10x10	0.0	10.2	1	0.9586	0.0010	0.9606
GNF 10x10	0.0	10.2	2	0.9721	0.0009	0.9739
GNF 10x10	0.0	10.2	3	0.9184	0.0008	0.9200
GNF 10x10	0.0	10.2	4	0.9183	0.0009	0.9201
GNF 10x10	0.0	10.2	5	0.9431	0.0008	0.9447
GNF 10x10	0.0	10.2	6	0.9909	0.0010	**0.9929**
GNF 10x10	0.0	10.2	7	0.9652	0.0008	0.9668
FANP 9x9[a]	0.0	11	1	0.9486	0.0009	0.9504
FANP 9x9	0.0	11	2	0.9559	0.0009	0.9577
FANP 9x9	0.0	11	3	0.9052	0.0008	0.9068
FANP 9x9	0.0	11	4	0.9056	0.0008	0.9072
FANP 9x9	0.0	11	5	0.9293	0.0010	0.9313
FANP 9x9	0.0	11	6	0.9791	0.0008	**0.9807**
FANP 9x9	0.0	11	7	0.9362	0.0009	0.9380
GNF 9x9	0.0	11	1	0.9491	0.0008	0.9507
GNF 9x9	0.0	11	2	0.9577	0.0008	0.9593
GNF 9x9	0.0	11	3	0.9051	0.0008	0.9067
GNF 9x9	0.0	11	4	0.9042	0.0009	0.9060
GNF 9x9	0.0	11	5	0.9287	0.0009	0.9305
GNF 9x9	0.0	11	6	0.9787	0.0008	**0.9803**
GNF 9x9	0.0	11	7	0.9556	0.0008	0.9572
GNF 8x8	0.0	11	1	0.9506	0.0009	0.9524
GNF 8x8	0.0	11	2	0.9563	0.0008	0.9579
GNF 8x8	0.0	11	3	0.9048	0.0008	0.9064
GNF 8x8	0.0	11	4	0.9052	0.0009	0.9070
GNF 8x8	0.0	11	5	0.9299	0.0009	0.9317
GNF 8x8	0.0	11	6	0.9764	0.0008	**0.9780**
GNF 8x8	0.0	11	7	0.9554	0.0009	0.9572

a. The Framatome D-lattice 9x9 assembly was modeled. However, the results presented here are applicable to the C-lattice as well
b. Limiting case shown in bold

6.3.4.2 Fuel Assembly Gadolinia Rod Study (2N=448)

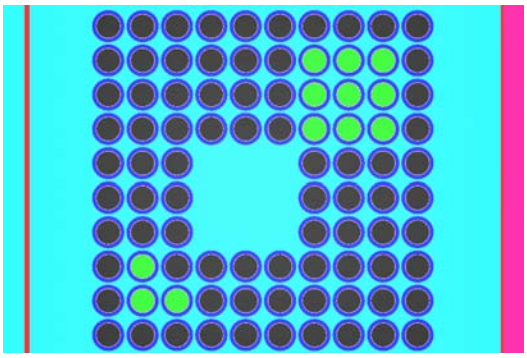
Fuel assemblies with lattice average U-235 enrichments of 5.0 wt% are qualified for transport in the RAJ-II shipping container by crediting the gadolinia-urania fuel rods present in the assembly. The gadolinia-urania fuel rods decrease system reactivity such that the $k_{eff} + 2\sigma$ remains below the 0.94254 USL. The gadolinia content of each gadolinia-urania fuel rod is limited to 75% of the value specified in Table 6-1. Scoping studies are performed using numerous gadolinia-urania fuel rod placement patterns in the orientation 6 models, from the fuel assembly orientation study, to find the pattern that yields the highest reactivity for each fuel assembly type. Of the patterns investigated, three patterns that produce the highest reactivity for each fuel assembly type are shown in Figure 6-22 - Figure 6-24. The calculations are performed using optimum moderator conditions. The results for the 14x2x16 RAJ-II container array transporting 10x10, 9x9, or 8x8 fuel assembies with gadolinia-urania fuel rods arranged in the patterns displayed in Figure 6-22 - Figure 6-24 are listed in Table 6-15. As shown in Table 6-15, the gadolinia-urania fuel rods hold the system reactivity below the 0.94254 USL. Based on the gadolinia-urania fuel rod pattern optimization calculations:

- Gadolinia-urania fuel rod Pattern G is selected for future FANP 10x10 fuel assembly sensitivity calculations,
- Gadolinia-urania fuel rod Pattern B is selected for future GNF 10x10 fuel assembly sensitivity calculations,
- Gadolinia-urania fuel rod Pattern A is selected for future FANP and GNF 9x9 fuel assembly sensitivity calculations,
- Gadolinia-urania fuel rod Pattern I is selected for future GNF 8x8 fuel assembly sensitivity calculations.

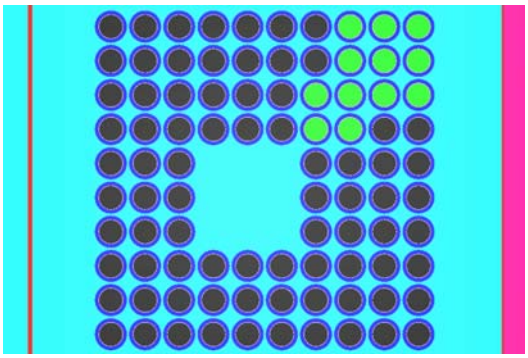
Table 6-15 RAJ-II Shipping Container 14x2x16 Array with Gadolinia-Urania Fuel Rods

Assembly Type	Pattern Designation	U-235 Enrich (wt%)	Gad Rod #	Pitch (cm)	Pellet Diameter (cm)	Clad ID (cm)	Clad OD (cm)	k_{eff}	σ	$k_{eff} + 2\sigma$
FANP 10x10	B	5.0	12	1.284	0.8882	0.9218	1.033	0.8716	0.0008	0.8732
FANP 10x10	F	5.0	12	1.284	0.8882	0.9218	1.033	0.8699	0.0008	0.8715
FANP 10x10	G	5.0	12	1.284	0.8882	0.9218	1.033	0.8732	0.0008	**0.8748**
GNF 10x10	B	5.0	12	1.2954	0.8941	0.9322	1.019	0.8886	0.0008	**0.8902**
GNF 10x10	G	5.0	12	1.2954	0.8941	0.9322	1.019	0.8871	0.0008	0.8887
GNF 10x10	H	5.0	12	1.2954	0.8941	0.9322	1.019	0.8880	0.0009	0.8898
FANP 9x9	A	5.0	10	1.4478	0.9398	0.9601	1.099	0.8644	0.0007	**0.8658**
FANP 9x9	B	5.0	10	1.4478	0.9398	0.9601	1.099	0.8605	0.0008	0.8621
FANP 9x9	E	5.0	10	1.4478	0.9398	0.9601	1.099	0.8354	0.0009	0.8372
GNF 9x9	A	5.0	10	1.4376	0.9550	0.9830	1.110	0.8579	0.0008	**0.8596**
GNF 9x9	B	5.0	10	1.4376	0.9550	0.9830	1.110	0.8572	0.0008	0.8588
GNF 9x9	F	5.0	10	1.4376	0.9550	0.9830	1.110	0.8524	0.0009	0.8540
GNF 8x8	E	5.0	7	1.6256	1.0439	1.0719	1.219	0.8779	0.0009	0.8797
GNF 8x8	G	5.0	7	1.6256	1.0439	1.0719	1.219	0.8726	0.0008	0.8742
GNF 8x8	I	5.0	7	1.6256	1.0439	1.0719	1.219	0.8800	0.0009	**0.8818**

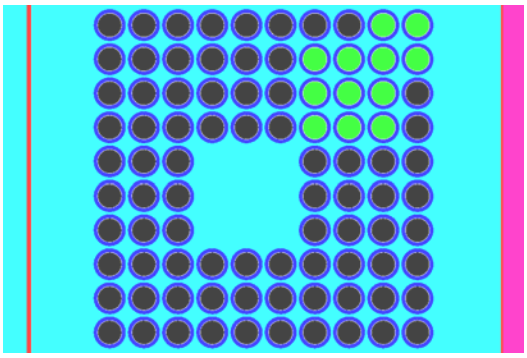
a. Limiting case(s) shown in bold



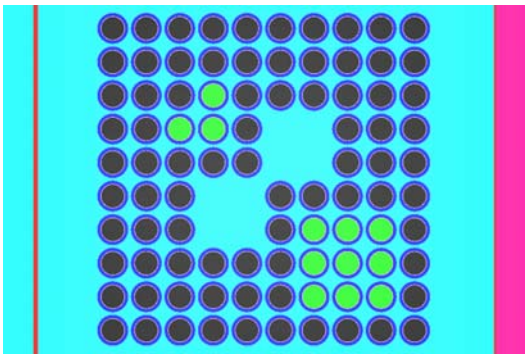
FANP 10x10 5.0 wt% ^{235}U, Pattern B



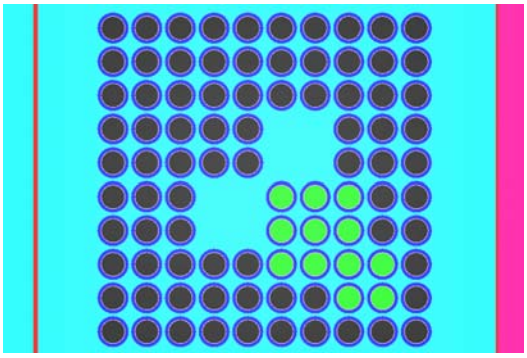
FANP 10x10 5.0 wt% ^{235}U, Pattern F



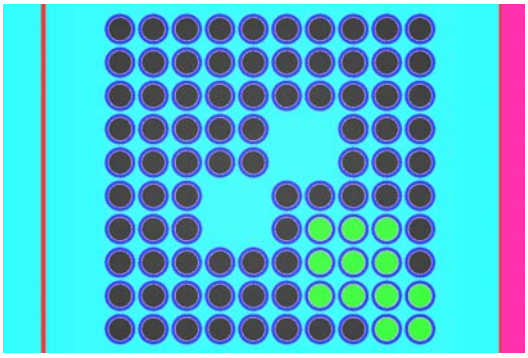
FANP 10x10 5.0 wt% ^{235}U, Pattern G



GNF 10x10 5.0 wt% ^{235}U, Pattern B

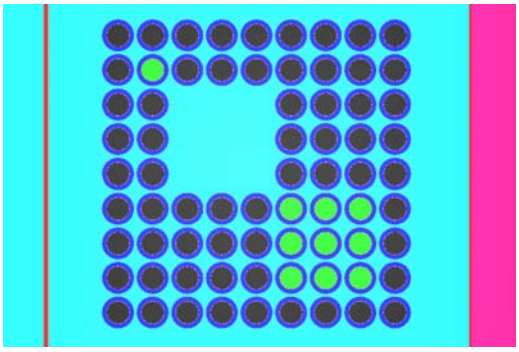


GNF 10x10 5.0 wt% ^{235}U, Pattern G

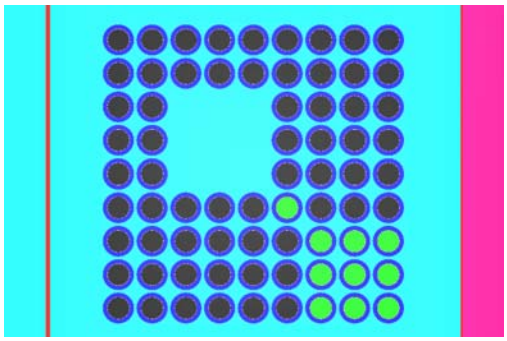


GNF 10x10 5.0 wt% ^{235}U, Pattern H

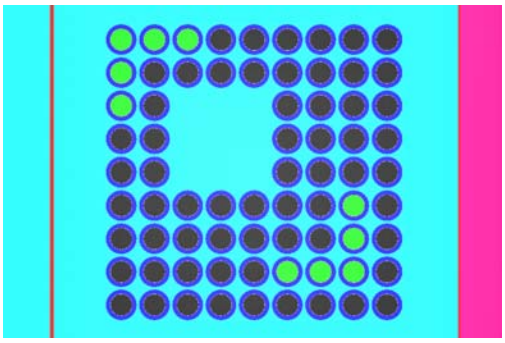
Figure 6-22 Gadolinia-Urania Fuel Rod Placement Pattern for 10x10 Fuel Assemblies at 5.0 wt% ^{235}U



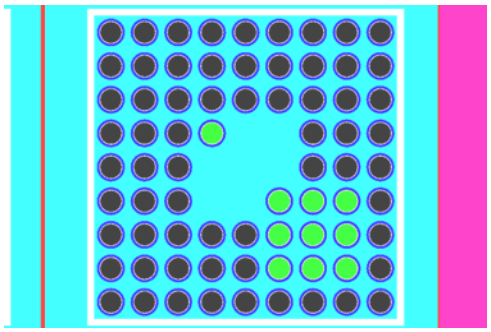
FANP 9x9 5.0 wt% ^{235}U, Pattern A



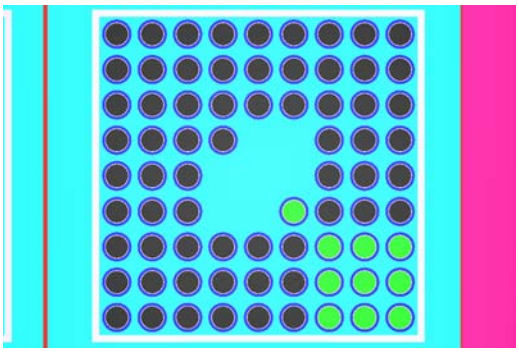
FANP 9x9 5.0 wt% ^{235}U, Pattern B



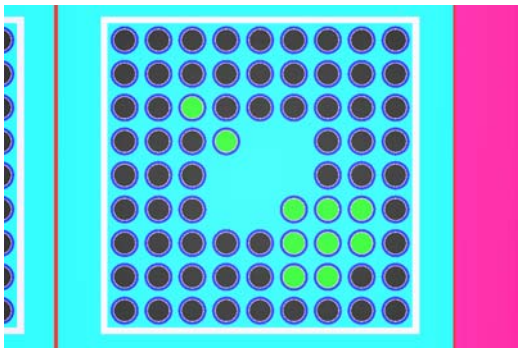
FANP 9x9 5.0 wt% ^{235}U, Pattern E



GNF 9x9 5.0 wt% ^{235}U, Pattern A

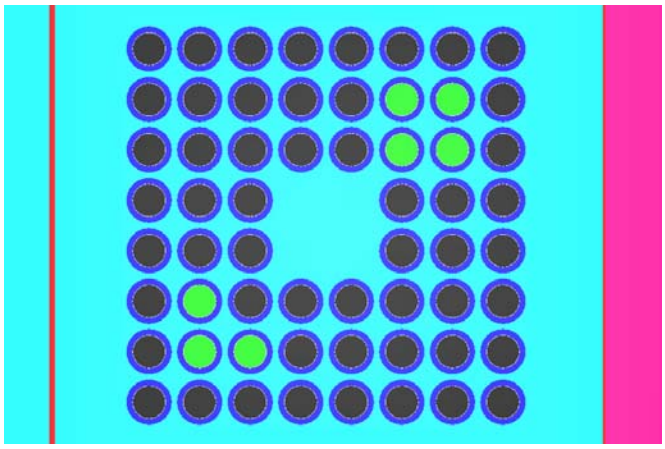


GNF 9x9 5.0 wt% ^{235}U, Pattern B

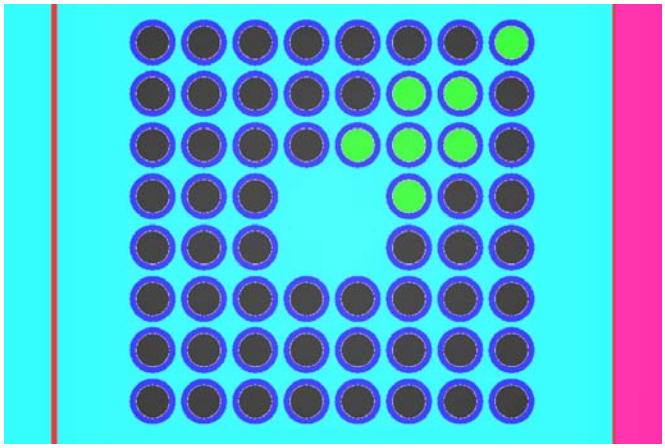


GNF 9x9 5.0 wt% ^{235}U, Pattern F

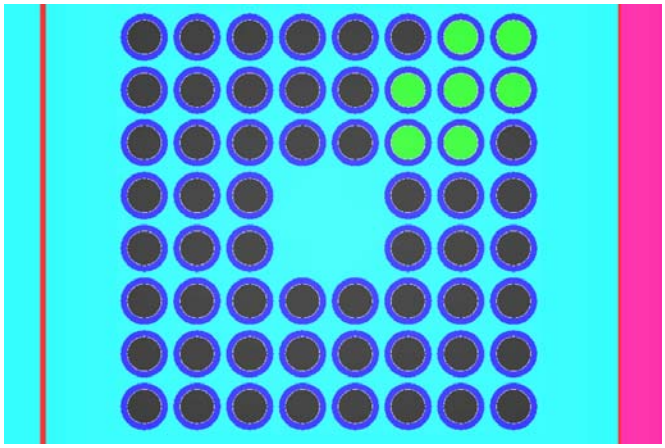
Figure 6-23 Gadolinia-Urania Fuel Rod Placement Pattern for 9x9 Fuel Assemblies at 5.0 wt% ^{235}U



GNF 8x8 5.0 wt% ^{235}U, Pattern E



GNF 8x8 5.0 wt% ^{235}U, Pattern G



GNF 8x8 5.0 wt% ^{235}U, Pattern I

Figure 6-24 Gadolinia-Urania Fuel Rod Placement Pattern for 8x8 Fuel Assemblies at 5.0 wt% ^{235}U

6.3.4.3 Fuel Assembly Channel Study (2N=448)

A calculation is performed to determine if the presence of channels around the fuel assembly increases system reactivity. The orientation 6 models with the gadolina-urania fuel rod patterns that produced the highest system reactivity from the previous studies are used and a zirconium channel is placed around each assembly as shown in Figure 6-16 RAJ-II Hypothetical Accident Condition Model with Channels. The channel thickness is varied from 0.17 cm to 0.3048 cm and the impact on reactivity is assessed. The fuel assembly channel is located in the reflector region for each fuel assembly. It has no effect on the assembly H/X ratio since it is not located within the fuel envelope. Therefore, removing it would not have the same impact on system reactivity as removing the internal grid structure. The results are shown in Table 6-16. Comparing the results in Table 6-16 and Table 6-15 indicates reactivity increases with the presence of channels due to increased neutron leakage from the inner fuel compartment, resulting in increased neutron interaction among containers in the array. Therefore, channels will be included in subsequent calculations.

Table 6-16 RAJ-II Sensitivity Analysis for Channeled Fuel Assemblies

Assembly Type	Channel Thickness (cm)	Poly Mass per Assembly (kg)	Pitch (cm)	Pellet Diameter (cm)	Clad ID (cm)	Clad OD (cm)	k_{eff}	σ	$k_{eff} + 2\sigma$
FANP 10x10	0.1700	10.2	1.284	0.8882	0.9218	1.033	0.8801	0.0008	0.8817
FANP 10x10	0.2032	10.2	1.284	0.8882	0.9218	1.033	0.8786	0.0008	0.8802
FANP 10x10	0.2540	10.2	1.284	0.8882	0.9218	1.033	0.8815	0.0009	**0.8833**
FANP 10x10	0.3048	10.2	1.284	0.8882	0.9218	1.033	0.8810	0.0008	0.8826
GNF 10x10	0.1700	10.2	1.2954	0.8941	0.9322	1.019	0.8922	0.0009	0.8940
GNF 10x10	0.2032	10.2	1.2954	0.8941	0.9322	1.019	0.8948	0.0008	0.8964
GNF 10x10	0.2540	10.2	1.2954	0.8941	0.9322	1.019	0.8947	0.0008	0.8963
GNF 10x10	0.3048	10.2	1.2954	0.8941	0.9322	1.019	0.8953	0.0008	**0.8969**
FANP 9x9	0.1700	11	1.4478	0.9398	0.9601	1.0998	0.8719	0.0009	0.8737
FANP 9x9	0.2032	11	1.4478	0.9398	0.9601	1.0998	0.8724	0.0009	0.8742
FANP 9x9	0.2540	11	1.4478	0.9398	0.9601	1.0998	0.8739	0.0008	0.8756
FANP 9x9	0.3048	11	1.4478	0.9398	0.9601	1.0998	0.8755	0.0009	**0.8773**
GNF 9x9	0.1700	11	1.4376	0.9550	0.9830	1.11	0.8626	0.0009	0.8644
GNF 9x9	0.2032	11	1.4376	0.9550	0.9830	1.11	0.8651	0.0009	0.8669
GNF 9x9	0.2540	11	1.4376	0.9550	0.9830	1.11	0.8654	0.0010	**0.8674**
GNF 9x9	0.3048	11	1.4376	0.9550	0.9830	1.11	0.8659	0.0008	0.8676
GNF 8x8	0.1700	11	1.6256	1.0439	1.0719	1.2192	0.8834	0.0010	0.8854
GNF 8x8	0.2032	11	1.6256	1.0439	1.0719	1.2192	0.8857	0.0008	0.8873
GNF 8x8	0.2540	11	1.6256	1.0439	1.0719	1.2192	0.8884	0.0009	0.8902
GNF 8x8	0.3048	11	1.6256	1.0439	1.0719	1.2192	0.8900	0.0009	**0.8918**

a. Limiting case(s) shown in bold

6.3.4.4 Polyethylene Mass Study (2N=448)

The effect that polyethylene mass has on reactivity for each fuel assembly design is considered for transport in the RAJ-II shipping container. The results of the previous sensitivity studies are taken into consideration for the polyethylene mass study. The worst case channeled (0.3048 cm thick channels) models, used in the previous study, are used for the polyethylene mass study. The polyethylene and clad volume fractions, shown in Table 6-13, are used in the model material description to represent the polyethylene and clad mixture. They are also used in the lattice cell description for resonance cross-section processing. The polyethylene coating thickness around the fuel rods is varied, and the effect on reactivity is determined. The results of the calculations, Table 6-24, are displayed in Figure 6-25 RAJ-II Array HAC Polyethylene Sensitivity. Although the polyethylene addition increases reactivity, the increase is gradual and the resulting system k_{eff} remains subcritical. Based on the results in Figure 6-25:

- a polyethylene mass of 10.2 kg/assembly (20.4 kg/container) is chosen for further FANP and GNF 10x10 calculations,

- an 11 kg/assembly (22 kg/container) polyethylene mass is selected for subsequent FANP 9x9, GNF 9x9, and GNF 8x8 fuel assembly calculations.

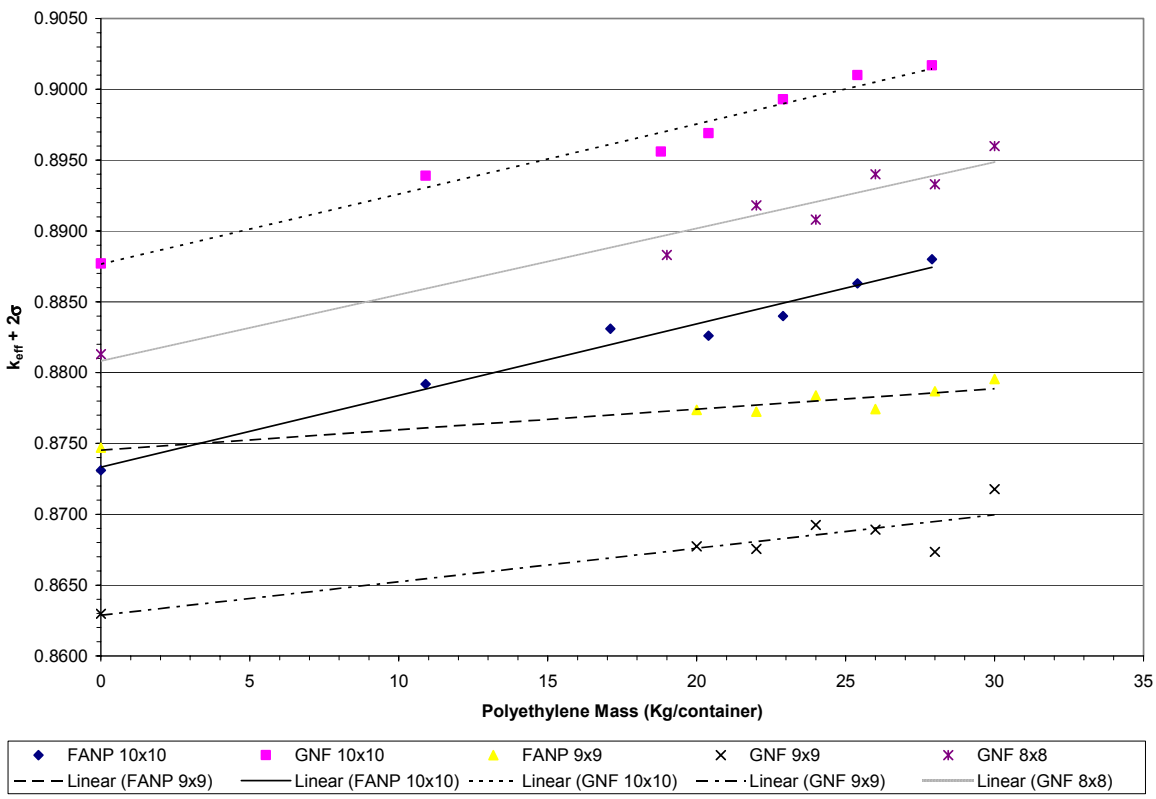


Figure 6-25 RAJ-II Array HAC Polyethylene Sensitivity

6.3.4.5 Fuel Rod Pitch Sensitivity Study (2N=448)

A fuel rod pitch sensitivity study is conducted using the worst case models from the polyethylene sensitivity study. The minimum fuel rod pitch is chosen to be at the point that the polyethylene coating on adjacent fuel rods contact. The maximum fuel rod pitch is chosen to be 4.1% greater than the reference fuel designs to bound the damage sustained during the 9 meter drop. The results are shown in Figure 6-26 RAJ-II Fuel Rod Pitch Sensitivity Study. Based on the results in Figure 6-26, the fuel assemblies are under-moderated such that increasing the pitch increases system reactivity. Based on the pitch sensitivity calculations (Table 6-25):

- a 1.350 cm fuel rod pitch is selected as the upper limit for FANP and GNF 10x10 pitch range,
- a 1.510 cm fuel rod pitch is selected as the upper limit for FANP and GNF 9x9 pitch range,
- a 1.6923 cm fuel rod pitch is selected as the upper limit for GNF 8x8 pitch range.

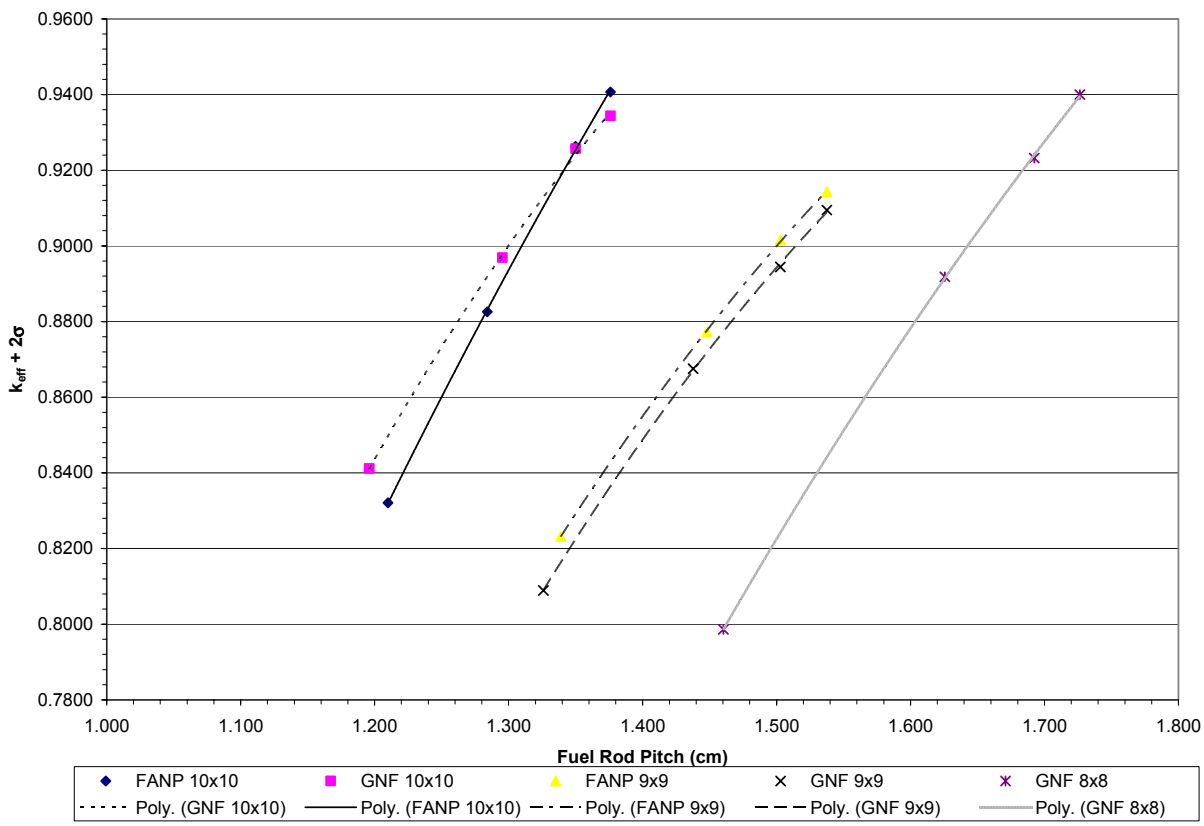


Figure 6-26 RAJ-II Fuel Rod Pitch Sensitivity Study

6.3.4.6 Fuel Pellet Diameter Sensitivity Study (2N=448)

With a polyethylene quantity chosen, the worst case orientation known, the channeled fuel effect assessed, and the worst case gadolinia-urania fuel rod patterns identified, a fuel pellet diameter sensitivity study is conducted. For the pellet diameter sensitivity study, the package array HAC model described in Section 6.3.1.2.2 is used for the study, fuel assembly orientation 6 is selected based on the results in Table 6-14, the maximum polyethylene amount for each fuel assembly design is chosen, the worst case gadolinia-urania rod pattern is selected, the inner container fuel compartment is maintained at optimum density water, an Alumina Silicate themal insulator envelopes the inner container fuel compartment, and water is removed from the outer container and between packages in the array. The results are shown in Figure 6-27 RAJ-II Array HAC Pellet Diameter Sensitivity Study. The results in Figure 6-27, demonstrate that reactivity increases as pellet diameter is increased. Pellet diameters of 0.895 cm for the FANP and GNF 10x10 designs, 0.96 cm for the Framatome and GNF 9x9 designs, and 1.05 cm for the GNF 8x8 design are found acceptable as the upper bounds for the fuel assembly design pellet ranges (Table 6-26).

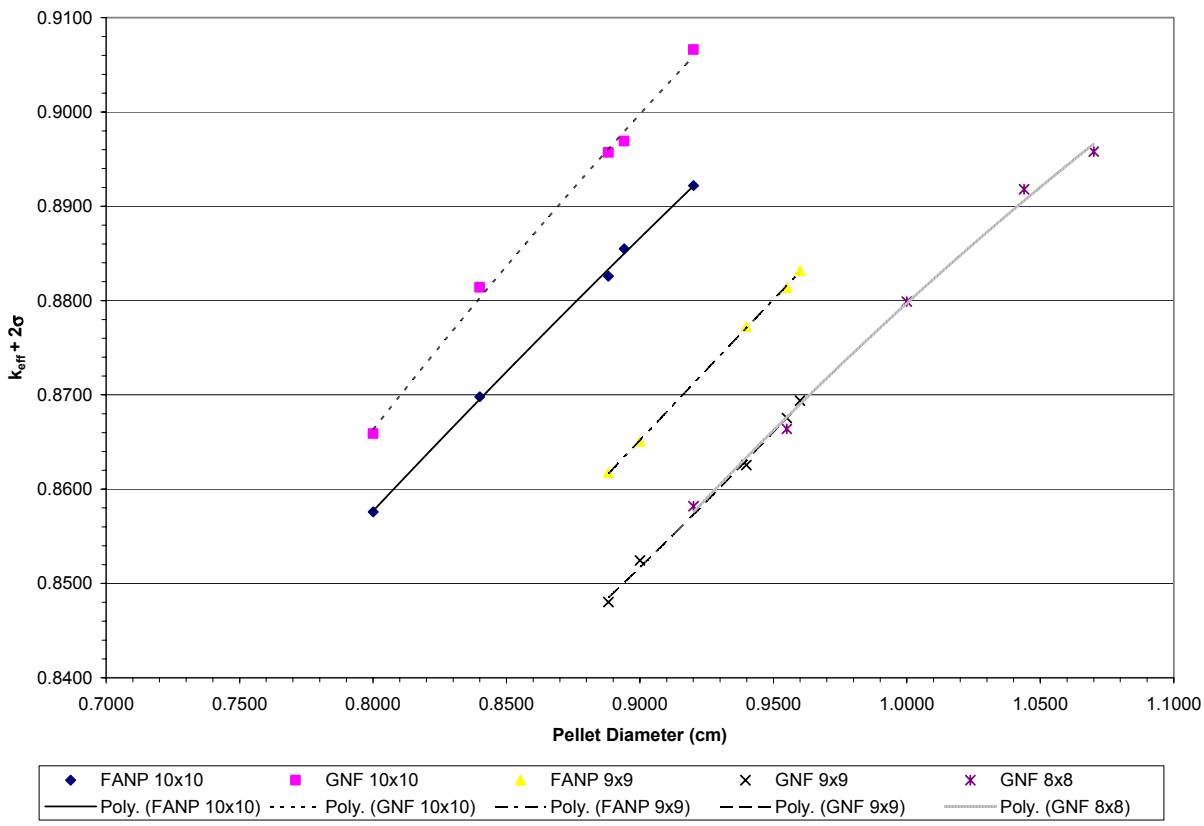


Figure 6-27 RAJ-II Array HAC Pellet Diameter Sensitivity Study

6.3.4.7 Fuel Rod Clad Thickness Sensitivity Study (2N=448)

Two sets of calculations are performed to assess the reactivity sensitivity to changes in cladding thickness. For the clad thickness sensitivity studies, the package array HAC model described in

Section 6.3.1.2.2 is used for the study, fuel assembly orientation 6 is selected based on the results in Table 6-14, the maximum polyethylene amount for each fuel assembly design is chosen, the worst case gadolinia-urania rod pattern is selected, the inner container fuel compartment is maintained at optimum density moderation, an Alumina Silicate themal insulator envelopes the inner container fuel compartment, and water is removed from the outer container and between packages in the array. For the first set of calculations, the inner clad diameter is adjusted to determine the effect on reactivity while the outer clad diameter is fixed at its nominal value shown in Table 6-4. The minimum value for the parameter search range is the pellet OD, while the maximum value for the range is the clad OD. The second set of calculations involves adjustments to the outer clad diameter while the inner clad diameter is held at its nominal value Table 6-4. Figure 6-28 RAJ-II Array HAC Fuel Rod Clad ID Sensitivity Study displays the results for the inner clad diameter sensitivity calculations, and Figure 6-29 RAJ-II Array HAC Fuel Rod Clad OD Sensitivity Study shows the results for the outer clad diameter sensitivity study. Both sets of results demonstrate that a decrease in the clad thickness results in an increase in system reactivity. The results also indicate that reactivity increases as the clad OD is decreased and increases as the clad ID is increased. Based on these results and fabrication constraints (Table 6-28 and Table 6-29):

- a 0.933 cm upper bound clad ID, and a 1.00 cm lower bound clad OD are selected for the FANP and GNF 10x10 parameter ranges,
- a 1.02 cm upper bound clad ID, and a 1.09 cm lower bound clad OD are selected for the FANP and GNF 9x9 parameter ranges,
- a 1.10 cm upper bound clad ID, and a 1.17 cm lower bound clad OD are selected for the GNF 8x8 parameter range.

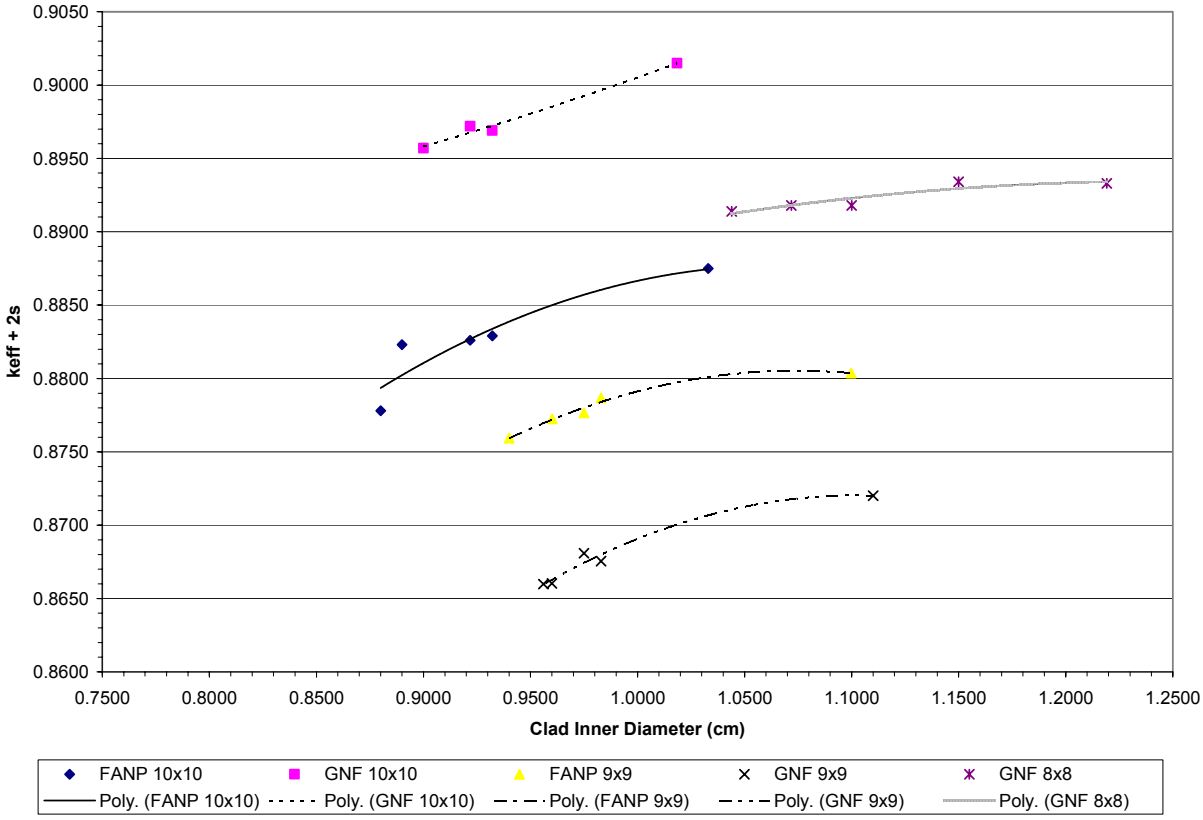


Figure 6-28 RAJ-II Array HAC Fuel Rod Clad ID Sensitivity Study

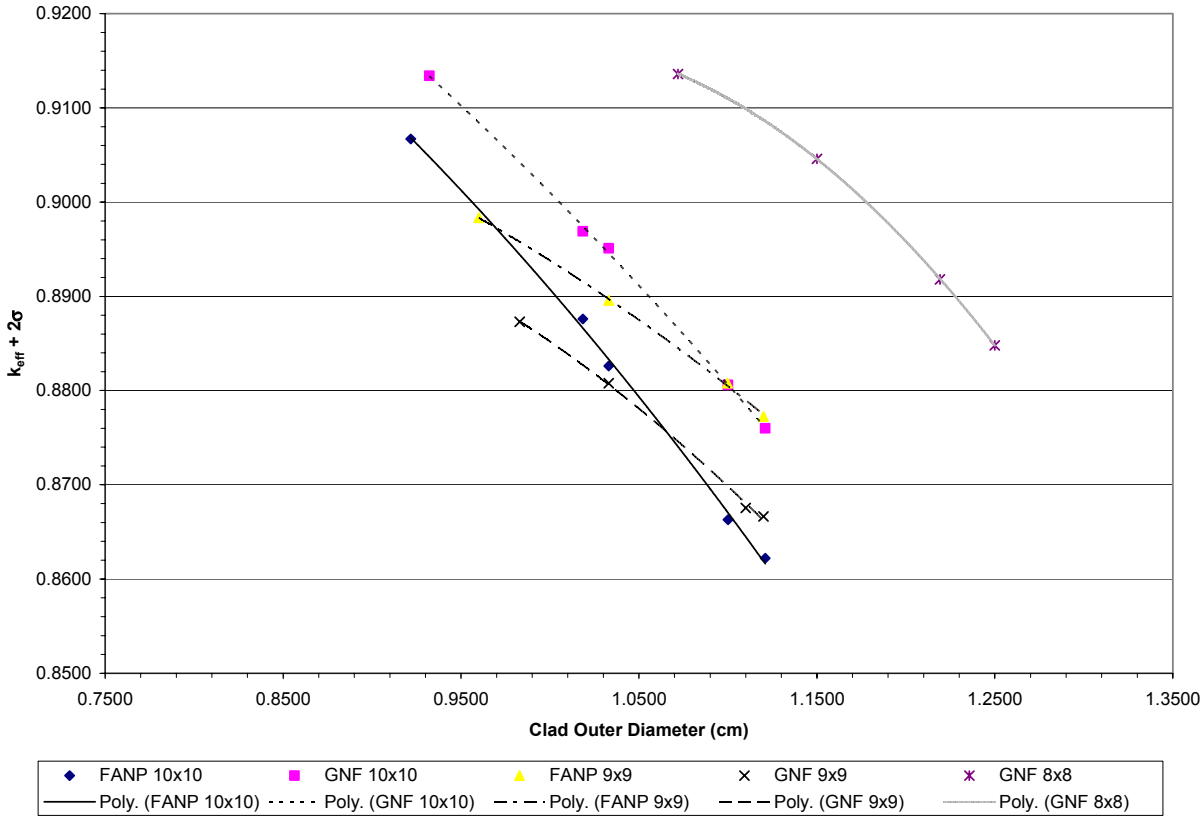


Figure 6-29 RAJ-II Array HAC Fuel Rod Clad OD Sensitivity Study

6.3.4.8 Worst Case Parameter Fuel Designs (2N=448)

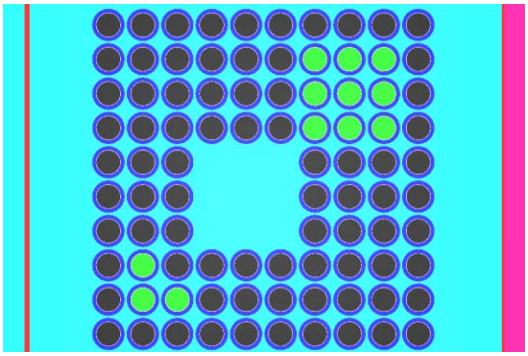
The previous calculations have varied single parameters and assessed the impact on reactivity. Since the ranges investigated are to be a part of the fuel loading criteria, an assessment must be made for more than one parameter change at a time. To validate the parameter ranges selected to appear in the fuel loading criteria, a fuel design is developed by assembling the worst case parameters for each design considered for transport in the RAJ-II container. Table 6-17 RAJ-II Array HAC Worst Case Parameter Fuel Designs contains the worst case parameters for each design. The worst case models from the clad ID and OD sensitivity study are used to conduct the worst case fuel parameter study. The polyethylene is smeared into the fuel rod cladding to accommodate the limitations in the lattice cell modeling for cross-section processing in SCALE. A search for the worst case gadolinia-urania fuel rod pattern is also conducted to validate the worst case fuel design. Numerous patterns were investigated for each fuel assembly with the worst case fuel parameters determined from the sensitivity studies. Of the patterns investigated, three patterns that produce the highest reactivity for each fuel assembly type are shown in Figure 6-22 - Figure 6-24. Additional calculations are performed to investigate the number of gadolinia-urania fuel rods needed based on fuel assembly U-235 enrichment. For each fuel assembly U-235 enrichment, a gadolinia-urania fuel rod pattern optimization study is conducted. The three patterns that produce the highest reactivity for each fuel assembly based on U-235 enrichment are shown in Figure 6-30 - Figure 6-32 . All results are listed in Table 6-17 and are

below the USL of 0.94254. Based on the results listed in Table 6-17, all worst case fuel assembly designs result in maximum system reactivities that are within the statistical uncertainty of one another.

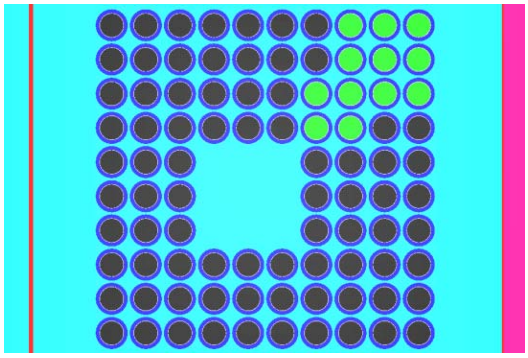
Table 6-17 RAJ-II Array HAC Worst Case Parameter Fuel Designs

Assembly Type	Gadolinia -Urania Fuel Rod Number	^{235}U Enrichment (wt%)	Poly Mass per Assembly (kg)	Pitch (cm)	Pellet Diameter (cm)	Clad ID (cm)	Clad OD (cm)	k_{eff}	σ	$k_{eff} + 2\sigma$
FANP 10x10	12	5.0	10.2	1.350	0.895	0.933	1.00	0.9368	0.0008	0.9384
FANP 10x10	10	4.6	10.2	1.350	0.895	0.933	1.00	0.9360	0.0009	0.9378
FANP 10x10	9	4.3	10.2	1.350	0.895	0.933	1.00	0.9325	0.0010	0.9345
FANP 10x10	8	4.2	10.2	1.350	0.895	0.933	1.00	0.9366	0.0009	**0.9384**
FANP 10x10	6	3.9	10.2	1.350	0.895	0.933	1.00	0.9353	0.0007	0.9367
FANP 10x10	4	3.6	10.2	1.350	0.895	0.933	1.00	0.9341	0.0009	0.9359
FANP 10x10	2	3.3	10.2	1.350	0.895	0.933	1.00	0.9305	0.0009	0.9323
FANP 10x10	0	2.9	10.2	1.350	0.895	0.933	1.00	0.9274	0.0008	0.9290
GNF 10x10	12	5.0	10.2	1.350	0.895	0.933	1.00	0.9393	0.0008	0.9409
GNF 10x10	10	4.6	10.2	1.350	0.895	0.933	1.00	0.9349	0.0010	0.9369
GNF 10x10	9	4.3	10.2	1.350	0.895	0.933	1.00	0.9346	0.0008	0.9362
GNF 10x10	8	4.2	10.2	1.350	0.895	0.933	1.00	0.9395	0.0009	**0.9413**
GNF 10x10	6	3.9	10.2	1.350	0.895	0.933	1.00	0.9377	0.0009	0.9395
GNF 10x10	4	3.6	10.2	1.350	0.895	0.933	1.00	0.9370	0.0008	0.9386
GNF 10x10	2	3.3	10.2	1.350	0.895	0.933	1.00	0.9344	0.0009	0.9362
GNF 10x10	0	2.9	10.2	1.350	0.895	0.933	1.00	0.9317	0.0007	0.9331
FANP 9x9	10	5.0	11	1.510	0.96	1.02	1.09	0.9191	0.0008	0.9207
FANP 9x9	8	4.7	11	1.510	0.96	1.02	1.09	0.9294	0.0008	**0.9310**
FANP 9x9	6	4.2	11	1.510	0.96	1.02	1.09	0.9242	0.0010	0.9262
FANP 9x9	4	3.8	11	1.510	0.96	1.02	1.09	0.9264	0.0007	0.9278
FANP 9x9	2	3.5	11	1.510	0.96	1.02	1.09	0.9257	0.0007	0.9271
FANP 9x9	0	3.0	11	1.510	0.96	1.02	1.09	0.9214	0.0008	0.9230
GNF 9x9	10	5.0	11	1.510	0.96	1.02	1.09	0.9151	0.0008	0.9167
GNF 9x9	8	4.8	11	1.510	0.96	1.02	1.09	0.9368	0.0009	**0.9386**
GNF 9x9	6	4.2	11	1.510	0.96	1.02	1.09	0.9294	0.0009	0.9312
GNF 9x9	4	3.8	11	1.510	0.96	1.02	1.09	0.9333	0.0007	0.9347
GNF 9x9	2	3.5	11	1.510	0.96	1.02	1.09	0.9311	0.0008	0.9327
GNF 9x9	0	3.0	11	1.510	0.96	1.02	1.09	0.9290	0.0008	0.9306
GNF 8x8	7	5.0	11	1.6923	1.05	1.10	1.17	0.9356	0.0008	**0.9372**
GNF 8x8	6	4.7	11	1.6923	1.05	1.10	1.17	0.9323	0.0009	0.9341
GNF 8x8	4	4.1	11	1.6923	1.05	1.10	1.17	0.9305	0.0008	0.9321
GNF 8x8	2	3.7	11	1.6923	1.05	1.10	1.17	0.9321	0.0008	0.9337
GNF 8x8	0	3.1	11	1.6923	1.05	1.10	1.17	0.9311	0.0008	0.9327

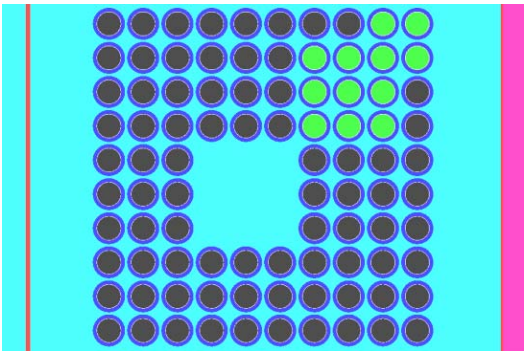
a. Limiting case(s) shown in bold



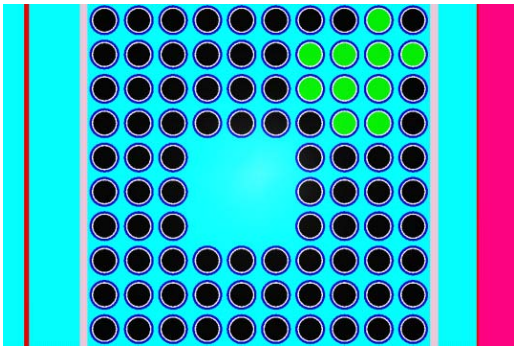
FANP 10x10 5.0 wt% ^{235}U, Pattern B



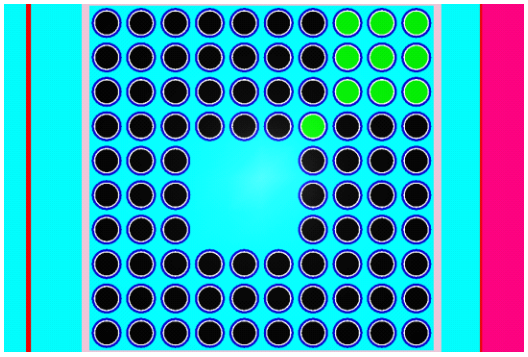
FANP 10x10 5.0 wt% ^{235}U, Pattern F



FANP 10x10 5.0 wt% ^{235}U, Pattern G



FANP 10x10 4.6 wt% ^{235}U, Pattern E



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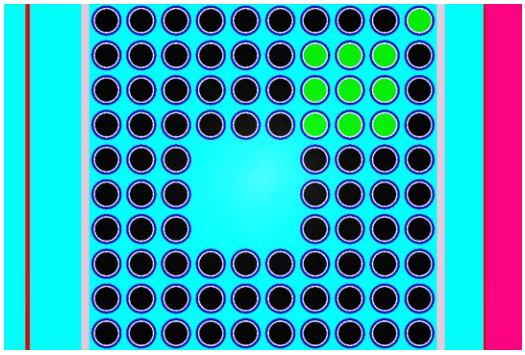
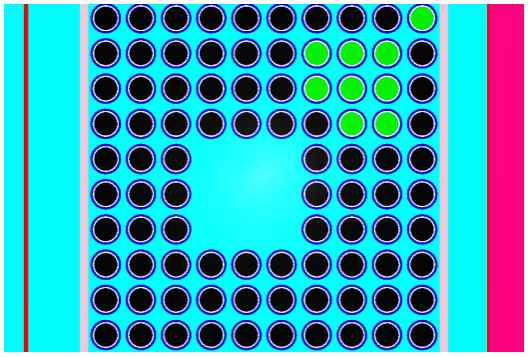
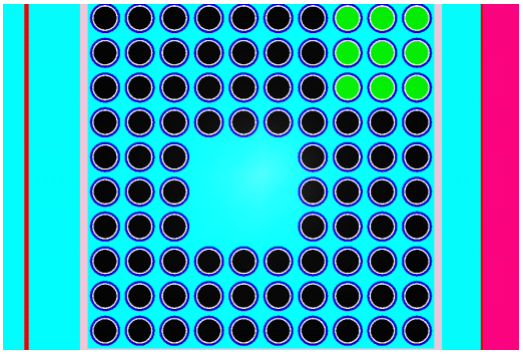


FANP 10x10 4.6 wt% ^{235}U, Pattern G

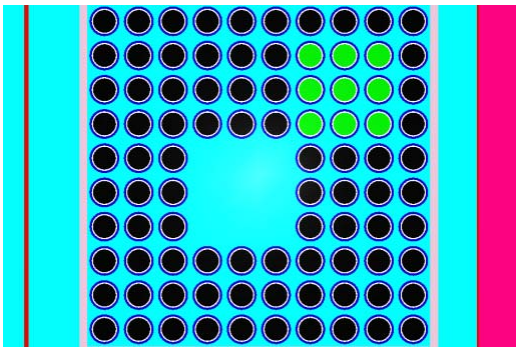
Figure 6-30 Gadolinia-Urania Fuel Rod Placement Pattern for 10x10 Fuel Assemblies



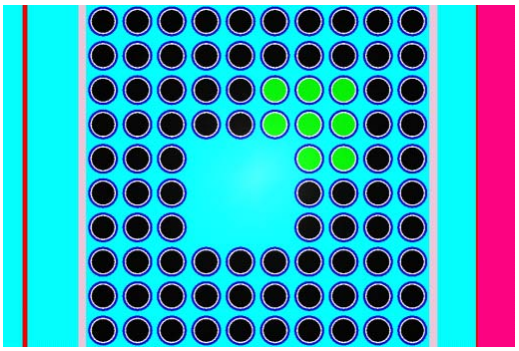
FANP 10x10 4.3 wt% ^{235}U, Pattern E



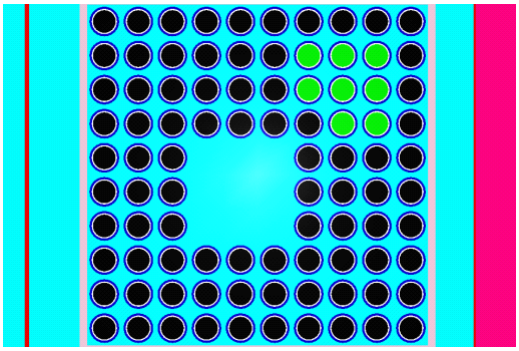
FANP 10x10 4.3 wt% ^{235}U, Pattern F



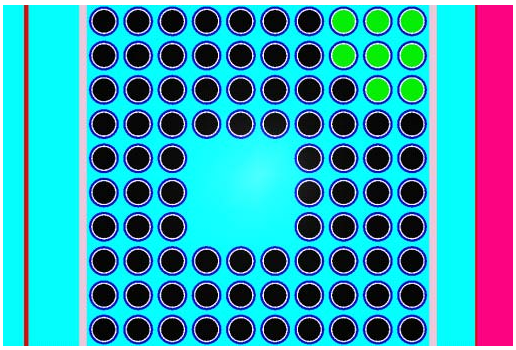
FANP 10x10 4.3 wt% ^{235}U, Pattern G



FANP 10x10 4.2 wt% ^{235}U, Pattern D

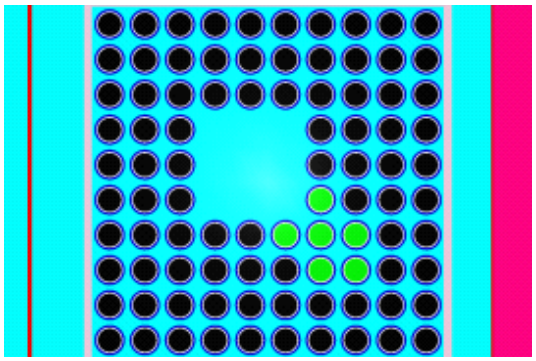


FANP 10x10 4.2 wt% ^{235}U, Pattern E

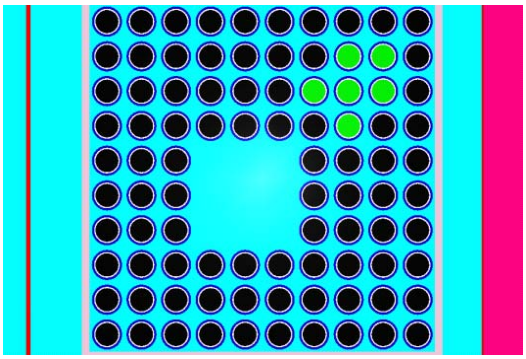


FANP 10x10 4.2 wt% ^{235}U, Pattern F

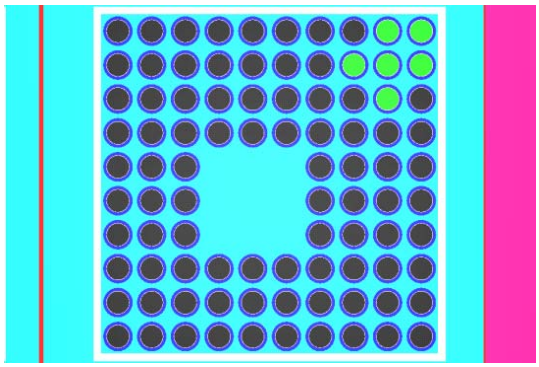
Figure 6-30 Gadolinia-Urania Fuel Rod Placement Pattern for 10x10 Fuel Assemblies (Continued)



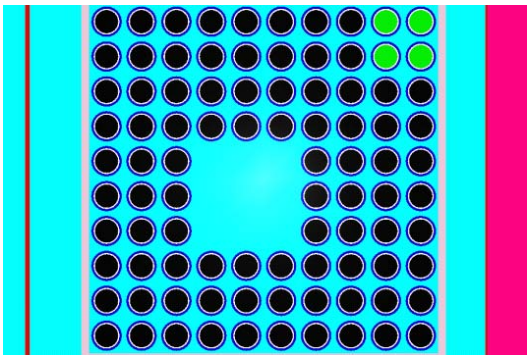
FANP 10x10 3.9 wt% ^{235}U, Pattern E



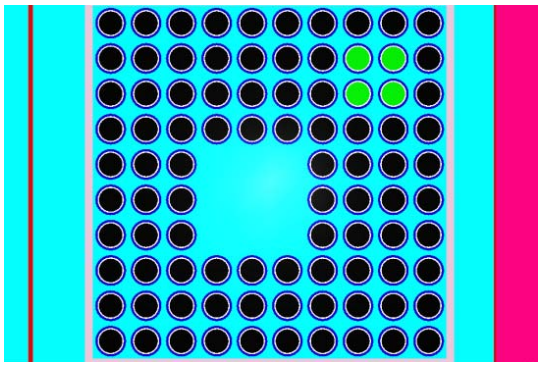
FANP 10x10 3.9 wt% ^{235}U, Pattern F



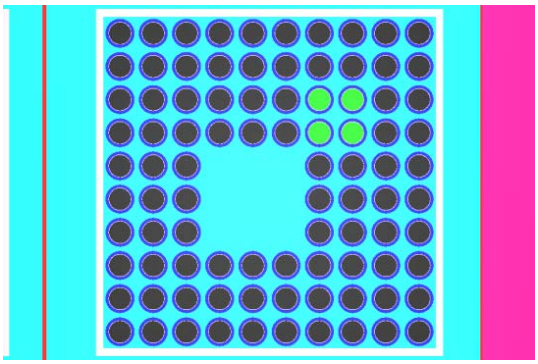
FANP 10x10 3.9 wt% ^{235}U, Pattern G



FANP 10x10 3.6 wt% ^{235}U, Pattern H

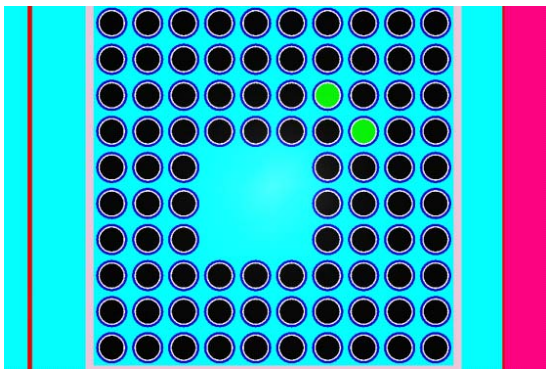


FANP 10x10 3.6 wt% ^{235}U, Pattern I

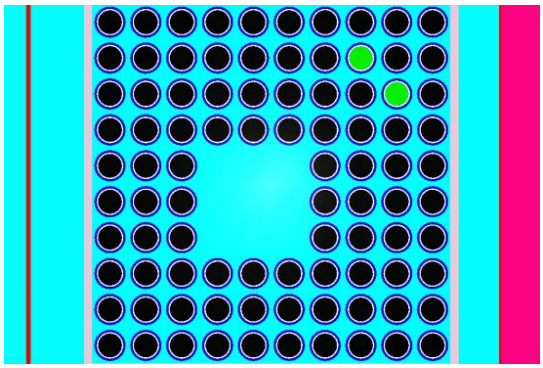


FANP 10x10 3.6 wt% ^{235}U, Pattern J

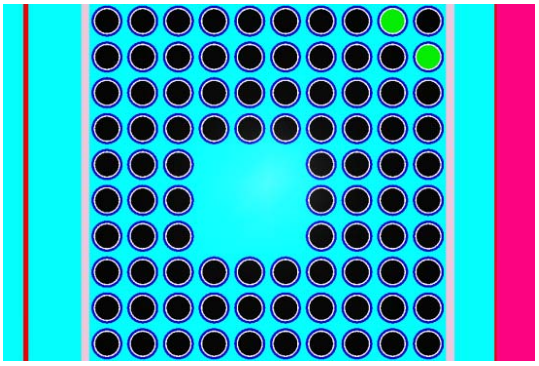
Figure 6-30 Gadolinia-Urania Fuel Rod Placement Pattern for 10x10 Fuel Assemblies (Continued)



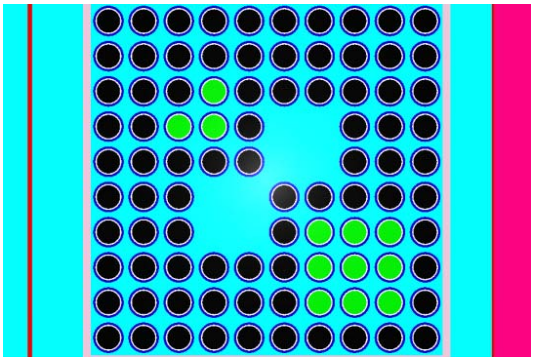
FANP 10x10 3.3 wt% ^{235}U, Pattern F



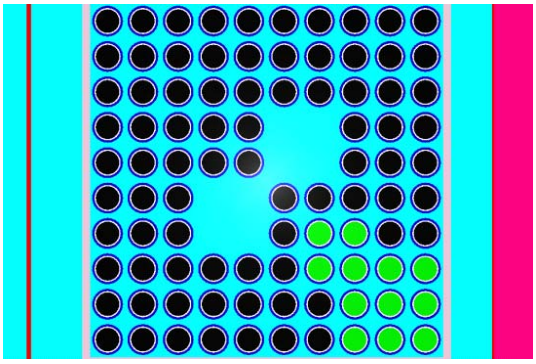
FANP 10x10 3.3 wt% ^{235}U, Pattern G



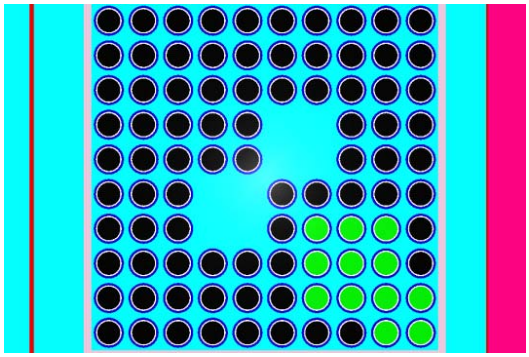
FANP 10x10 3.3 wt% ^{235}U, Pattern H



GNF 10x10 5.0 wt% ^{235}U, Pattern B

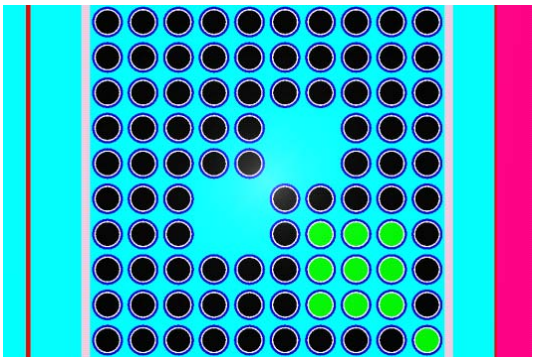


GNF 10x10 5.0 wt% ^{235}U, Pattern F

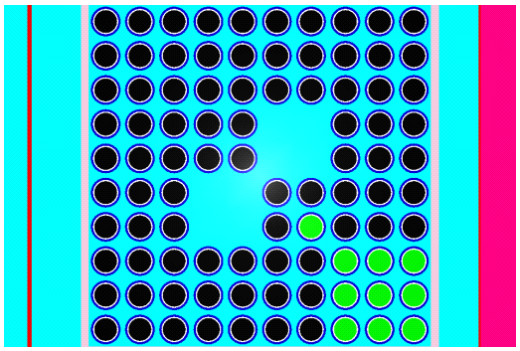


GNF 10x10 5.0 wt% ^{235}U, Pattern H

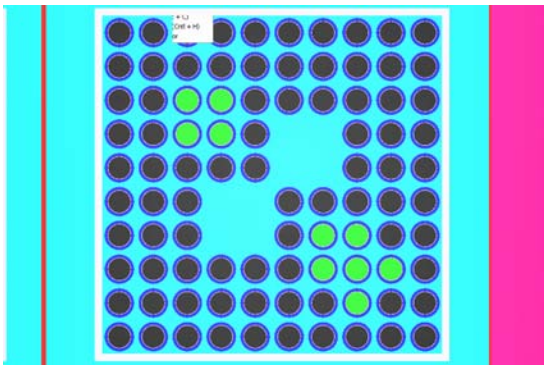
Figure 6-30 Gadolinia-Urania Fuel Rod Placement Pattern for 10x10 Fuel Assemblies (Continued)



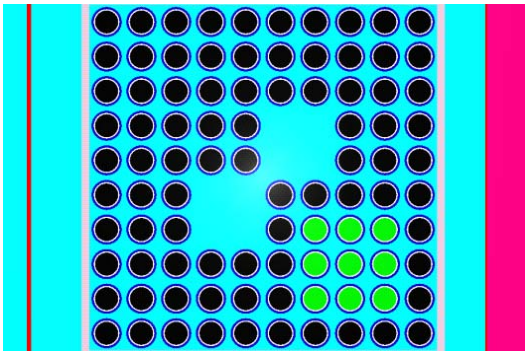
GNF 10x10 4.6 wt% ^{235}U, Pattern F



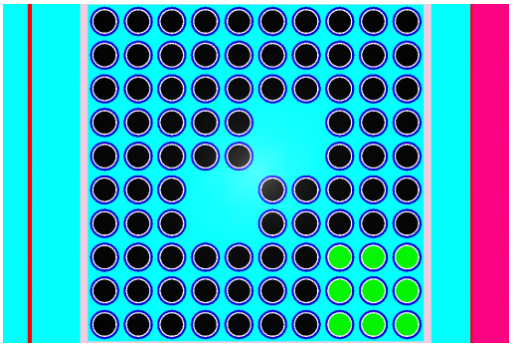
GNF 10x10 4.6 wt% ^{235}U, Pattern G



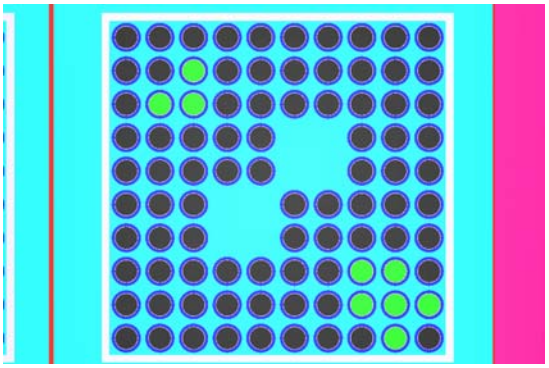
GNF 10x10 4.6 wt% ^{235}U, Pattern I



GNF 10x10 4.3 wt% ^{235}U, Pattern F

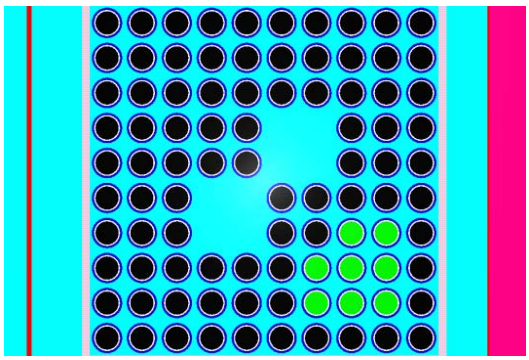


GNF 10x10 4.3 wt% ^{235}U, Pattern G

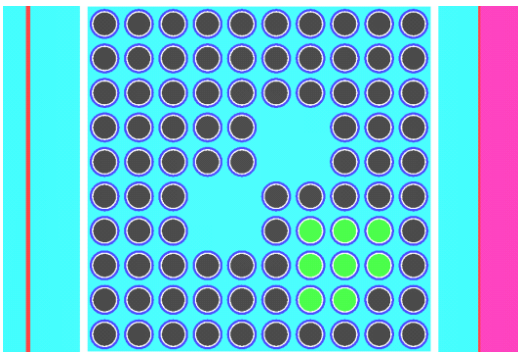


GNF 10x10 4.3 wt% ^{235}U, Pattern J

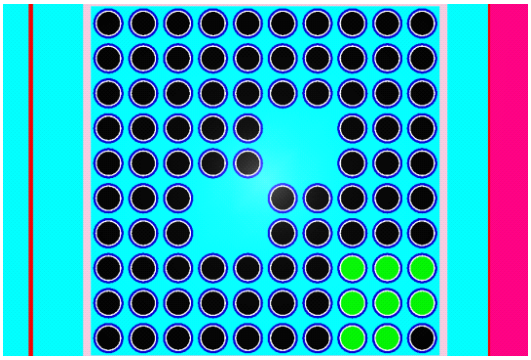
Figure 6-30 Gadolinia-Urania Fuel Rod Placement Pattern for 10x10 Fuel Assemblies (Continued)



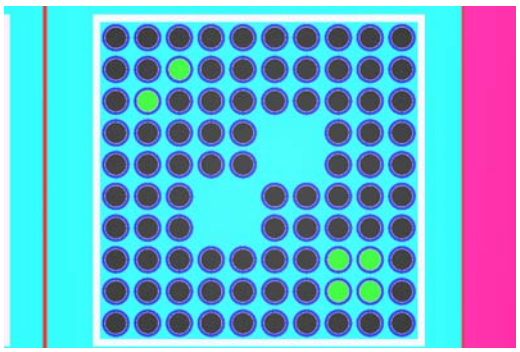
GNF 10x10 4.2 wt% ^{235}U, Pattern F



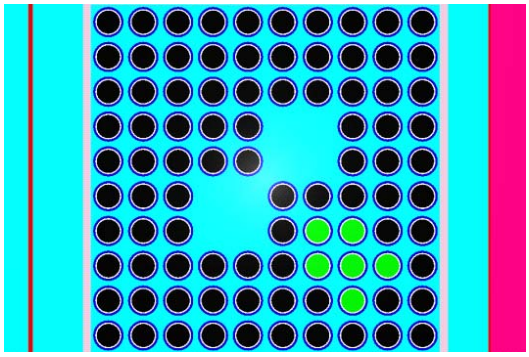
GNF 10x10 4.2 wt% ^{235}U, Pattern I



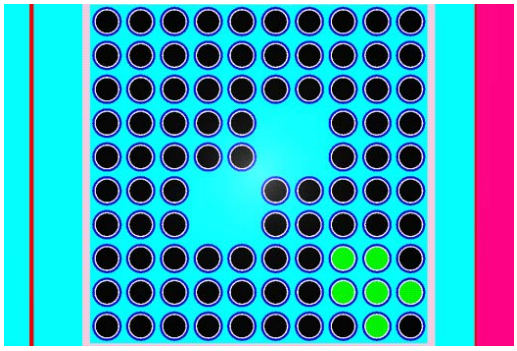
GNF 10x10 4.2 wt% ^{235}U, Pattern J



GNF 10x10 3.9 wt% ^{235}U, Pattern G

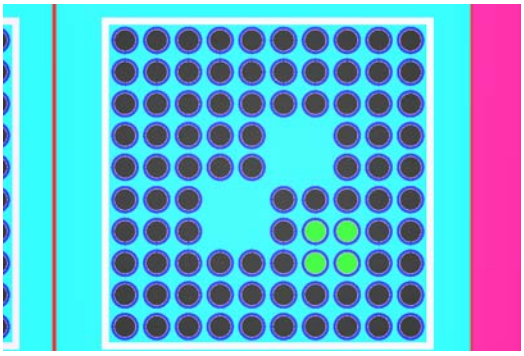


GNF 10x10 3.9 wt% ^{235}U, Pattern J

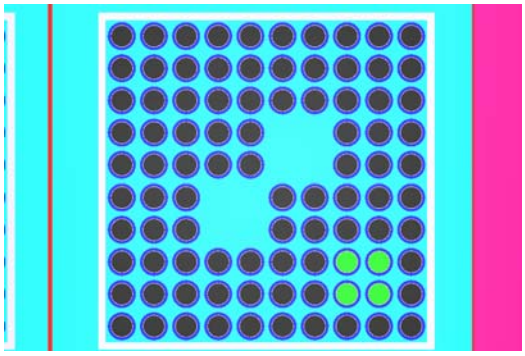


GNF 10x10 3.9 wt% ^{235}U, Pattern K

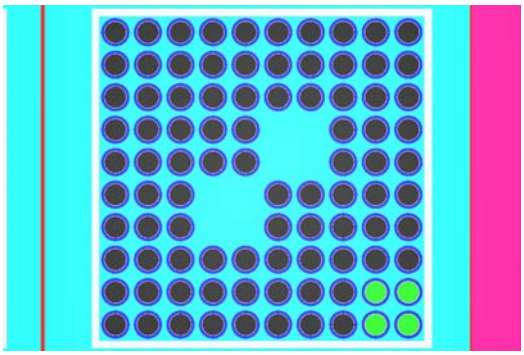
Figure 6-30 Gadolinia-Urania Fuel Rod Placement Pattern for 10x10 Fuel Assemblies (Continued)



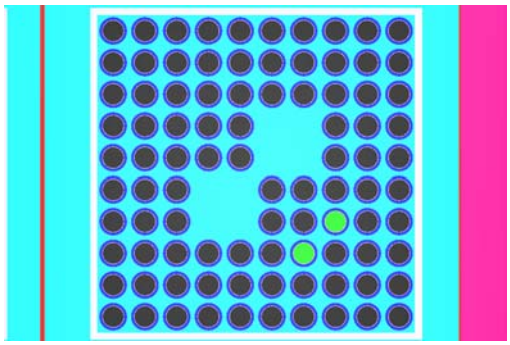
GNF 10x10 3.6 wt% ^{235}U, Pattern F



GNF 10x10 3.6 wt% ^{235}U, Pattern G

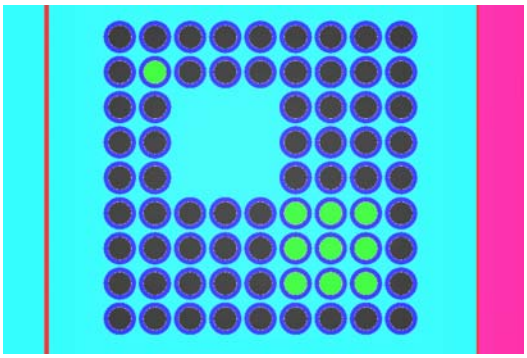


GNF 10x10 3.6 wt% ^{235}U, Pattern H

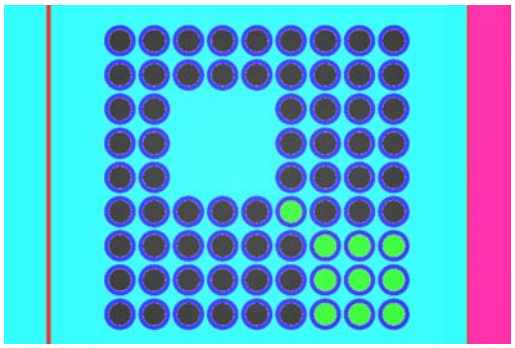


GNF 10x10 3.3 wt% ^{235}U, Pattern A

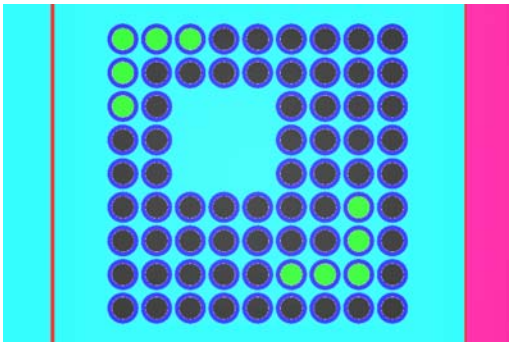
Figure 6-30 Gadolinia-Urania Fuel Rod Placement Pattern for 10x10 Fuel Assemblies (Continued)



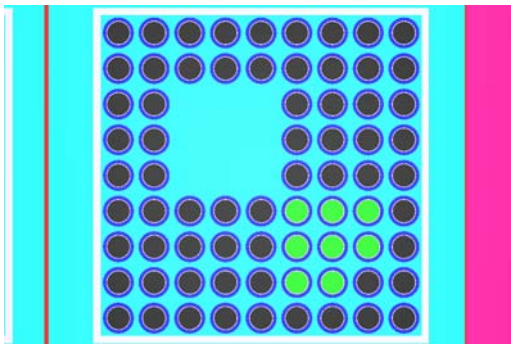
FANP 9x9 5.0 wt% ^{235}U, Pattern A



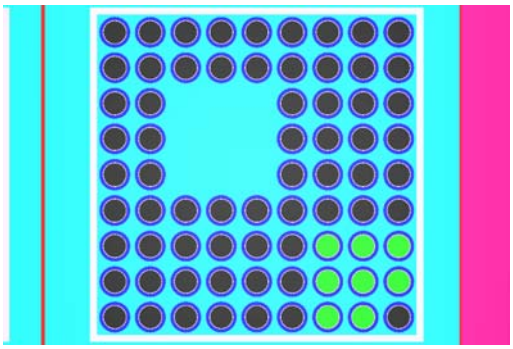
FANP 9x9 5.0 wt% ^{235}U, Pattern B



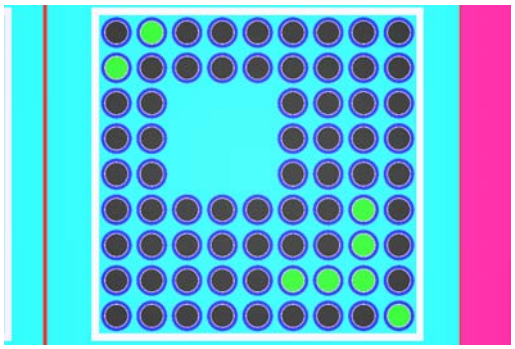
FANP 9x9 5.0 wt% ^{235}U, Pattern E



FANP 9x9 4.7 wt% ^{235}U, Pattern A

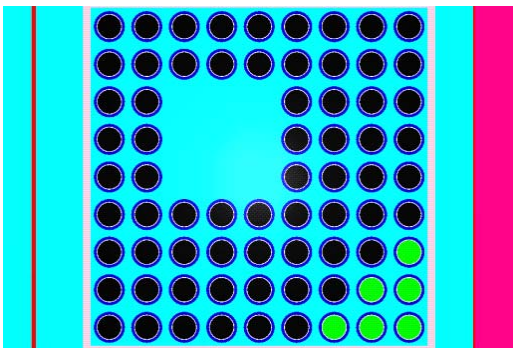


FANP 9x9 4.7 wt% ^{235}U, Pattern B

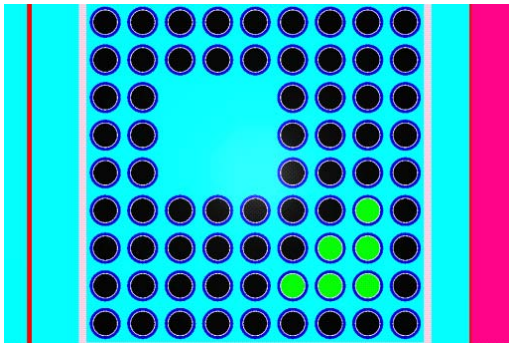


FANP 9x9 4.7 wt% ^{235}U, Pattern E

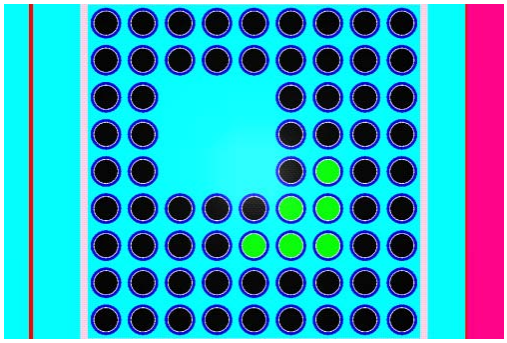
Figure 6-31 Gadolinia-Urania Fuel Rod Placement Pattern for 9x9 Fuel Assemblies



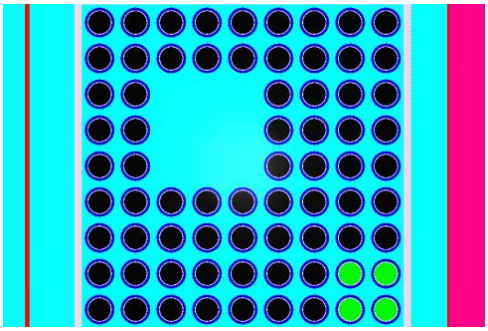
FANP 9x9 4.2 wt% U-235, Pattern A



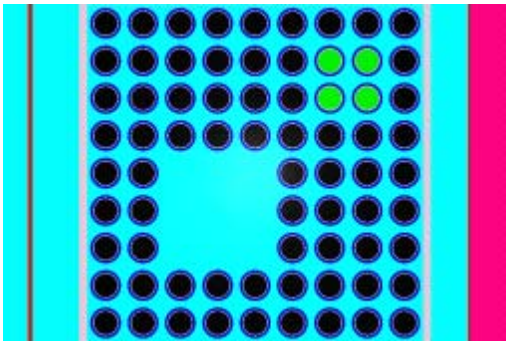
FANP 9x9 4.2 wt% U-235, Pattern B



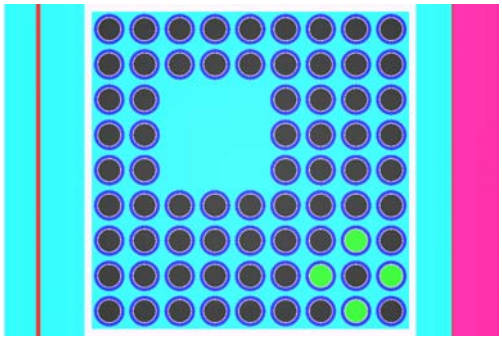
FANP 9x9 4.2 wt% U-235, Pattern C



FANP 9x9 3.8 wt% U-235, Pattern A

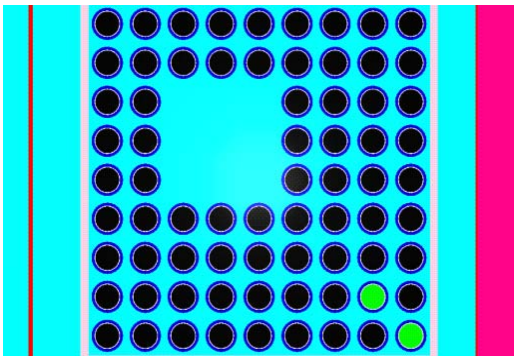


FANP 9x9 3.8 wt% U-235, Pattern B

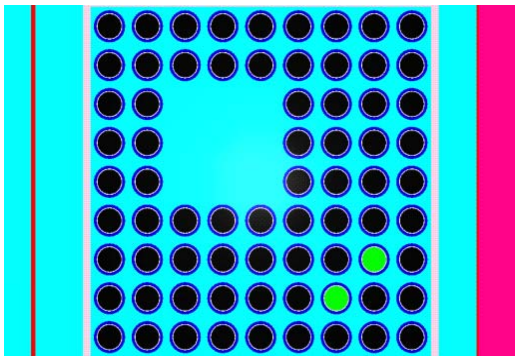


FANP 9x9 3.8 wt% U-235, Pattern F

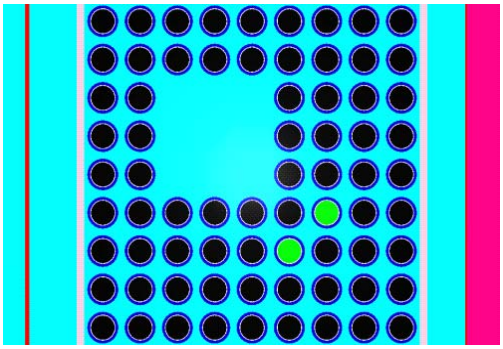
Figure 6-31 Gadolinia-Urania Fuel Rod Placement Pattern for 9x9 Fuel Assemblies (Continued)



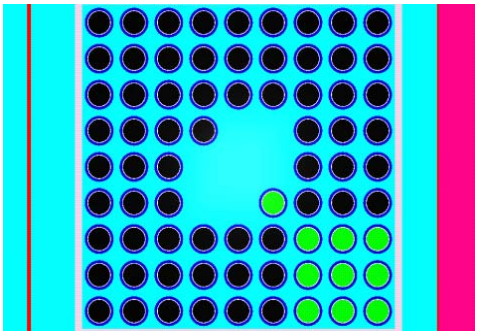
FANP 9x9 3.5 wt% U-235, Pattern B



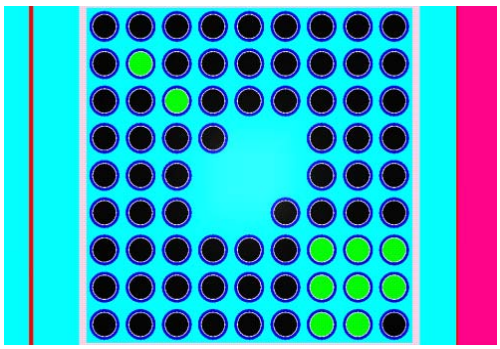
FANP 9x9 3.5 wt% U-235, Pattern C



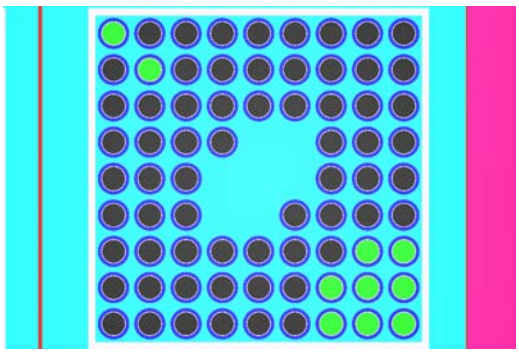
FANP 9x9 3.5 wt% U-235, Pattern D



GNF 9x9 5.0 wt% U-235, Pattern B

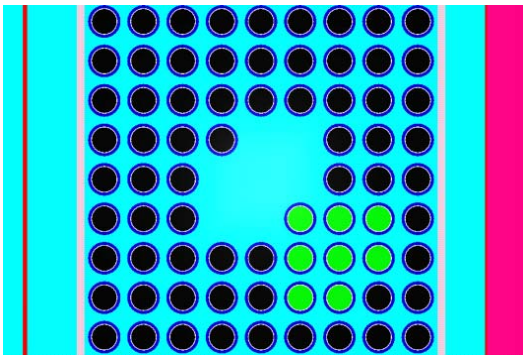


GNF 9x9 5.0 wt% U-235, Pattern G

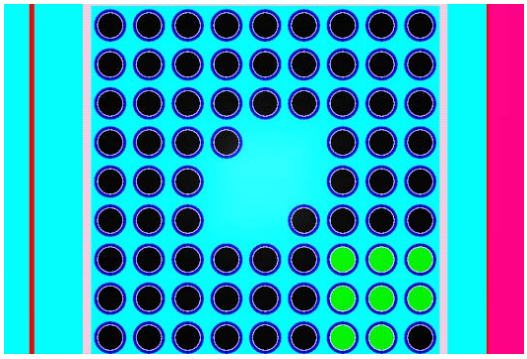


GNF 9x9 5.0 wt% U-235, Pattern H

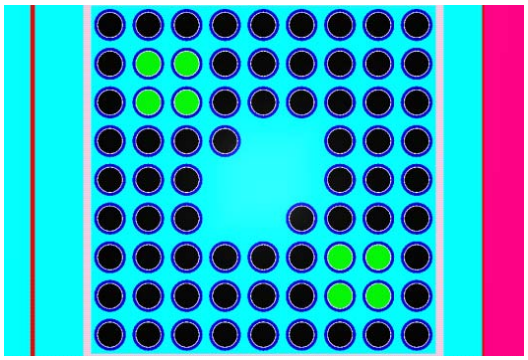
Figure 6-31 Gadolinia–Urania Fuel Rod Placement Pattern for 9X9 Fuel Assemblies (Continued)



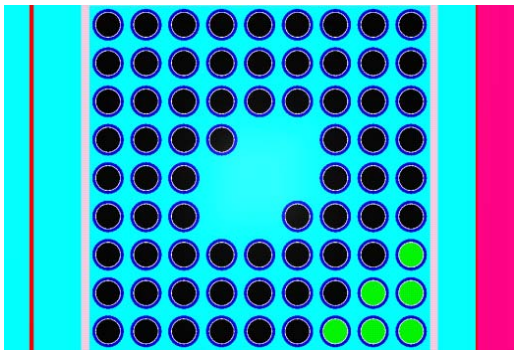
GNF 9x9 4.8 wt% U-235, Pattern A



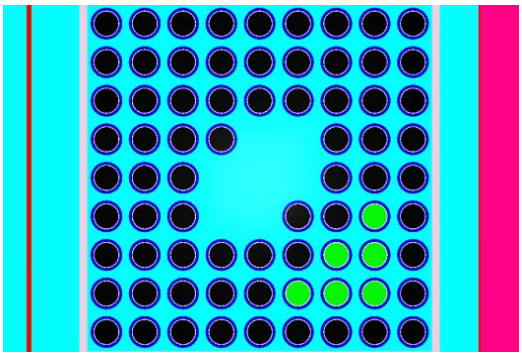
GNF 9x9 4.8 wt% U-235, Pattern B



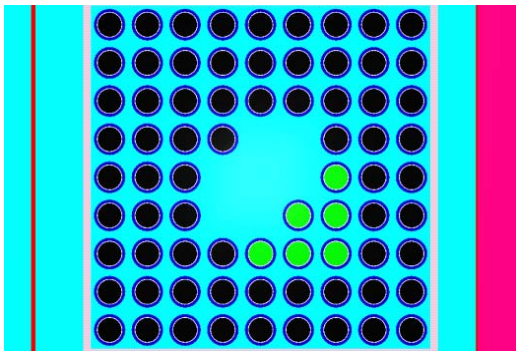
GNF 9x9 4.8 wt% U-235, Pattern H



GNF 9x9 4.2 wt% U-235, Pattern A

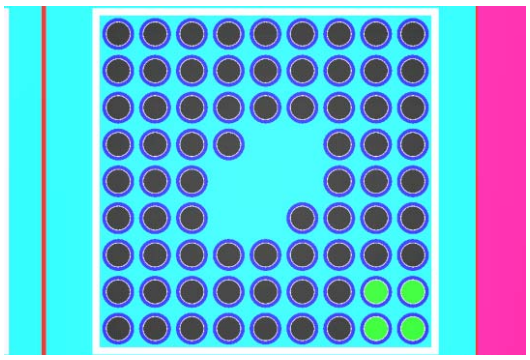


GNF 9x9 4.2 wt% U-235, Pattern B

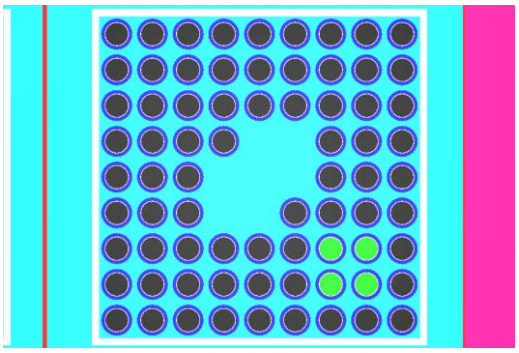


GNF 9x9 4.2 wt% U-235, Pattern C

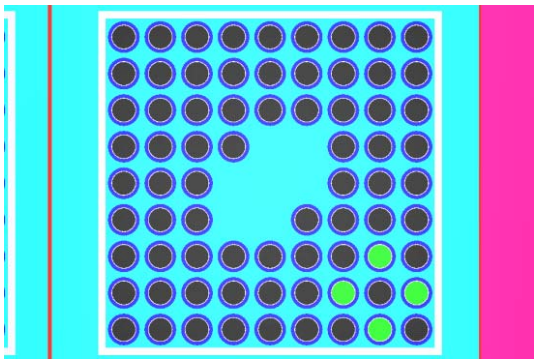
Figure 6-31 Gadolinia–Urania Fuel Rod Placement Pattern for 9X9 Fuel Assemblies (Continued)



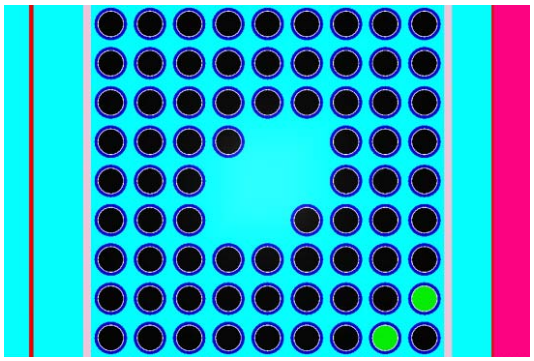
GNF 9x9 3.8 wt% ^{235}U, Pattern A



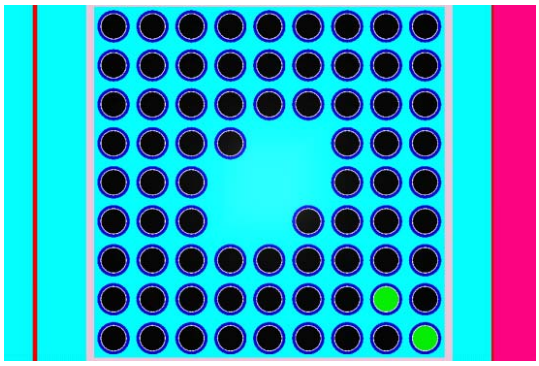
GNF 9x9 3.8 wt% ^{235}U, Pattern B



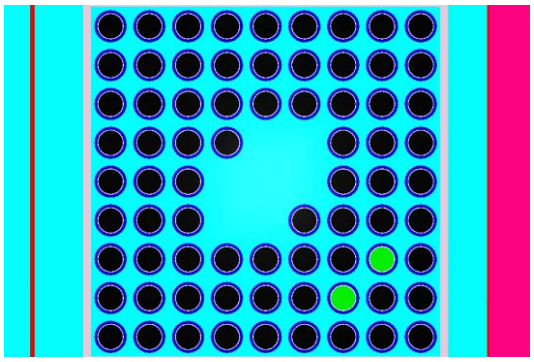
GNF 9x9 3.8 wt% ^{235}U, Pattern F



GNF 9x9 3.5 wt% ^{235}U, Pattern A

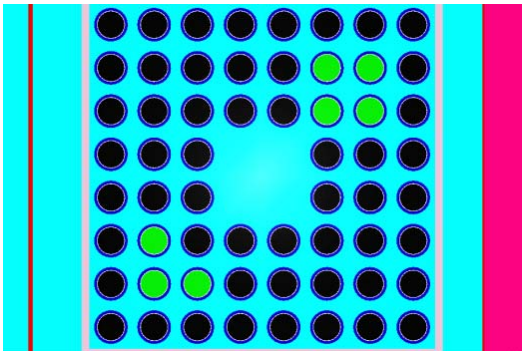


GNF 9x9 3.5 wt% ^{235}U, Pattern B

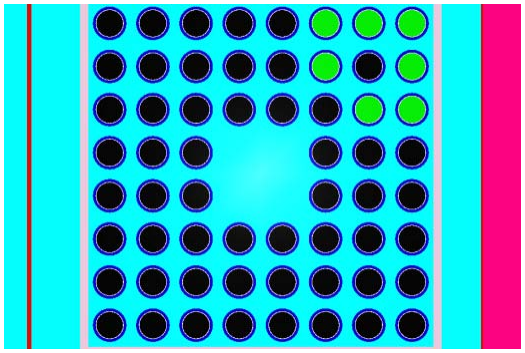


GNF 3.5 wt% ^{235}U, Pattern C

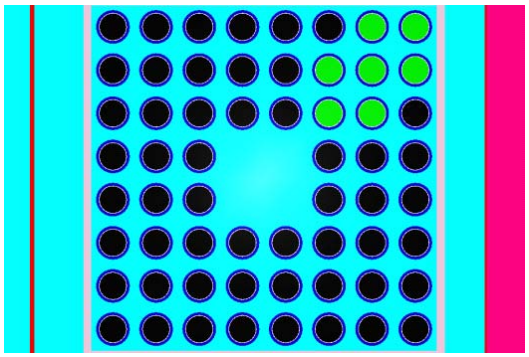
Figure 6-31 Gadolinia–Urania Fuel Rod Placement Pattern for 9X9 Fuel Assemblies (Continued)



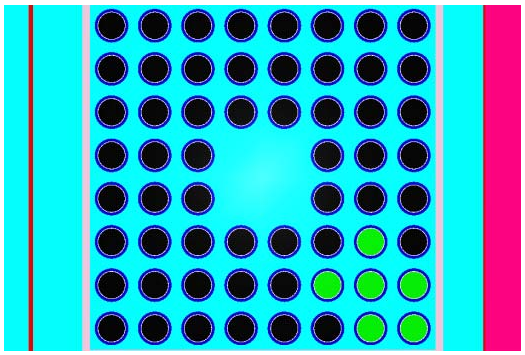
GNF 8x8 5.0 wt% ^{235}U, Pattern E



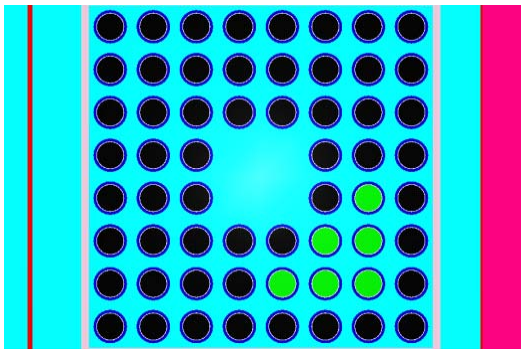
GNF 8x8 5.0 wt% ^{235}U, Pattern H



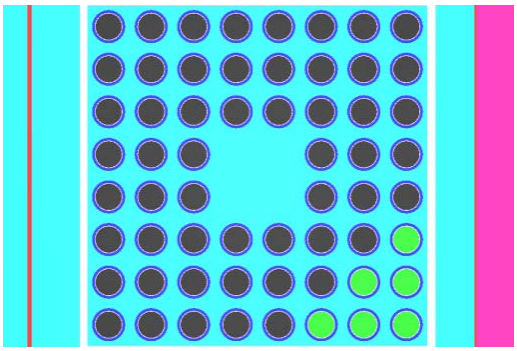
GNF 8x8 5.0 wt% ^{235}U, Pattern I



GNF 8x8 4.7 wt% ^{235}U, Pattern B

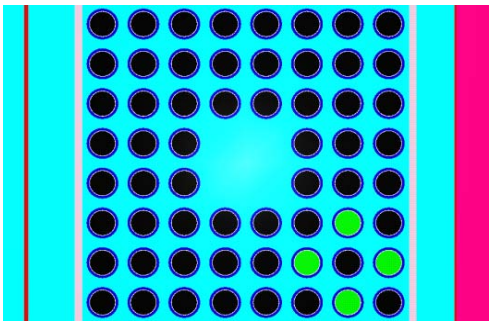


GNF 8x8 4.7 wt% ^{235}U, Pattern C

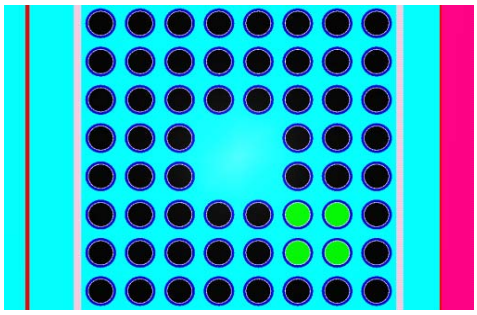


GNF 8x8 4.7 wt% ^{235}U, Pattern D

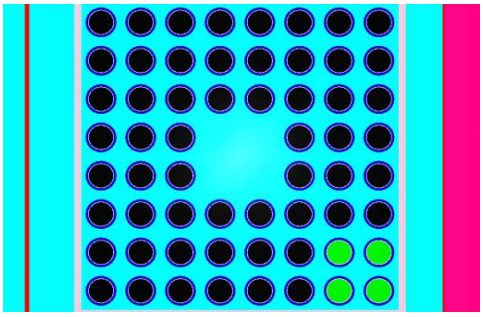
Figure 6-32 Gadolinia-Urania Fuel Rod Placement Pattern for 8x8 Fuel Assemblies



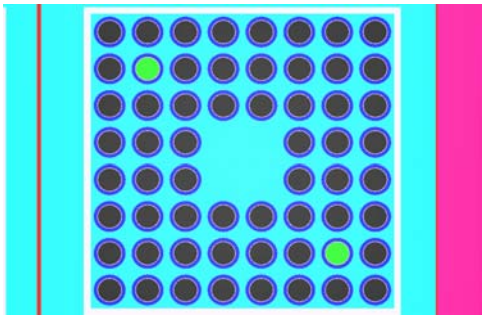
GNF 8x8 4.1 wt%^{235}U, Pattern B



GNF 8x8 4.1 wt%^{235}U, Pattern C



GNF 8x8 4.1 wt%^{235}U, Pattern D



GNF 8x8 3.7 wt%^{235}U, Pattern A

Figure 6-32 Gadolinia-Urania Fuel Rod Placement Pattern for 8x8 Fuel Assemblies (Continued)

6.3.4.9 Part Length Fuel Rod Study (2N=448)

The FANP 10x10, FANP 9x9, GNF 10x10, and GNF 9x9 worst case designs are used to investigate the impact that part length fuel rods have on system reactivity. The worst case part length fuel rod patterns identified by performing scoping studies for the 10x10 designs are shown in Figure 6-33 and Figure 6-34. The worst case part length fuel rod patterns identified by performing scoping studies for the 9x9 designs are shown in Figure 6-35 and Figure 6-36. The fuel rod lengths for the part length rods are half that of the normal rod, and calculations showed that reducing the length further decreases system reactivity. To maintain the same amount of polyethylene when the part length rods are inserted, the polyethylene is redistributed to all rods in the assembly. The worst case models from the moderator density sensitivity study are used to conduct the part length fuel rod study, and the worst case fuel parameters listed in Table 6-17 are utilized. The part length fuel rod study results are contained in Table 6-18. All results for the FANP 9x9, the FANP 10x10, and the GNF 9x9 are below the USL of 0.94254. Several cases for the GNF 10x10 fuel design are above the USL of 0.94254. Therefore, an increased clad thickness is investigated for the 10x10 designs to reduce the system reactivity; these cases are included at the end of Table 6-18. The increased clad thickness for the 10x10 designs reduce system reactivity and all 10x10 results are below the USL of 0.94254. Comparing the results in Table 6-18 with those in Table 6-17 reveals the system reactivity remains about the same for the 9x9 fuel assembly designs with part length fuel rods. The FANP 10x10 and GNF 10x10 fuel designs are more reactive with the part length fuel rod configuration. Based on the results in Table 6-17 and Table 6-18:

- The maximum system reactivity with FANP 10x10 fuel assemblies having part length fuel rods and gadolinia-urania fuel is statistically greater than the maximum system reactivity with FANP 10x10 fuel assemblies having gadolinia-urania fuel and no part length fuel rods. The configuration that yields the highest $k_{eff} + 2\sigma$ consists of fuel assemblies with a lattice average enrichment of 5.0 wt% U-235, 12 gadolinia-urania fuel rods enriched to 2.0 wt% gadolinia arranged in Pattern G, and 10 part length fuel rods. With the clad thickness for the fuel assemblies increased from 0.0335 cm to 0.0381 cm, the $k_{eff} + 2\sigma$ for this configuration is 0.9394.

- The maximum system reactivity with GNF 10x10 fuel assemblies having part length fuel rods and gadolinia-urania fuel is statistically greater than the maximum system reactivity with GNF 10x10 fuel assemblies having gadolinia-urania fuel and no part length fuel rods. The configuration that yields the highest $k_{eff} + 2\sigma$ consists of fuel assemblies with a lattice average enrichment of 5.0 wt% U-235, 12 gadolinia-urania fuel rods enriched to 2.0 wt% gadolinia arranged in Pattern H, and 12 part length fuel rods. With the clad thickness for the fuel assemblies increased from 0.0335 cm to 0.0381 cm, the $k_{eff} + 2\sigma$ for this configuration is 0.9418.

- Based on fuel parameter changes made to the 10x10 designs to lower reactivity, a 0.9338 cm upper bound clad ID, and a 1.01 cm lower bound clad OD are established for the GNF 10x10 parameter ranges. The 0.9330 cm upper bound clad ID and 1.00 cm lower bound clad OD may still be used for the FANP 10x10 design since the fuel assembly with this configuration remained below the USL of 0.94254.

- The most reactive FANP 9x9 configuration consists of fuel assemblies with a lattice average enrichment of 4.7 wt% U-235 and 8 gadolinia-urania fuel rods enriched to 2.0 wt% gadolinia arranged in Pattern A and 8 part length rods. The $k_{eff} + 2\sigma$ for this configuration is 0.9303.

- The most reactive GNF 9x9 configuration consists of fuel assemblies with a lattice average enrichment of 4.7 wt% U-235 and 8 gadolinia-urania fuel rods enriched to 2.0 wt% gadolinia arranged in Pattern B and 8 part length fuel rods. The $k_{eff} + 2\sigma$ for this configuration is 0.9407.

- The most reactive GNF 8x8 configuration consists of fuel assemblies with a lattice average enrichment of 5.0 wt% U-235, 7 gadolinia-urania fuel rods enriched to 2.0 wt% gadolinia arranged in Pattern I, and no part length fuel rods. The $k_{eff} + 2\sigma$ for this configuration is 0.9372 (Table 6-17). The GNF 8x8 fuel assembly is not evaluated for part length fuel rods.

The GNF 10x10 assembly is chosen as the overall bounding fuel type since the $k_{eff} + 2\sigma$ is among the largest numerical values, however, the system reactivity of the 10x10, and 9x9 worst case fuel assembly designs in the 14x2x16 RAJ-II container array are statistically indistinquishable.

Table 6-18 RAJ-II Array HAC Part Length Fuel Rod Calculations

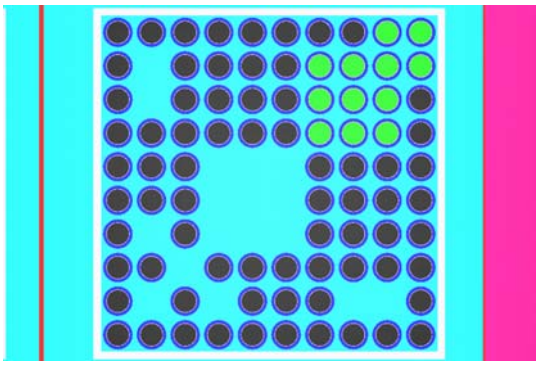
Assembly Type	Number of Part Length Rods	Gadolinia -Urania Fuel Rod Number	^{235}U Enrichment (wt%)	Pitch (cm)	Pellet Diameter (cm)	Clad ID (cm)	Clad OD (cm)	k_{eff}	σ	$k_{eff} + 2\sigma$
FANP 10x10	8	0	2.9	1.350	0.895	0.933	1.00	0.9228	0.0008	0.9244
FANP 10x10	8	2	3.3	1.350	0.895	0.933	1.00	0.9282	0.0008	0.9298
FANP 10x10	8	4	3.6	1.350	0.895	0.933	1.00	0.9332	0.0008	0.9348
FANP 10x10	8	6	3.9	1.350	0.895	0.933	1.00	0.9327	0.0008	0.9343
FANP 10x10	8	8	4.2	1.350	0.895	0.933	1.00	0.9367	0.0008	0.9383
FANP 10x10	8	9	4.3	1.350	0.895	0.933	1.00	0.9282	0.0008	0.9298
FANP 10x10	8	10	4.6	1.350	0.895	0.933	1.00	0.9363	0.0009	0.9381
FANP 10x10	8	12	5.0	1.350	0.895	0.933	1.00	0.9403	0.0008	**0.9419**
FANP 10x10	10	0	2.9	1.350	0.895	0.933	1.00	0.9224	0.0008	0.9240
FANP 10x10	10	2	3.3	1.350	0.895	0.933	1.00	0.9283	0.0008	0.9299
FANP 10x10	10	4	3.6	1.350	0.895	0.933	1.00	0.9330	0.0007	0.9344
FANP 10x10	10	6	3.9	1.350	0.895	0.933	1.00	0.9333	0.0008	0.9349
FANP 10x10	10	8	4.2	1.350	0.895	0.933	1.00	0.9367	0.0008	0.9383
FANP 10x10	10	9	4.3	1.350	0.895	0.933	1.00	0.9301	0.0008	0.9317
FANP 10x10	10	10	4.6	1.350	0.895	0.933	1.00	0.9379	0.0009	0.9397
FANP 10x10	10	12	5.0	1.350	0.895	0.933	1.00	0.9399	0.0008	**0.9415**
FANP 10x10	12	0	2.9	1.350	0.895	0.933	1.00	0.9234	0.0008	0.9250
FANP 10x10	12	2	3.3	1.350	0.895	0.933	1.00	0.9281	0.0008	0.9297
FANP 10x10	12	4	3.6	1.350	0.895	0.933	1.00	0.9329	0.0008	0.9345
FANP 10x10	12	6	3.9	1.350	0.895	0.933	1.00	0.9319	0.0008	0.9335

Assembly Type	Number of Part Length Rods	Gadolinia -Urania Fuel Rod Number	^{235}U Enrichment (wt%)	Pitch (cm)	Pellet Diameter (cm)	Clad ID (cm)	Clad OD (cm)	k_{eff}	σ	$k_{eff} + 2\sigma$
FANP 10x10	12	8	4.2	1.350	0.895	0.933	1.00	0.9356	0.0008	0.9372
FANP 10x10	12	9	4.3	1.350	0.895	0.933	1.00	0.9294	0.0007	0.9308
FANP 10x10	12	10	4.6	1.350	0.895	0.933	1.00	0.9371	0.0008	0.9387
FANP 10x10	12	12	5.0	1.350	0.895	0.933	1.00	0.9404	0.0009	**0.9422**
FANP 10x10	14	0	2.9	1.350	0.895	0.933	1.00	0.9225	0.0008	0.9241
FANP 10x10	14	2	3.3	1.350	0.895	0.933	1.00	0.9274	0.0008	0.9290
FANP 10x10	14	4	3.6	1.350	0.895	0.933	1.00	0.9326	0.0009	0.9344
FANP 10x10	14	6	3.9	1.350	0.895	0.933	1.00	0.9313	0.0008	0.9329
FANP 10x10	14	8	4.2	1.350	0.895	0.933	1.00	0.9348	0.0010	0.9368
FANP 10x10	14	9	4.3	1.350	0.895	0.933	1.00	0.9310	0.0008	0.9326
FANP 10x10	14	10	4.6	1.350	0.895	0.933	1.00	0.9371	0.0008	0.9387
FANP 10x10	14	12	5.0	1.350	0.895	0.933	1.00	0.9393	0.0009	**0.9411**
GNF 10x10	8	0	2.9	1.350	0.895	0.933	1.00	0.9321	0.0007	0.9335
GNF 10x10	8	2	3.3	1.350	0.895	0.933	1.00	0.9327	0.0007	0.9341
GNF 10x10	8	4	3.6	1.350	0.895	0.933	1.00	0.9395	0.0010	0.9415
GNF 10x10	8	6	3.9	1.350	0.895	0.933	1.00	0.9367	0.0008	0.9383
GNF 10x10	8	8	4.2	1.350	0.895	0.933	1.00	0.9402	0.0008	**0.9418**
GNF 10x10	8	9	4.3	1.350	0.895	0.933	1.00	0.9369	0.0009	0.9387
GNF 10x10	8	10	4.6	1.350	0.895	0.933	1.00	0.9376	0.0009	0.9394
GNF 10x10	8	12	5.0	1.350	0.895	0.933	1.00	0.9386	0.0010	0.9406
GNF 10x10	10	0	2.9	1.350	0.895	0.933	1.00	0.9300	0.0008	0.9316
GNF 10x10	10	2	3.3	1.350	0.895	0.933	1.00	0.9319	0.0008	0.9335
GNF 10x10	10	4	3.6	1.350	0.895	0.933	1.00	0.9380	0.0009	0.9398
GNF 10x10	10	6	3.9	1.350	0.895	0.933	1.00	0.9347	0.0008	0.9363
GNF 10x10	10	8	4.2	1.350	0.895	0.933	1.00	0.9419	0.0010	**0.9439**
GNF 10x10	10	9	4.3	1.350	0.895	0.933	1.00	0.9374	0.0008	0.9390
GNF 10x10	10	10	4.6	1.350	0.895	0.933	1.00	0.9385	0.0009	0.9403
GNF 10x10	10	12	5.0	1.350	0.895	0.933	1.00	0.9412	0.0008	0.9428
GNF 10x10	12	0	2.9	1.350	0.895	0.933	1.00	0.9300	0.0007	0.9314
GNF 10x10	12	2	3.3	1.350	0.895	0.933	1.00	0.9316	0.0007	0.9330
GNF 10x10	12	4	3.6	1.350	0.895	0.933	1.00	0.9377	0.0009	0.9395
GNF 10x10	12	6	3.9	1.350	0.895	0.933	1.00	0.9352	0.0008	0.9368
GNF 10x10	12	8	4.2	1.350	0.895	0.933	1.00	0.9408	0.0009	0.9426
GNF 10x10	12	9	4.3	1.350	0.895	0.933	1.00	0.9374	0.0008	0.9390
GNF 10x10	12	10	4.6	1.350	0.895	0.933	1.00	0.9406	0.0009	0.9424
GNF 10x10	12	12	5.0	1.350	0.895	0.933	1.00	0.9415	0.0008	**0.9431**
GNF 10x10	14	0	2.9	1.350	0.895	0.933	1.00	0.9277	0.0008	0.9293
GNF 10x10	14	2	3.3	1.350	0.895	0.933	1.00	0.9305	0.0008	0.9321
GNF 10x10	14	4	3.6	1.350	0.895	0.933	1.00	0.9374	0.0009	0.9392
GNF 10x10	14	6	3.9	1.350	0.895	0.933	1.00	0.9347	0.0008	0.9363
GNF 10x10	14	8	4.2	1.350	0.895	0.933	1.00	0.9401	0.0009	**0.9419**
GNF 10x10	14	9	4.3	1.350	0.895	0.933	1.00	0.9370	0.0009	0.9388
GNF 10x10	14	10	4.6	1.350	0.895	0.933	1.00	0.9381	0.0009	0.9399
GNF 10x10	14	12	5.0	1.350	0.895	0.933	1.00	0.9401	0.0008	0.9417
FANP 9x9	8	0	3.0	1.510	0.96	1.02	1.09	0.9168	0.0008	0.9184
FANP 9x9	8	2	3.5	1.510	0.96	1.02	1.09	0.9219	0.0008	0.9235
FANP 9x9	8	4	3.8	1.510	0.96	1.02	1.09	0.9234	0.0009	0.9252
FANP 9x9	8	6	4.2	1.510	0.96	1.02	1.09	0.9227	0.0007	0.9241
FANP 9x9	8	8	4.7	1.510	0.96	1.02	1.09	0.9287	0.0008	**0.9303**

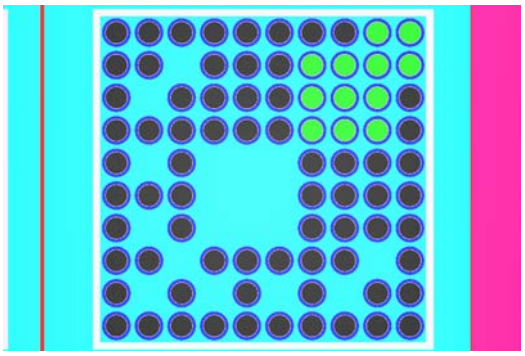
Assembly Type	Number of Part Length Rods	Gadolinia -Urania Fuel Rod Number	^{235}U Enrichment (wt%)	Pitch (cm)	Pellet Diameter (cm)	Clad ID (cm)	Clad OD (cm)	k_{eff}	σ	$k_{eff} + 2\sigma$
FANP 9x9	8	10	5.0	1.510	0.96	1.02	1.09	0.9165	0.0008	0.9181
FANP 9x9	10	0	3.0	1.510	0.96	1.02	1.09	0.9139	0.0008	0.9155
FANP 9x9	10	2	3.5	1.510	0.96	1.02	1.09	0.9195	0.0008	0.9211
FANP 9x9	10	4	3.8	1.510	0.96	1.02	1.09	0.9189	0.0008	0.9205
FANP 9x9	10	6	4.2	1.510	0.96	1.02	1.09	0.9208	0.0008	0.9224
FANP 9x9	10	8	4.7	1.510	0.96	1.02	1.09	0.9256	0.0009	**0.9274**
FANP 9x9	10	10	5.0	1.510	0.96	1.02	1.09	0.9135	0.0009	0.9153
FANP 9x9	12	0	3.0	1.510	0.96	1.02	1.09	0.9100	0.0007	0.9114
FANP 9x9	12	2	3.5	1.510	0.96	1.02	1.09	0.9155	0.0007	0.9169
FANP 9x9	12	4	3.8	1.510	0.96	1.02	1.09	0.9168	0.0008	0.9184
FANP 9x9	12	6	4.2	1.510	0.96	1.02	1.09	0.9147	0.0007	0.9161
FANP 9x9	12	8	4.7	1.510	0.96	1.02	1.09	0.9208	0.0008	**0.9224**
FANP 9x9	12	10	5.0	1.510	0.96	1.02	1.09	0.9087	0.0009	0.9105
GNF 9x9	8	0	3.0	1.510	0.96	1.02	1.09	0.9261	0.0008	0.9277
GNF 9x9	8	2	3.5	1.510	0.96	1.02	1.09	0.9311	0.0008	0.9327
GNF 9x9	8	4	3.8	1.510	0.96	1.02	1.09	0.9303	0.0008	0.9319
GNF 9x9	8	6	4.2	1.510	0.96	1.02	1.09	0.9293	0.0008	0.9309
GNF 9x9	8	8	4.7	1.510	0.96	1.02	1.09	0.9391	0.0008	**0.9407**
GNF 9x9	8	10	5.0	1.510	0.96	1.02	1.09	0.9140	0.0008	0.9156
GNF 9x9	10	0	3.0	1.510	0.96	1.02	1.09	0.9249	0.0009	0.9267
GNF 9x9	10	2	3.5	1.510	0.96	1.02	1.09	0.9315	0.0008	0.9331
GNF 9x9	10	4	3.8	1.510	0.96	1.02	1.09	0.9287	0.0008	0.9303
GNF 9x9	10	6	4.2	1.510	0.96	1.02	1.09	0.9297	0.0009	0.9315
GNF 9x9	10	8	4.7	1.510	0.96	1.02	1.09	0.9377	0.0008	**0.9393**
GNF 9x9	10	10	5.0	1.510	0.96	1.02	1.09	0.9048	0.0008	0.9064
GNF 9x9	12	0	3.0	1.510	0.96	1.02	1.09	0.9235	0.0008	0.9251
GNF 9x9	12	2	3.5	1.510	0.96	1.02	1.09	0.9294	0.0009	0.9312
GNF 9x9	12	4	3.8	1.510	0.96	1.02	1.09	0.9288	0.0009	0.9306
GNF 9x9	12	6	4.2	1.510	0.96	1.02	1.09	0.9263	0.0008	0.9279
GNF 9x9	12	8	4.7	1.510	0.96	1.02	1.09	0.9370	0.0009	**0.9388**
GNF 9x9	12	10	5.0	1.510	0.96	1.02	1.09	0.9056	0.0008	0.9072
FANP 10x10	8	0	2.9	1.350	0.895	0.9338	1.01	0.9203	0.0008	0.9219
FANP 10x10	8	2	3.3	1.350	0.895	0.9338	1.01	0.9150	0.0008	0.9166
FANP 10x10	8	4	3.6	1.350	0.895	0.9338	1.01	0.9290	0.0008	0.9306
FANP 10x10	8	6	3.9	1.350	0.895	0.9338	1.01	0.9303	0.0008	0.9319
FANP 10x10	8	8	4.2	1.350	0.895	0.9338	1.01	0.9292	0.0008	0.9308
FANP 10x10	8	9	4.3	1.350	0.895	0.9338	1.01	0.9293	0.0008	0.9309
FANP 10x10	8	10	4.6	1.350	0.895	0.9338	1.01	0.9335	0.0008	0.9351
FANP 10x10	8	12	5.0	1.350	0.895	0.9338	1.01	0.9353	0.0009	**0.9371**
FANP 10x10	10	0	2.9	1.350	0.895	0.9338	1.01	0.9218	0.0008	0.9234
FANP 10x10	10	2	3.3	1.350	0.895	0.9338	1.01	0.9265	0.0008	0.9281
FANP 10x10	10	4	3.6	1.350	0.895	0.9338	1.01	0.9320	0.0008	0.9336
FANP 10x10	10	6	3.9	1.350	0.895	0.9338	1.01	0.9311	0.0008	0.9327
FANP 10x10	10	8	4.2	1.350	0.895	0.9338	1.01	0.9345	0.0008	0.9361
FANP 10x10	10	9	4.3	1.350	0.895	0.9338	1.01	0.9296	0.0009	0.9314
FANP 10x10	10	10	4.6	1.350	0.895	0.9338	1.01	0.9369	0.0009	0.9387
FANP 10x10	10	12	5.0	1.350	0.895	0.9338	1.01	0.9376	0.0009	**0.9394**
FANP 10x10	12	0	2.9	1.350	0.895	0.9338	1.01	0.9216	0.0008	0.9232
FANP 10x10	12	2	3.3	1.350	0.895	0.9338	1.01	0.9256	0.0008	0.9272

Assembly Type	Number of Part Length Rods	Gadolinia -Urania Fuel Rod Number	^{235}U Enrichment (wt%)	Pitch (cm)	Pellet Diameter (cm)	Clad ID (cm)	Clad OD (cm)	k_{eff}	σ	$k_{eff} + 2\sigma$
FANP 10x10	12	4	3.6	1.350	0.895	0.9338	1.01	0.9314	0.0009	0.9332
FANP 10x10	12	6	3.9	1.350	0.895	0.9338	1.01	0.9319	0.0007	0.9333
FANP 10x10	12	8	4.2	1.350	0.895	0.9338	1.01	0.9345	0.0008	0.9361
FANP 10x10	12	9	4.3	1.350	0.895	0.9338	1.01	0.9277	0.0008	0.9293
FANP 10x10	12	10	4.6	1.350	0.895	0.9338	1.01	0.9347	0.0009	0.9365
FANP 10x10	12	12	5.0	1.350	0.895	0.9338	1.01	0.9370	0.0009	**0.9388**
FANP 10x10	14	0	2.9	1.350	0.895	0.9338	1.01	0.9207	0.0008	0.9223
FANP 10x10	14	2	3.3	1.350	0.895	0.9338	1.01	0.9247	0.0009	0.9265
FANP 10x10	14	4	3.6	1.350	0.895	0.9338	1.01	0.9291	0.0008	0.9307
FANP 10x10	14	6	3.9	1.350	0.895	0.9338	1.01	0.9301	0.0009	0.9319
FANP 10x10	14	8	4.2	1.350	0.895	0.9338	1.01	0.9324	0.0008	0.9340
FANP 10x10	14	9	4.3	1.350	0.895	0.9338	1.01	0.9293	0.0008	0.9309
FANP 10x10	14	10	4.6	1.350	0.895	0.9338	1.01	0.9352	0.0008	0.9368
FANP 10x10	14	12	5.0	1.350	0.895	0.9338	1.01	0.9370	0.0009	**0.9388**
GNF 10x10	8	0	2.9	1.350	0.895	0.9338	1.01	0.9292	0.0008	0.9308
GNF 10x10	8	2	3.3	1.350	0.895	0.9338	1.01	0.9296	0.0009	0.9314
GNF 10x10	8	4	3.6	1.350	0.895	0.9338	1.01	0.9357	0.0010	0.9377
GNF 10x10	8	6	3.9	1.350	0.895	0.9338	1.01	0.9354	0.0009	0.9372
GNF 10x10	8	8	4.2	1.350	0.895	0.9338	1.01	0.9399	0.0008	**0.9415**
GNF 10x10	8	9	4.3	1.350	0.895	0.9338	1.01	0.9346	0.0010	0.9366
GNF 10x10	8	10	4.6	1.350	0.895	0.9338	1.01	0.9376	0.0009	0.9394
GNF 10x10	8	12	5.0	1.350	0.895	0.9338	1.01	0.9375	0.0008	0.9391
GNF 10x10	10	0	2.9	1.350	0.895	0.9338	1.01	0.9292	0.0008	0.9308
GNF 10x10	10	2	3.3	1.350	0.895	0.9338	1.01	0.9296	0.0008	0.9312
GNF 10x10	10	4	3.6	1.350	0.895	0.9338	1.01	0.9371	0.0008	0.9387
GNF 10x10	10	6	3.9	1.350	0.895	0.9338	1.01	0.9370	0.0008	0.9386
GNF 10x10	10	8	4.2	1.350	0.895	0.9338	1.01	0.9372	0.0008	0.9388
GNF 10x10	10	9	4.3	1.350	0.895	0.9338	1.01	0.9363	0.0009	0.9381
GNF 10x10	10	10	4.6	1.350	0.895	0.9338	1.01	0.9345	0.0009	0.9363
GNF 10x10	10	12	5.0	1.350	0.895	0.9338	1.01	0.9375	0.0008	**0.9391**
GNF 10x10	12	0	2.9	1.350	0.895	0.9338	1.01	0.9276	0.0008	0.9292
GNF 10x10	12	2	3.3	1.350	0.895	0.9338	1.01	0.9309	0.0008	0.9325
GNF 10x10	12	4	3.6	1.350	0.895	0.9338	1.01	0.9373	0.0009	0.9391
GNF 10x10	12	6	3.9	1.350	0.895	0.9338	1.01	0.9347	0.0009	0.9365
GNF 10x10	12	8	4.2	1.350	0.895	0.9338	1.01	0.9374	0.0009	0.9392
GNF 10x10	12	9	4.3	1.350	0.895	0.9338	1.01	0.9333	0.0009	0.9351
GNF 10x10	12	10	4.6	1.350	0.895	0.9338	1.01	0.9378	0.0008	0.9394
GNF 10x10	12	12	5.0	1.350	0.895	0.9338	1.01	0.9404	0.0007	**0.9418**
GNF 10x10	14	0	2.9	1.350	0.895	0.9338	1.01	0.9261	0.0008	0.9277
GNF 10x10	14	2	3.3	1.350	0.895	0.9338	1.01	0.9299	0.0008	0.9315
GNF 10x10	14	4	3.6	1.350	0.895	0.9338	1.01	0.9345	0.0008	0.9361
GNF 10x10	14	6	3.9	1.350	0.895	0.9338	1.01	0.9351	0.0009	0.9369
GNF 10x10	14	8	4.2	1.350	0.895	0.9338	1.01	0.9376	0.0009	0.9394
GNF 10x10	14	9	4.3	1.350	0.895	0.9338	1.01	0.9353	0.0008	0.9369
GNF 10x10	14	10	4.6	1.350	0.895	0.9338	1.01	0.9368	0.0009	0.9386
GNF 10x10	14	12	5.0	1.350	0.895	0.9338	1.01	0.9398	0.0008	**0.9414**

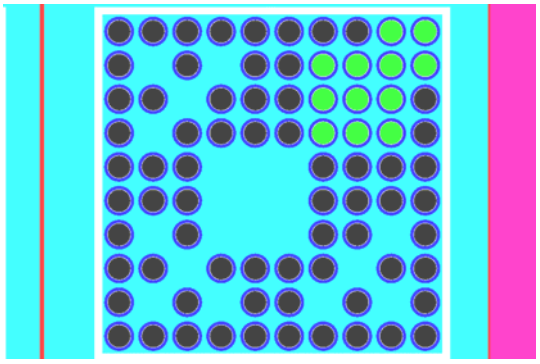
a. Limiting case(s) shown in bold



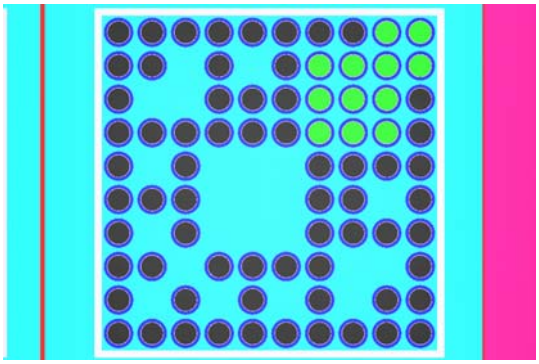
FANP 10x10 5.0 wt% ^{235}U, 8 Part Length Rods



FANP 10x10 5.0 wt% ^{235}U, 10 Part Length Rods

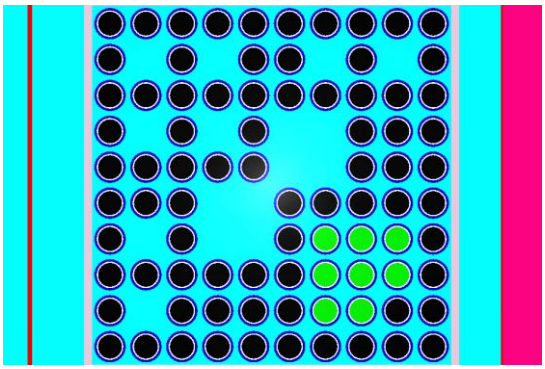


FANP 10x10 5.0 wt% ^{235}U, 12 Part Length Rods

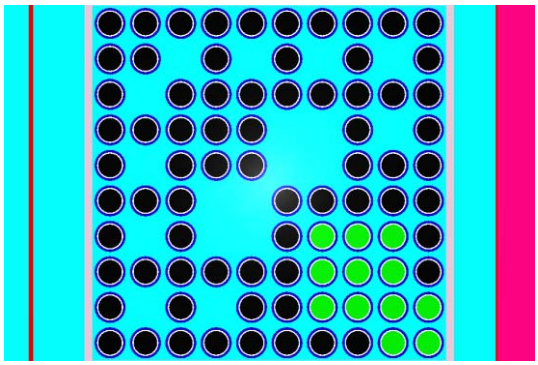


FANP 10x10 5.0 wt% ^{235}U, 14 Part Length Rods

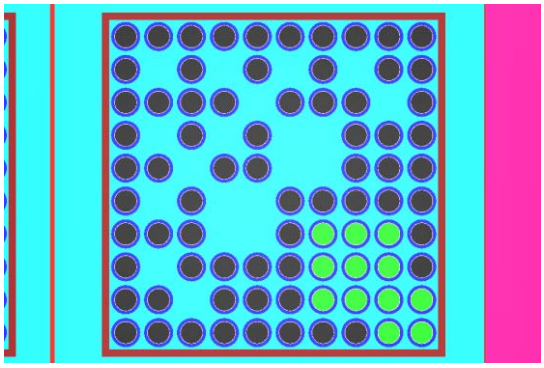
Figure 6-33 FANP 10x10 Worst Case Fuel Parameters Model with Part Length Fuel Rods



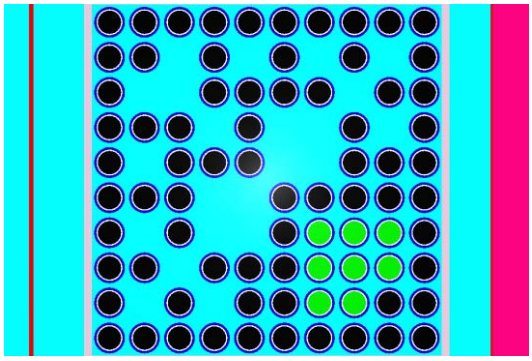
GNF 10x10 4.2 wt% ^{235}U, 8 Part Length Rods



GNF 10x10 5.0 wt% ^{235}U, 10 Part Length Rods

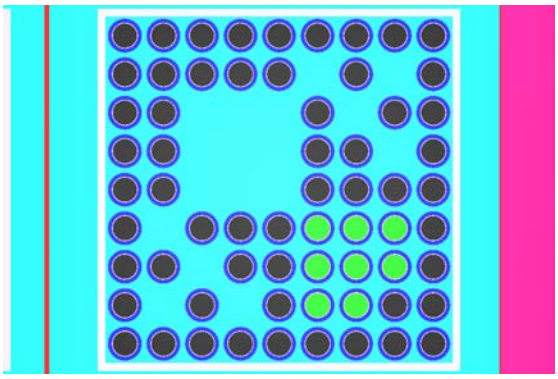


GNF 10x10 5.0 wt% ^{235}U, 12 Part Length Rods

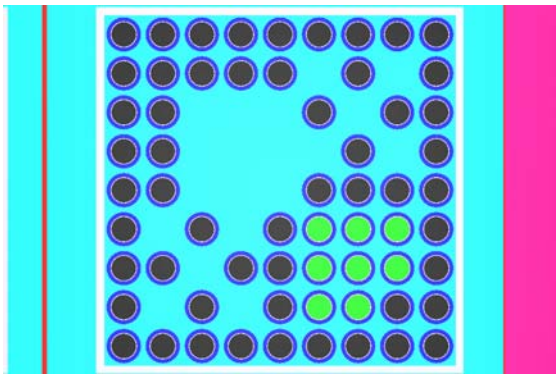


GNF 10x10 4.2 wt% ^{235}U, 14Part Length Rods

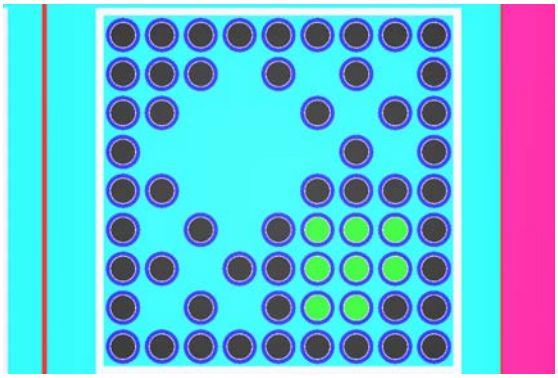
Figure 6-34 GNF 10x10 Worst Case Fuel Parameters Model with Part Length Fuel Rods



FANP 9x9 4.7 wt% ^{235}U, 8 Part Length Rods

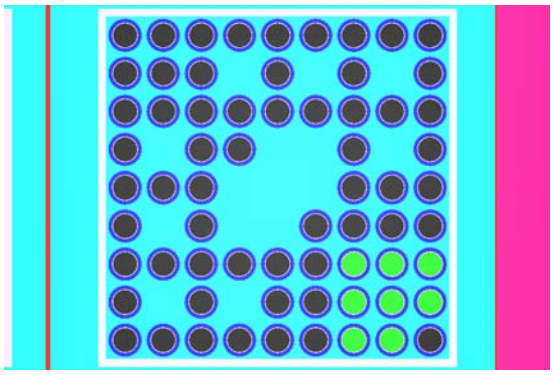


FANP 9x9 4.7 wt% ^{235}U, 10 Part Length Rods

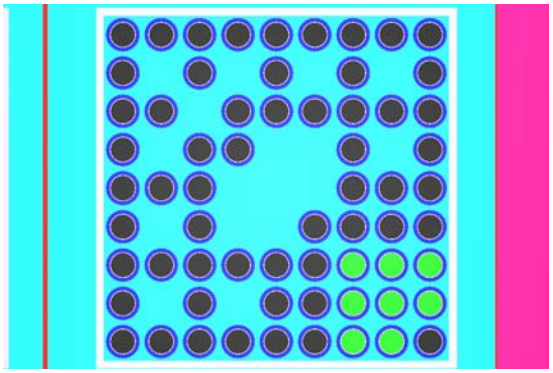


FANP 9x9 4.7 wt% ^{235}U, 12 Part Length Rods

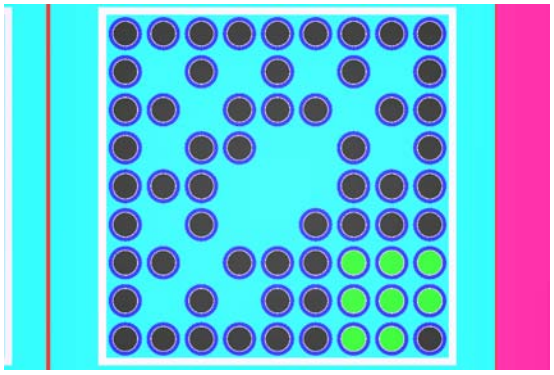
Figure 6-35 FANP 9x9 Worst Case Fuel Parameters Model with Part Length Fuel Rods



GNF 9x9 4.8 wt% ^{235}U, 8 Part Length Rods



GNF 9x9 4.8 wt% ^{235}U, 10 Part Length Rods



GNF 9x9 4.8 wt% ^{235}U, 12 Part Length Rods

Figure 6-36 GNF 9x9 Worst Case Fuel Parameters Model with Part Length Fuel Rods

6.3.4.10 Moderator Density Study (2N=448)

The worst case design from Table 6-18 RAJ-II Array HAC Part Length Fuel Rod Calculations is used to conduct a moderator density sensitivity analysis. The GNF 10x10 fuel bundle is chosen for the study since it resulted in the highest reactivity in Table 6-18. Previous calculations demonstrated the worst case condition for maximum reactivity is a configuration in which there is no moderator between the RAJ-II shipping packages. The moderator density study is conducted by varying the moderator density inside the inner container fuel compartment. The outer region of the inner container is filled with the Alumina Silicate thermal insulating material. The results of the moderator density study, Table 6-29, are shown in Figure 6-37. As shown in Figure 6-37, all cases peak at full moderator density. Therefore, a moderator density of 1.0 g/cm^3 is chosen as the worst case moderator condition for the RAJ-II inner container fuel compartment.

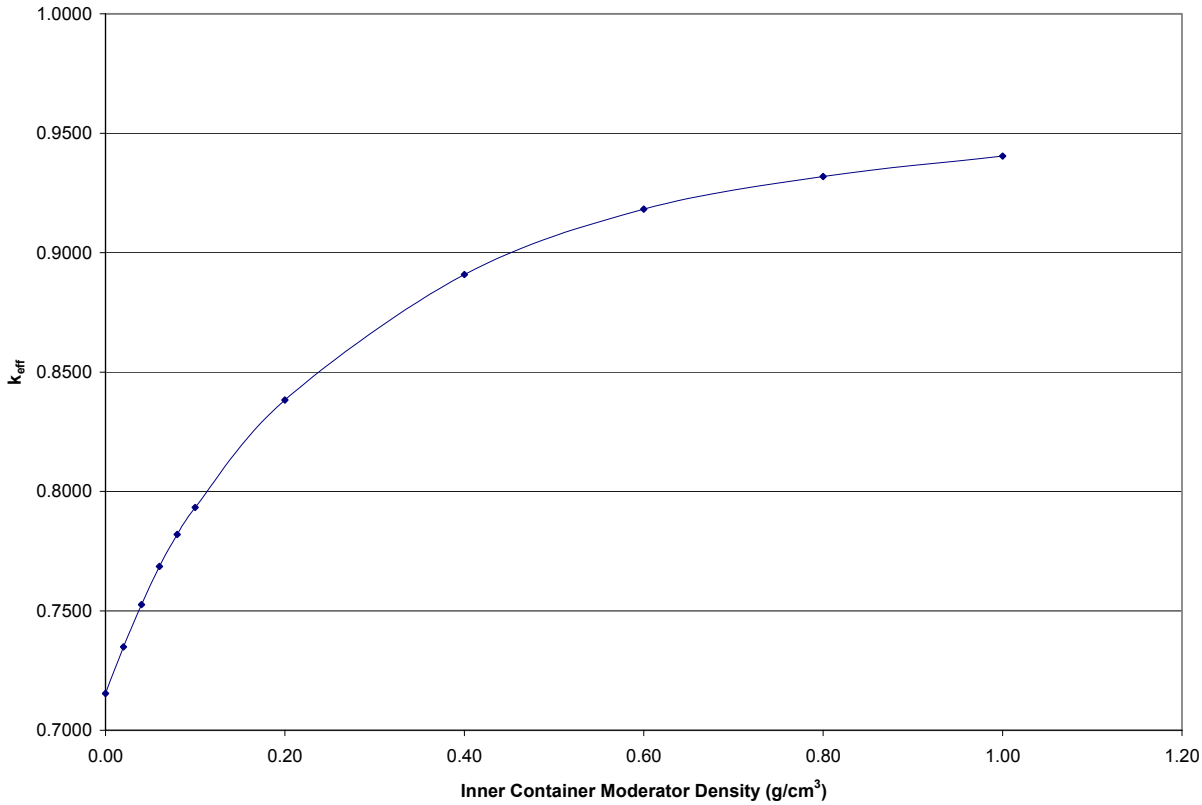


Figure 6-37 Moderator Density Sensitivity Study for the RAJ-II HAC Worst Case Parameter Fuel Design

6.3.4.11 Material Distribution Reactivity Study (2N=448, 2N=100)

A study is performed to determine the worst packing material distribution within the RAJ-II inner container. The material normally present around the inner container fuel compartment is a thermal insulator consisting of Alumina Silicate. The material normally lining the inner container

fuel compartment is a polyethylene foam material which has a density in the range 0.05 – 0.075 g/cm^3.

The first part of the material distribution study investigates replacing the Alumina Silicate alternately with full density water and void while the inner container fuel compartment is filled with full density water. The GNF 10x10 fuel bundle is chosen for the study since it resulted in the highest reactivity in Table 6-18. In addition, the worst case RAJ-II model is used in a 14x2x16 array (2N=448). The results are shown in Table 6-19. The first three cases in Table 6-19 show the most reactive condition is achieved with the Alumina Silicate thermal insulator in place. Therefore, the Alumina Silicate thermal insulator will remain a part of the worst case RAJ-II model.

The second part of the material distribution study investigates placing the polyethylene foam material in its proper location within the RAJ-II fuel assembly compartment. Until this point, the polyethylene foam was assumed to burn away in the fire that also melted the polyethylene spacers. It should be noted that it is extremely unlikely that this configuration would exist post thermal excursion. The polyethylene foam would be as susceptible to the fire as the polyethylene spacers. However, the incomplete foam burn is considered in this study for conservatism. The GNF 10x10 fuel bundle is chosen for the study since it resulted in the highest reactivity in Table 6-18. In addition, the worst case RAJ-II model is used in a 14x2x16 array (2N=448). The results are shown in Table 6-19. As shown in Table 6-19, the most reactive condition is achieved with the full thickness of ethafoam in place. Since the k_{eff} values exceed the 0.94254 USL with the polyethylene foam in place, the package array size is reduced to 10x1x10 (2N=100) to meet the acceptance criterion (last row in Table 6-19). The full thickness of ethafoam will be maintained for the remaining RAJ-II calculations since that configuration resulted in the highest k_{eff} value.

Table 6-19 RAJ-II Inner Container Thermal Insulator Region and Polyethylene Foam Material Study

Fuel Type	Array Size	Inner Container Foam Space	Insulator Space Fill	k_{eff}	σ	$k_{eff} + 2\sigma$
GNF 10x10	14x2x16 (2N=448)	Water	Thermal Ins.	0.9404	0.0007	0.9418
GNF 10x10	14x2x16 (2N=448)	Water	Water	0.7938	0.0009	0.7956
GNF 10x10	14x2x16 (2N=448)	Water	None	0.9362	0.0008	0.9378
GNF 10x10	14x2x16 (2N=448)	¼ Foam Thickness-Water	Thermal Ins.	0.9618	0.0009	0.9636
GNF 10x10	14x2x16 (2N=448)	½ Foam Thickness-Water	Thermal Ins.	0.9808	0.0009	0.9826
GNF 10x10	14x2x16 (2N=448)	5/8 Foam Thickness-Water	Thermal Ins.	0.9902	0.0008	0.9918

Fuel Type	Array Size	Inner Container Foam Space	Insulator Space Fill	k_{eff}	σ	k_{eff} + 2σ
GNF 10x10	14x2x16 (2N=448)	¾ Foam Thickness-Water	Thermal Ins.	0.9943	0.0008	0.9959
GNF 10x10	14x2x16 (2N=448)	7/8 Foam Thickness-Water	Thermal Ins.	0.9965	0.0008	0.9981
GNF 10x10	14x2x16 (2N=448)	Full Foam Thickness	Thermal Ins.	0.9971	0.0010	**0.9991**
GNF 10x10	10x1x10 (2N=100)	Full Foam Thickness	Thermal Ins.	0.9378	0.0009	0.9396

6.3.4.12 Inner Container Partial Flooding Study (2N=100)

Calculations are run in which the fuel bundle rows are partially filled within the RAJ-II inner fuel compartment as shown in Figure 6-39. The GNF 10x10 fuel bundle is chosen for the analysis since it produced the highest reactivity in Figure 6-37. The RAJ-II HAC model from the polyethylene foam study is used with an array size of 10x1x10 (2N=100). The results are shown in Table 6-20. As shown in Table 6-20, the most reactive condition exists when water fully covers each fuel bundle. Therefore, the inner container fuel compartment will be fully flooded with water in the worst case RAJ-II model.

Table 6-20 RAJ-II Inner Container Partially Filled with Moderator

Fuel Type	Fuel Rows Filled	Moderator Density (g/cm^3)	k_{eff}	σ	k_{eff} + 2σ
GNF 10x10	1	1.00	0.6643	0.0007	0.6657
GNF 10x10	3	1.00	0.7678	0.0009	0.7696
GNF 10x10	5	1.00	0.8653	0.0008	0.8669
GNF 10x10	7	1.00	0.9212	0.0008	0.9228
GNF 10x10	9	1.00	0.9355	0.0009	0.9373
GNF 10x10	10	1.00	0.9378	0.0009	**0.9396**

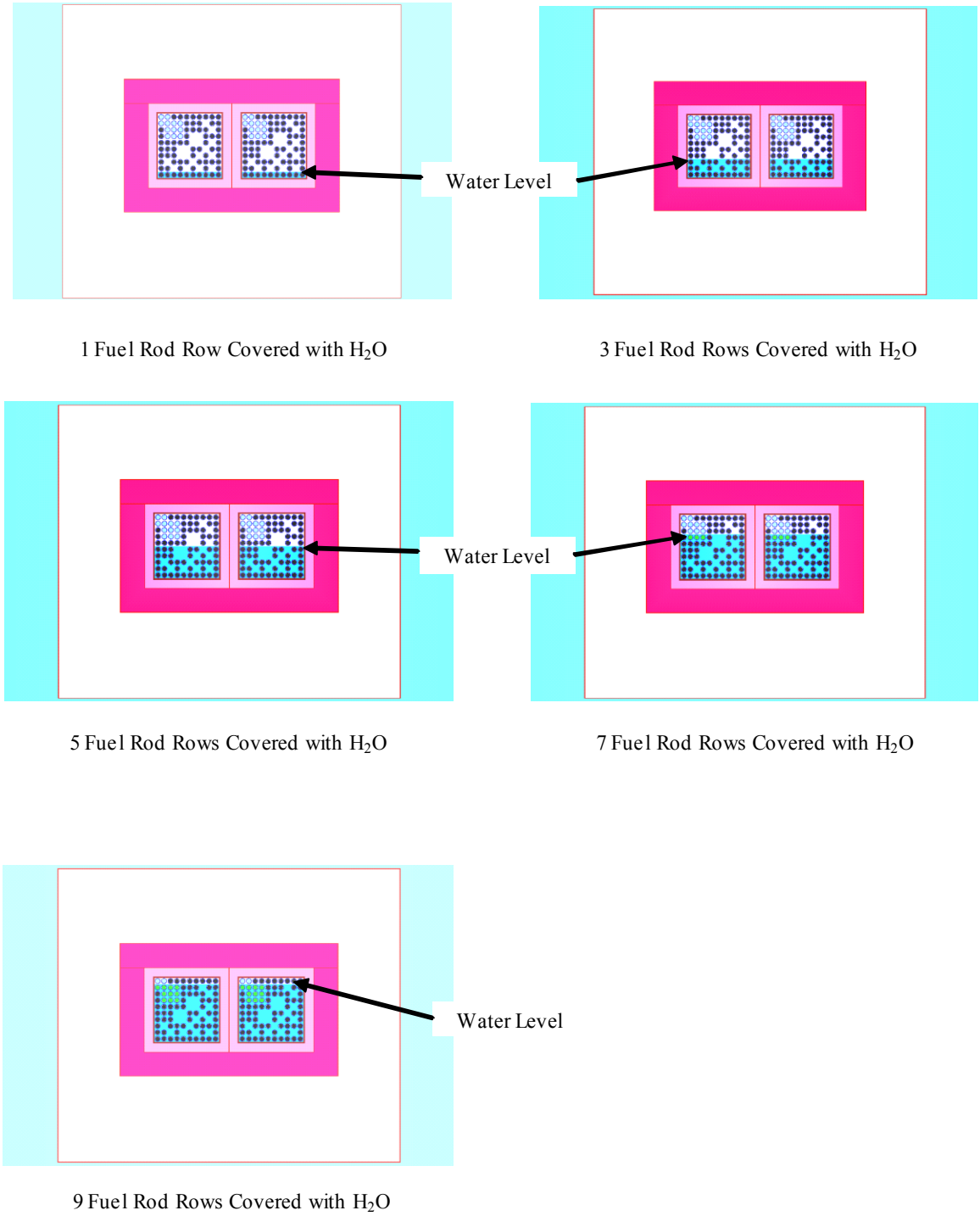


Figure 6-38 RAJ-II Inner Container Fuel Compartment Flooding Cases

6.3.4.13 RAJ-II Container Spacing Study (2N=100)

Calculations performed previously assume the RAJ-II shipping containers are resting next to one another with no spacing between them. A container pitch sensitivity study is conducted to determine if reactivity increases as containers are moved away from one another. The HAC model used in the inner container partial flooding study is used for the pitch sensitivity study with an array size of 10x1x10 (2N=100). The GNF 10x10 fuel assemblies with an average lattice enrichment of 5.0 wt% U-235, 12 gadolinia-urania fuel rods enriched to 2.0 wt % gadolinia, and 12 part length fuel rods is used. The worst case fuel parameters listed in Table 6-18 for the GNF 10x10 fuel design are utilized. The edge-to-edge separation is increased from 0 to 10 cm and the reactivity impact is observed. The results shown in Table 6-21 show a decrease in reactivity with increased spacing between containers. Therefore, the most reactive container configuration occurs when there is minimum spacing between containers.

Table 6-21 RAJ-II Array Spacing Sensitivity Study

Assembly Type	Interspersed Moderator Density (g/cm^3)	Container Pitch (cm)	Pitch (cm)	Pellet Diameter (cm)	Clad ID (cm)	Clad OD (cm)	k_{eff}	σ	$k_{eff} + 2\sigma$
GNF 10x10	0.0	71.926	1.350	0.895	0.9338	1.01	0.9378	0.0009	**0.9396**
GNF 10x10	0.0	74.426	1.350	0.895	0.9338	1.01	0.9259	0.0009	0.9277
GNF 10x10	0.0	76.926	1.350	0.895	0.9338	1.01	0.9122	0.0008	0.9138
GNF 10x10	0.0	81.926	1.350	0.895	0.9338	1.01	0.8865	0.0008	0.8881

6.4 SINGLE PACKAGE EVALUATION

Based on the sensitivity studies performed in this section, the single package and package array normal transport condition and HAC calculations are performed using the GNF 10x10 at an average lattice enrichment of 5.0 wt % U-235, twelve 2.0 wt% gadolinia fuel rods, and 12 part length fuel rods.

6.4.1 Configuration

The single package model described in Section 6.3.1.1 is used to demonstrate criticality safety of the RAJ-II shipping container using the worst case fuel design. The GNF 10x10 at an average lattice enrichment of 5.0 wt % U-235, twelve 2.0 wt% gadolinia fuel rods, and 12 part length fuel rods is used for the NTC and HAC evaluations. A moderator density study is conducted under both hypothetical accident and normal conditions. In the HAC study, the water density in the inner package is varied while the void in the outer container is maintained. For the normal conditions of transport, the moderator density is uniformly varied.

6.4.2 Single Package Results

The results for the single package normal conditions of transport evaluation are displayed in Figure 6-39. The results for the single package HAC evaluation are shown in Figure 6-40. The results in the figures indicate reactivity for the single package increases with increasing moderator density. The highest k_{eff} is achieved for both cases at full density moderation in the inner container. The polyethylene foam remains in place for the NTC single package configuration, but the polyethylene foam is removed from the HAC single package configuration. Removing the polyethylene foam in the HAC single package model, decreases neutron leakage which increases reactivity for a single container. In addition, full density moderation is included in the outer container for the single package NTC configuration. In both cases, the k_{eff} remains far below the USL of 0.94254. The maximum $k_{eff} + 2\sigma$ for the single package normal conditions of transport case is 0.6689 (Table 6-30), and the maximum $k_{eff} + 2\sigma$ for the single package HAC case is 0.6951 (Table 6-31). Therefore, criticality safety is established for the single package RAJ-II container.

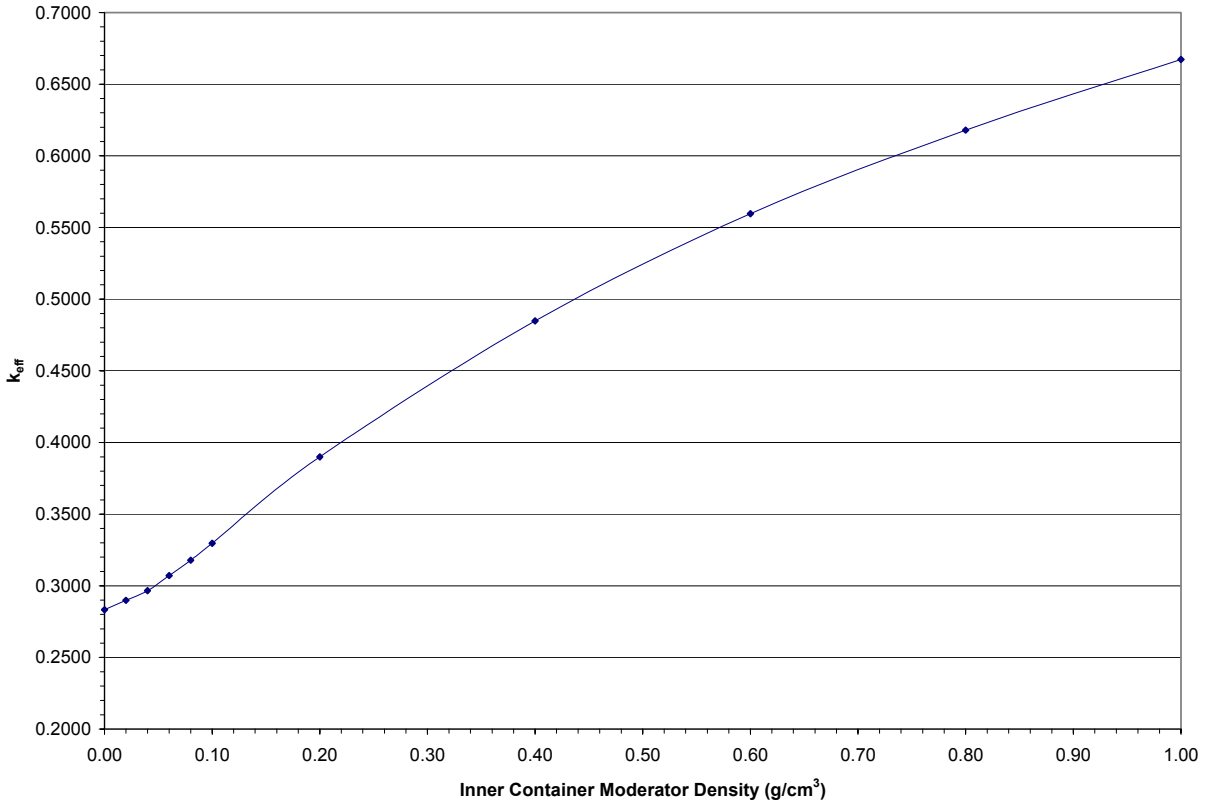


Figure 6-39 RAJ-II Single Package Normal Conditions of Transport Results

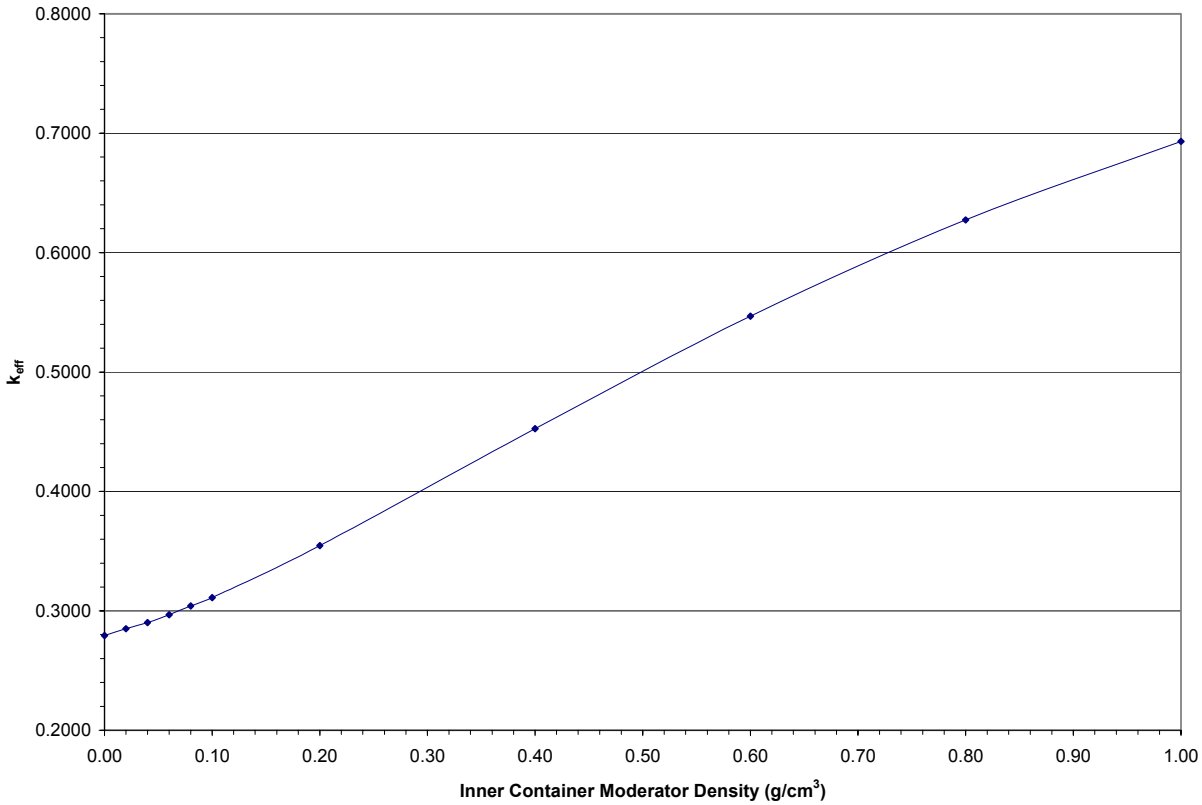


Figure 6-40 RAJ-II Single Package HAC Results

6.5 EVALUATION OF PACKAGE ARRAYS UNDER NORMAL CONDITIONS OF TRANSPORT

6.5.1 Configuration

The package array normal condition model described in Section 6.3.1.2.1 is used to demonstrate criticality safety of the RAJ-II shipping container using the GNF 10x10 worst case fuel design at an average lattice enrichment of 5.0 wt % U-235, twelve 2.0 wt% gadolinia fuel rods, and 12 part length fuel rods. The calculation using the normal conditions of transport model involves a moderator density sensitivity study. In the model, the moderator density is uniformly varied and the system reactivity is observed.

6.5.2 Package Array NCT Results

The results of the package array normal condition model calculations are shown in Figure 6-41. The reactivity peaks with no moderator present . A decreasing trend continues until the moderator density reaches 0.4 g/cm^3 at which point reactivity increases almost linearly to full water density. The maximum $k_{eff} + 2\sigma$ obtained is 0.8535 (Table 6-32) which is below the USL

of 0.94254. Therefore, criticality safety of the RAJ-II shipping container is demonstrated under normal conditions of transport.

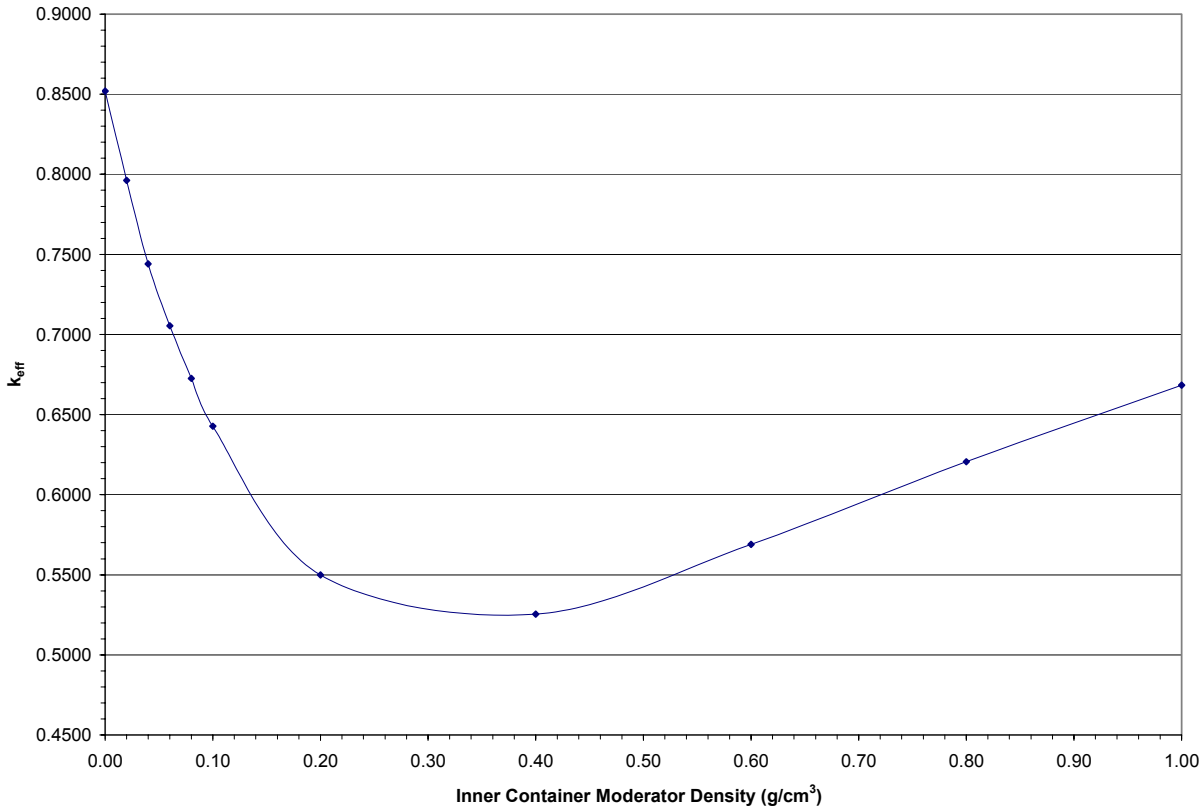


Figure 6-41 RAJ-II Package Array Under Normal Conditions of Transport Results

6.6 PACKAGE ARRAYS UNDER HYPOTHETICAL ACCIDENT CONDITIONS

6.6.1 Configuration

The package array hypothetical accident condition model described in Section 6.3.1.2.2 is used to demonstrate criticality safety of a 10x1x10 array (2N=100) of RAJ-II shipping containers using the GNF 10x10 worst case fuel design at an average lattice enrichment of 5.0 wt % U-235, twelve 2.0 wt% gadolinia fuel rods, and 12 part length fuel rods. The calculation using the HAC model involves a moderator density sensitivity study. In the study, no moderator is present in the outer container while the moderator density inside the inner container is varied. The polyethylene foam inside the inner container fuel compartment is modeled because previous calculations demonstrated this configuration to be the most reactive.

6.6.2 Package Array HAC Results

The results of the package array (2N=10x1x10=100 array) HAC model calculations are shown in Figure 6-42. The system reactivity begins at its lowest value and increases with increasing interspersed moderator density. This trend highlights the neutronics of the problem. Initially, no moderator, other than the polyethylene surrounding the fuel rods, is present to thermalize neutrons that enter the inner container. As the inner container moderator density increases, higher energy neutrons pass into adjacent containers and thermalize in the vicinity of the fuel creating a more reactive situation. The maximum $k_{eff} + 2\sigma$ for the package array HAC case is 0.9396 (Table 6-33) which is below the USL of 0.94254. Therefore, criticality safety of the RAJ-II shipping container is demonstrated for the package array under hypothetical accident conditions.

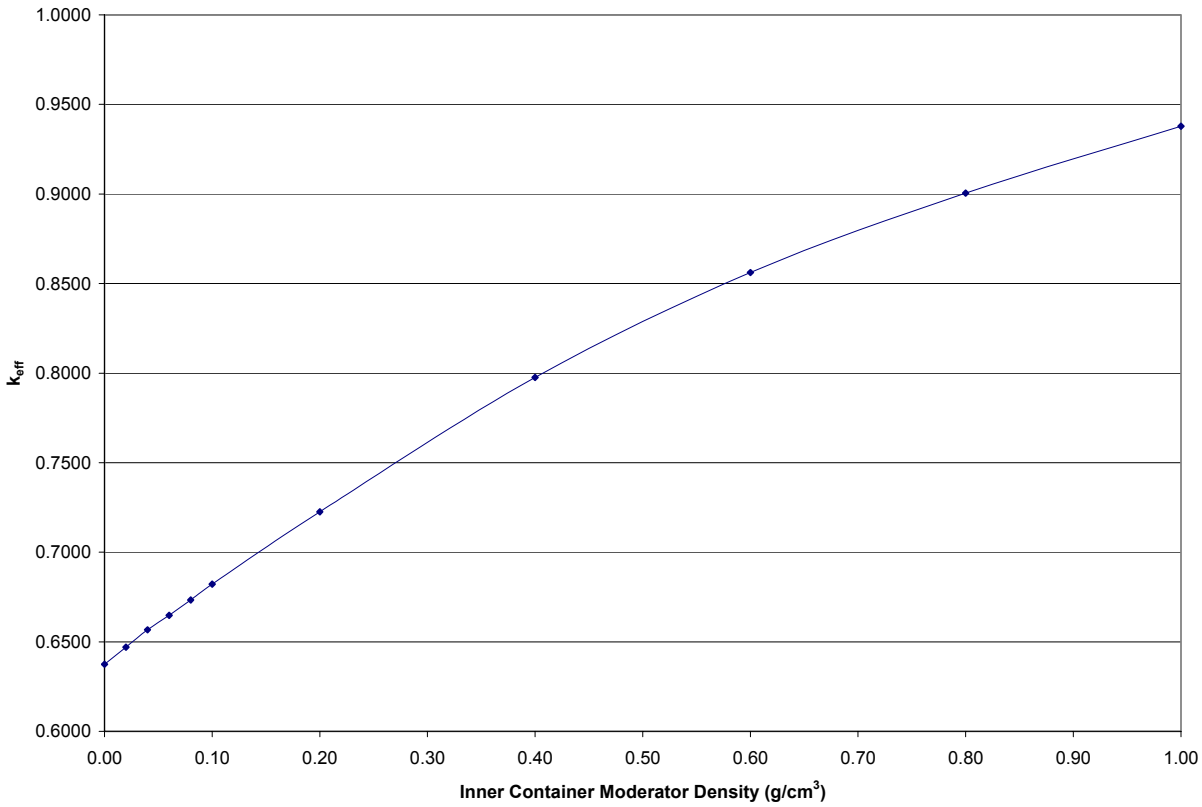


Figure 6-42 RAJ-II Package Array Hypothetical Accident Condition Results

6.6.2.1 Pu-239 Effect on Reactivity for the RAJ-II Package Array Hypothetical Accident Condition

Because the fuel scheduled for transport in the RAJ-II could have a small Pu-239 content, the effect on the RAJ-II Package HAC reactivity is investigated. The maximum plutonium concentration (3.04×10^{-9} gPu-239/gU) listed in Table 1-3 of the SAR is added to the worst case package array HAC model (10x1x10 array), determined in the previous sections, and the k_{eff} is calculated. The results showed no statistically significant difference between the cases with and without plutonium. The $k_{eff} \pm 2\sigma$ for the worst case with plutonium is 0.9406. The $k_{eff} + 2\sigma$ for the worst case without plutonium, calculated in Section 6.6.2, is 0.9396. Both results remain below the USL of 0.94254. Therefore, the plutonium is justifiably neglected in the RAJ-II evaluation.

6.7 Fuel Rod Transport in the RAJ-II

Studies are conducted to allow transport of UO_2 fuel rods in the RAJ-II container. Several configurations are investigated including: loose fuel rods, fuel rods bundled together, and fuel rods contained in 5-inch stainless steel pipe/protective case. The model uses the 10x10, 9x9, or 8x8 worst case fuel rod designs developed in Section 6.3.4. A 6-mil layer of polyethylene encircles each fuel rod in the model to bound protective packing material that may be used for fuel rod transport.

6.7.1 Loose Fuel Rod Study

The package array model under hypothetical accident conditions is used for fuel rod calculations in the RAJ-II, since it was demonstrated to be more reactive than the normal conditions of transport, package array model. The worst case fuel rods are arranged in a square pitch array inside each RAJ-II transport compartment. Scoping studies indicated little difference between the square and triangular pitch array, therefore the square pitch array is chosen for convenience. The inner container is filled with full density water and the outer container has no water, which facilitates leakage of neutrons into neighboring containers. The fuel rod pitch is varied, and the results are illustrated with curves. The curves are shown Figure 6-43 Fuel Rod Pitch Sensitivity Study and corresponding calculational data listed in Table 6-22 Fuel Rod Pitch Sensitivity Study Results. The results demonstrate that a fully loaded inner compartment in which the rods are all in contact with each other is a supercritical configuration. As a result, a minimum number of fuel rods to ensure subcriticality cannot be established for the RAJ-II shipping container. A maximum fuel rod quantity to ensure subcriticality can be established for the loose configuration. For all three fuel designs, a maximum of 25 fuel rods may be safely transported in each RAJ- II fuel assembly compartment. The 8x8 rod design is limiting as shown in Figure 6-43 and Table 6-22 Fuel Rod Pitch Sensitivity Study Results.

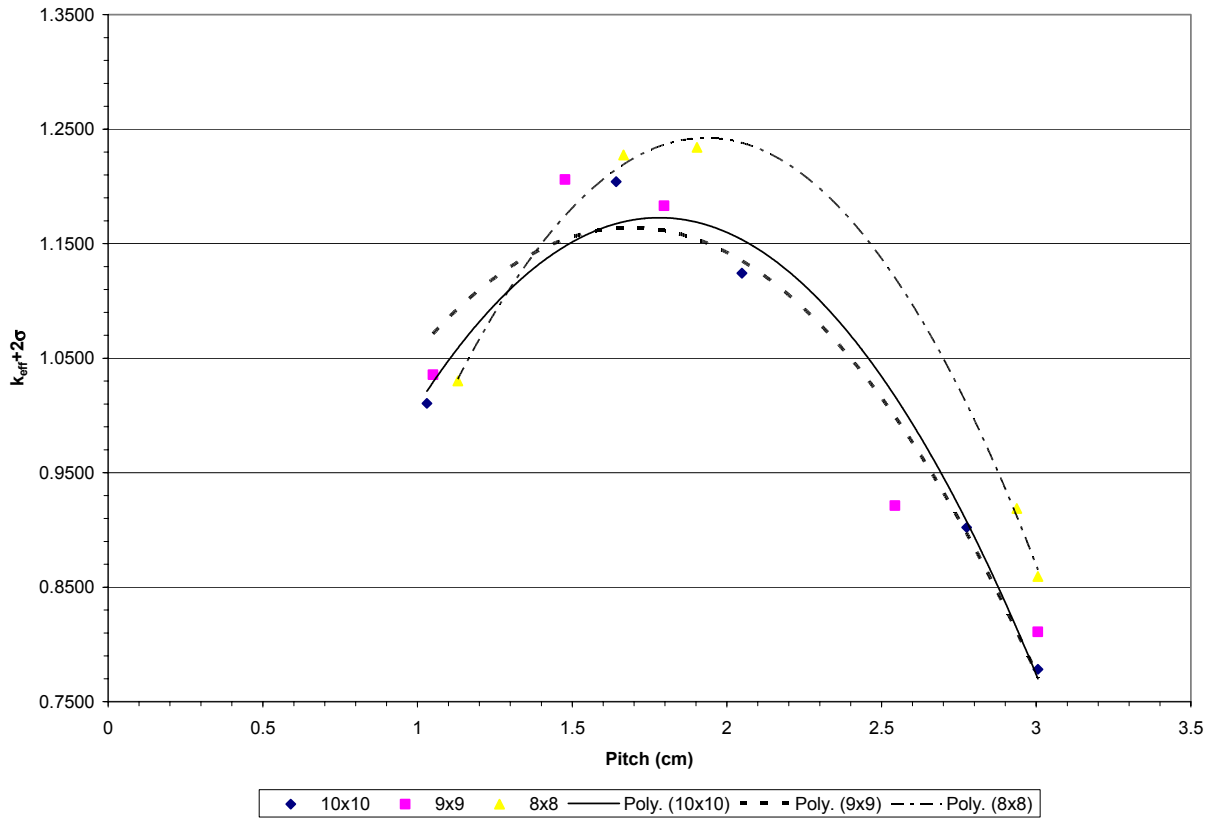


Figure 6-43 Fuel Rod Pitch Sensitivity Study

Table 6-22 Fuel Rod Pitch Sensitivity Study Results

Fuel Rod Type	Fuel Rod Pitch (cm)	Fuel Rod Number	Fuel Pellet OD (cm)	Clad Inner Diameter (cm)	Clad Outer Diameter (cm)	k_{eff}	σ	$k_{eff} + 2\sigma$
10x10	1.0305	289	0.9	1.000	1.000	1.0092	0.0007	1.0106
10x10	1.6416	100	0.9	1.000	1.000	1.2024	0.0009	1.2042
10x10	2.0484	64	0.9	1.000	1.000	1.1224	0.0009	1.1242
10x10	2.7754	34	0.9	1.000	1.000	0.9005	0.0008	0.9021
10x10	3.0056	25	0.9	1.000	1.000	0.7769	0.0007	0.7783
9x9	1.0505	256	0.9600	1.0200	1.0200	1.0341	0.0007	1.0355
9x9	1.4770	121	0.9600	1.0200	1.0200	1.2045	0.0008	1.2061
9x9	1.7972	81	0.9600	1.0200	1.0200	1.1816	0.0008	1.1832
9x9	2.5432	34	0.9600	1.0200	1.0200	0.9196	0.0008	0.9212
9x9	3.0056	25	0.9600	1.0200	1.0200	0.8096	0.0007	0.8110
8x8	1.1305	225	1.05	1.1000	1.1000	1.0288	0.0007	1.0302
8x8	1.6662	100	1.05	1.1000	1.1000	1.2259	0.0008	1.2275
8x8	1.9035	81	1.05	1.1000	1.1000	1.2328	0.0007	1.2342
8x8	2.9370	30	1.05	1.1000	1.1000	0.9172	0.0008	0.9188
8x8	3.0056	25	1.05	1.1000	1.1000	0.8577	0.0008	0.8593

The results in Table 6-22 Fuel Rod Pitch Sensitivity Study Results are based on calculations performed with full water density inside the inner container. It appears the maximum fuel rod quantity allowable for the 10x10 and 9x9 fuel rods should be 34, while that for the 8x8 fuel rods should be 30. However, the rod configurations at full moderator densities represent an overmoderated condition in which reactivity peaks at a reduced moderator density. Therefore, calculations are performed with 25 fuel rods in each transport compartment for each fuel rod type, and the moderator density inside the inner container is varied from 0.4 g/cm^3 to 1.00 g/cm^3 to investigate the possibility that reactivity peaks at a lower moderator density. The results of these calculations are shown in Table 6-23. The peak reactivity for all the fuel rod types occurs at a moderator density of 0.6 g/cm^3 and are all below the USL of 0.94254. Therefore, criticality safety for loose fuel rod transport with a maximum of 25 rods in each transport compartment is demonstrated.

Table 6-23 Fuel Rod Maximum Quantity at Reduced Moderator Densities

Fuel Rod Type	Fuel Rod Pitch (cm)	Fuel Rod Number	Inner Container Moderator Density (g/cm^3)	Fuel Pellet OD (cm)	Clad Inner Diameter (cm)	Clad Outer Diameter (cm)	k_{eff}	σ	$k_{eff} + 2\sigma$
10x10	3.0056	25	0.40	0.9	1.000	1.000	0.7875	0.0009	0.7893
10x10	3.0056	25	0.60	0.9	1.000	1.000	0.8113	0.0008	**0.8129**
10x10	3.0056	25	0.80	0.9	1.000	1.000	0.8012	0.0007	0.8026
10x10	3.0056	25	1.00	0.9	1.000	1.000	0.7769	0.0007	0.7783
9x9	3.0056	25	0.40	0.9600	1.0200	1.0200	0.8128	0.0008	0.8144
9x9	3.0056	25	0.60	0.9600	1.0200	1.0200	0.8404	0.0008	**0.8420**
9x9	3.0056	25	0.80	0.9600	1.0200	1.0200	0.8321	0.0008	0.8337
9x9	3.0056	25	1.00	0.9600	1.0200	1.0200	0.8096	0.0007	0.8110
8x8	3.0056	25	0.40	1.05	1.1000	1.1000	0.8529	0.0008	0.8545
8x8	3.0056	25	0.60	1.05	1.1000	1.1000	0.8832	0.0008	**0.8848**
8x8	3.0056	25	0.80	1.05	1.1000	1.1000	0.8799	0.0009	0.8817
8x8	3.0056	25	1.00	1.05	1.1000	1.1000	0.8577	0.0008	0.8593

a. Limiting case(s) shown in bold

6.7.2 Fuel Rods Bundled Together

Based on the results in the previous calculation, there is no advantage to bundling fuel rods together since close packed rods do not guarantee subcriticality. Besides, the straps holding the fuel rods together in the bundle may fail during an accident, and the rods could move about the transport compartment without restraint. Therefore, the maximum number of fuel rods allowable in each RAJ-II fuel compartment when fuel rods are transported in bundles is 25 for all types.

6.7.3 Fuel Rods Transported in 5-Inch Stainless Steel Pipe

A fuel rod pitch sensitivity study is conducted for the transport of fuel rods inside 5-inch stainless steel pipe, residing in the RAJ-II fuel compartment. The package array model under hypothetical accident conditions is used for fuel rod calculations in the RAJ-II container, since it was demonstrated to be more reactive than the normal conditions of transport, package array model. The GNF 10x10, the GNF 9x9, and the GNF 8x8 worst case fuel rod designs are used for the study. Since the 5-inch stainless steel pipe presents a more difficult volume to accommodate rods in a square pitch, a triangular pitch array is used for the rod configuration. The pipe's stainless steel wall is also neglected for conservatism. The fuel rod configuration inside the pipe is shown in Figure 6-44 for the GNF 8x8 fuel rods. The volume inside the pipe is filled with water at a density sufficient for optimum moderation. The inner fuel compartment volume outside the pipe is modeled with no material present to maximize neutron interaction among packages in the array.

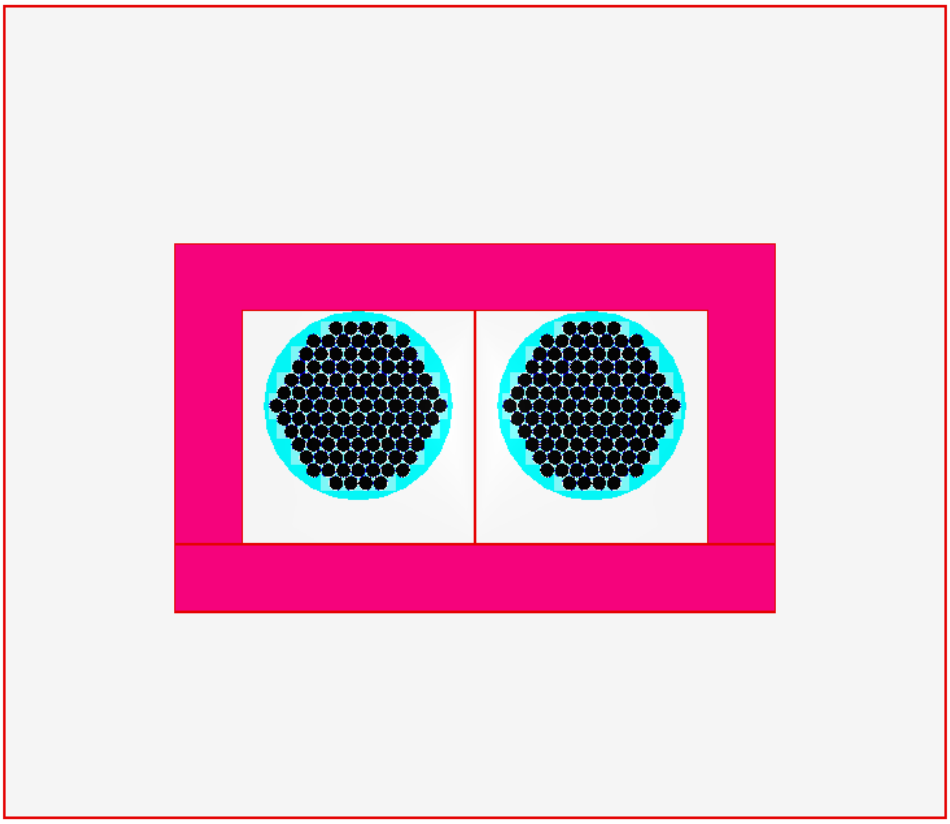


Figure 6-44 RAJ-II with Fuel Rods in 5-Inch Stainless Steel Pipes for Transport

The results for fuel rod transport in a SS pipe within the RAJ-II container for the all rod designs are displayed in Figure 6-45. As shown in Figure 6-45, optimum peaks are formed above the USL of 0.94254. Therefore, the stainless steel pipe may be used to ship a limited number of fuel rods. The maximum number of 10x10 fuel rods that may be transported in the stainless steel pipe is 30. The maximum number of 9x9 fuel rods that may be transported in the stainless steel pipe is 26. The maximum number of 8x8 fuel rods that may be transported in the stainless steel pipe is 22. The $k_{eff} + 2\sigma$ values (Table 6-34) for all fuel rod types with the appropriate fuel rod quantity are below the USL of 0.94254. Therefore, criticality safety is demonstrated for fuel rod transport inside a SS pipe within the RAJ-II container.

The optimum peak for the 10x10 fuel rods is greater than that for the 9x9 or 8x8 fuel rods in the SS pipe. Since the reactivity peak for the 8x8 fuel rod in the loose rod study is greater than that for the 10x10 fuel rods in the SS pipe, it is chosen as the bounding fuel assembly type.

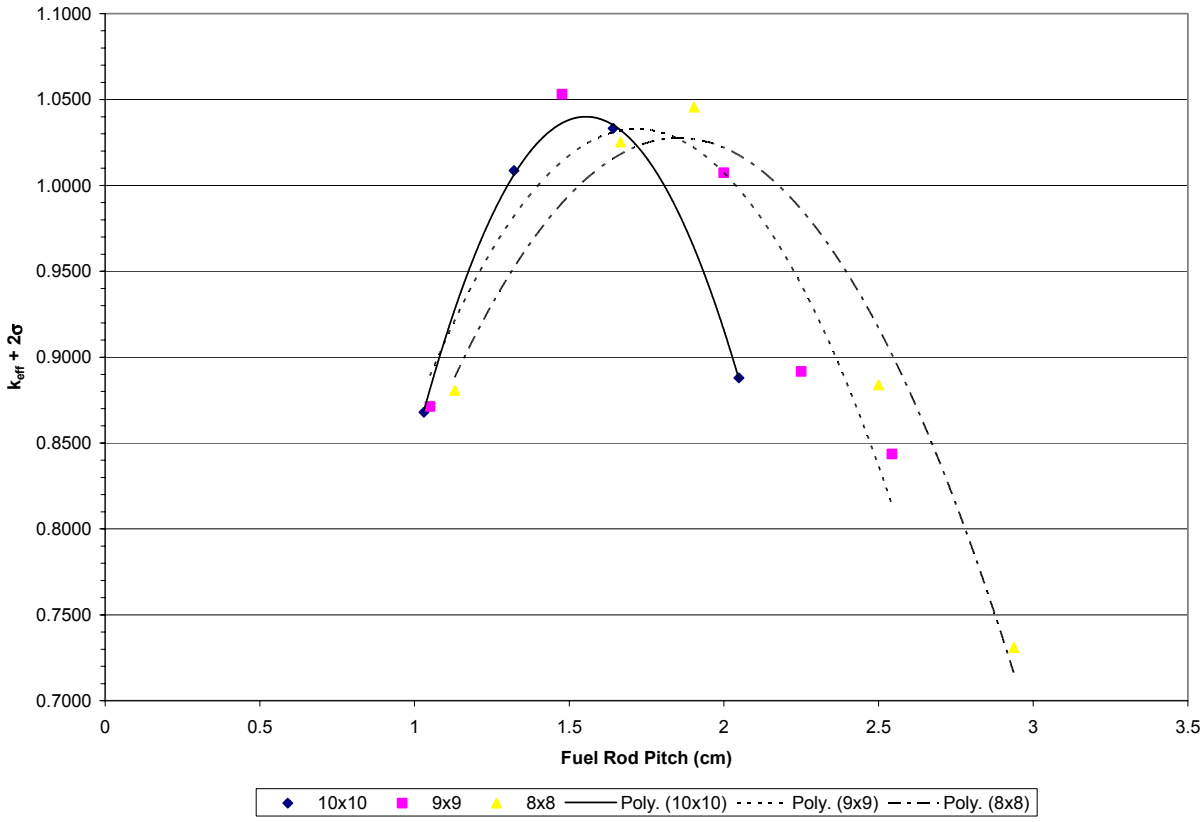


Figure 6-45 RAJ-II Fuel Rod Transport in Stainless Steel Pipe

6.7.4 Fuel Rods Transported in Stainless Steel Protective Case

The fuel rod pitch sensitivity study conducted for the transport of fuel rods inside the 5-inch stainless steel pipe described in Section 6.7.3 bounds the transport of fuel rods in the protective case. The protective case cross-section is 89 mm (3.50 inches) by 80 mm (3.15 inches). Based on this small cross-sectional area, the total number of fuel rods that will fit in the protective case is less than the total for the 5-inch pipe. Based on the calculations for the stainless steel pipe, the maximum number of 10x10 fuel rods that may be transported in the protective case is 30, the maximum number of 9x9 fuel rods that may be transported in in the protective case is 26, the maximum number of 8x8 fuel rods that may be transported in in the protective case is 22.

6.7.5 Single Package Fuel Rod Transport Evaluation

6.7.5.1 Configuration

The single package model described in Section 6.3.1.1 is used to demonstrate criticality safety of the RAJ-II shipping container using the worst case fuel design. The single package is evaluated under both normal conditions of transport and hypothetical accident conditions. The evaluation consists of a moderator density sensitivity study. For the normal conditions of transport model, the moderator density is uniformly varied. In contrast, the moderator density is fixed in the inner container for the hypothetical accident condition model, and the moderator in the outer container is varied. Based on the results in Table 6-22, the GNF 8x8 worst case fuel rod design is used for the study since it produced the highest reactivity peak among all fuel rods considered.

6.7.5.2 Single Package Fuel Rod Transport Result

The results for the single package, loose fuel rod, normal conditions of transport evaluation are displayed in Figure 6-46. The results for the single package, loose fuel rod, HAC evaluation are shown in Figure 6-47. The results in the figures indicate reactivity for the single package increases with increasing moderator density. The highest k_{eff} is achieved for both cases at full density moderation. In both cases, the k_{eff} remains far below the USL of 0.94254. The maximum $k_{eff} + 2\sigma$ for the single package normal conditions of transport case is 0.6381 (Table 6-35), and the maximum $k_{eff} + 2\sigma$ for the single package HAC case is 0.6548 (Table 6-36). Therefore, criticality safety is established for the single package RAJ-II container transporting up to 25 loose fuel rods.

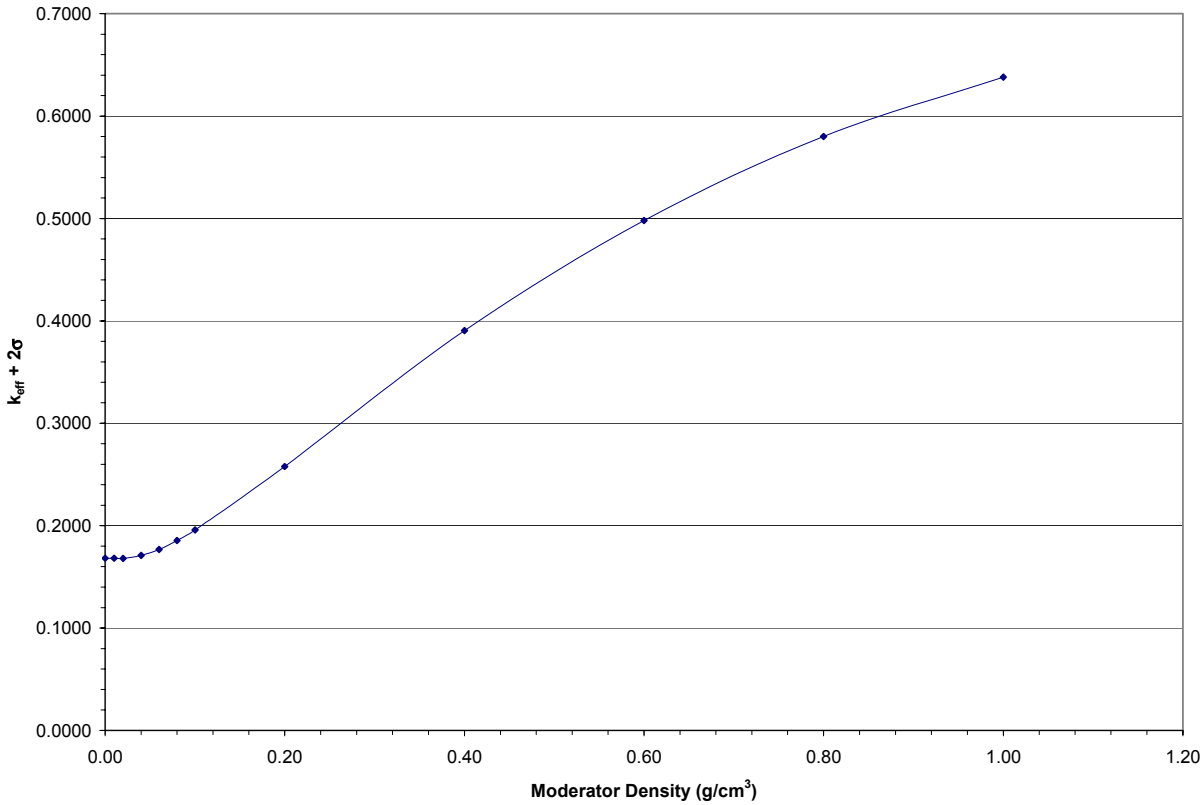


Figure 6-46 RAJ-II Fuel Rod Single Package Under Normal Conditions of Transport

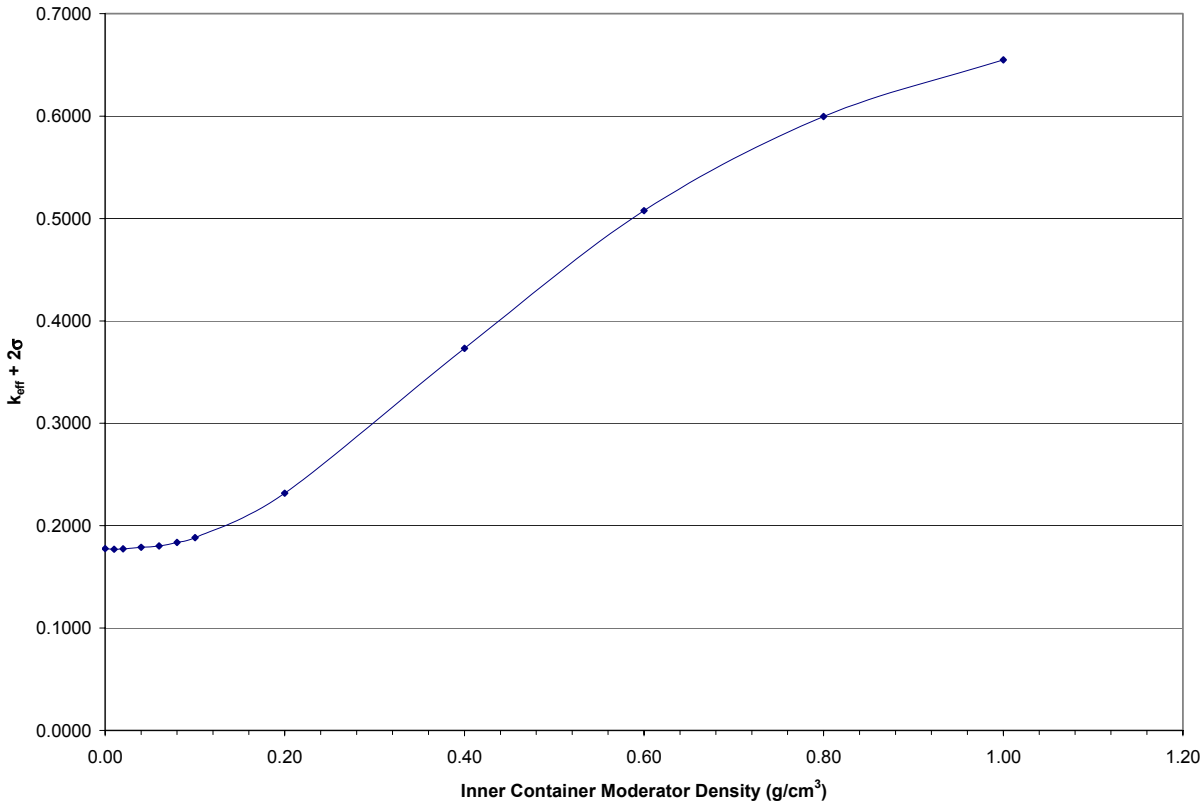


Figure 6-47 RAJ-II Fuel Rod Transport Single Package HAC

6.7.6 Evaluation of Package Arrays with Fuel Rods Under Normal Conditions of Transport

The package array normal condition model described in Section 6.3.1.2.1 is used to demonstrate criticality safety of the RAJ-II shipping container when transporting fuel rods. Based on the results in Table 6-22, the GNF 8x8 worst case fuel rod design is used for the study since it produced the highest reactivity peak among all fuel rod designs considered. The calculation using the package array normal conditions of transport model for fuel rod transport involves a moderator density sensitivity study. In the model, the moderator density is uniformly varied and the system reactivity is observed.

6.7.6.1 Package Array NCT Fuel Rod Transport Results

The results of the package array fuel rod transport normal condition model calculations are shown in Figure 6-48. As shown, the reactivity initially increases then decreases as the moderator density increases until a density of 0.4 g/cm^3 is reached, then it increases essentially linearly until full density is reached. The maximum $k_{eff} + 2\sigma$ obtained is 0.6381 (Table 6-37) which is below the USL of 0.94254. Therefore, criticality safety of the RAJ-II shipping container with fuel rods is demonstrated under normal conditions of transport.

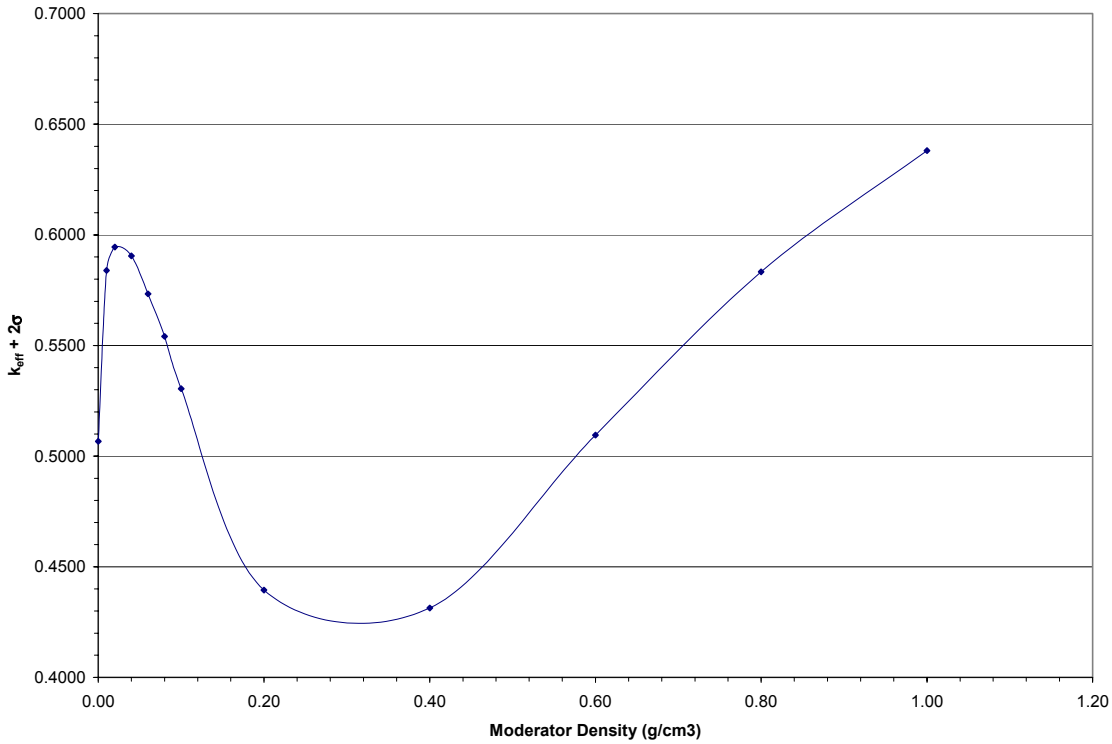


Figure 6-48 RAJ-II Package Array Under Normal Conditions of Transport with Loose Fuel Rods

6.7.7 Fuel Rod Transport Package Arrays Under Hypothetical Accident Conditions

The package array hypothetical accident condition model described in Section 6.3.1.2.2 is used to demonstrate criticality safety of a 10x1x10 array (2N=100) of RAJ-II shipping containers when transporting loose fuel rods. Based on the results in Table 6-22, the GNF 8x8 worst case fuel rod design is used for the study since it produced the highest reactivity peak among the fuel rod designs considered. The calculation using the HAC model involves a moderator density sensitivity study. In the study, there is no interspersed moderator, and the moderator density inside the inner container is varied. The polyethylene foam lines the inner container fuel compartment since the configuration resulted in the most reactive conditions.

6.7.7.1 Package Array HAC Fuel Rod Transport Results

The results of the package array HAC model calculations are shown in

Figure 6-49. The reactivity begins at its lowest value and increases with increasing internal moderator density until a peak is reached at a density of 0.6 g/cm^3. The maximum $k_{eff} + 2\sigma$ for the package array fuel rod transport HAC case is 0.8745 (Table 6-38), which is below the USL of 0.94254. Therefore, criticality safety of the RAJ-II shipping container is demonstrated for the package array under hypothetical accident conditions when fuel rods are being transported.

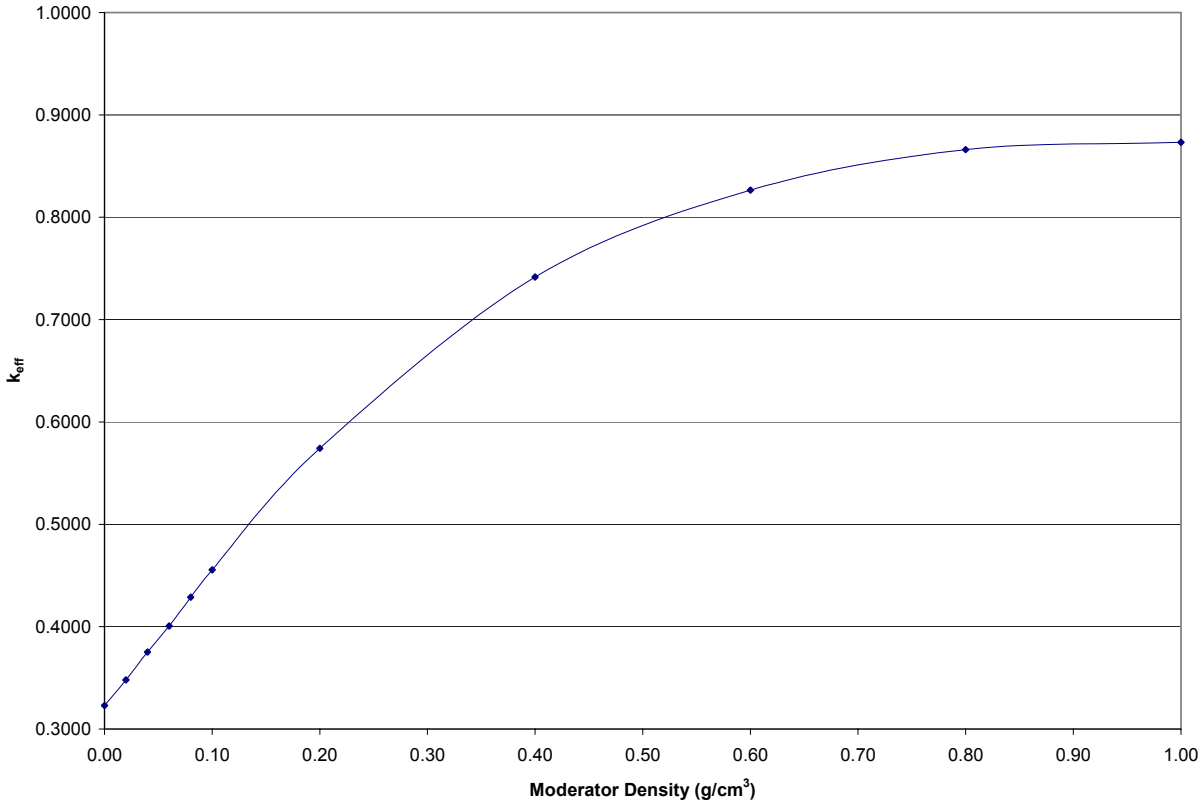


Figure 6-49 RAJ-II Fuel Rod Transport Under HAC

6.8 FISSILE MATERIAL PACKAGES FOR AIR TRANSPORT

This package is not intended for the air transport of fissile material.

6.9 CONCLUSION

Based on the calculations that have been documented, the RAJ-II shipping container is qualified to transport UO_2 fuel assemblies, including 10x10, 9x9, and 8x8 BWR designs, in accordance with the criticality safety requirements of the IAEA and 10 CFR 71. The fuel assemblies may be channeled or un-channeled.

The calculations documented in Chapter 6.0 also demonstrate a finite 10x1x10 array of damaged, or a 21x3x24 array of un-damaged packages remains below a k_{eff} of 0.95 with optimum interspersed moderation. Therefore, the calculations support a CSI of 1.0.

In addition, the calculations demonstrate UO_2 fuel rods may be packaged within the RAJ-II inner container in 5-inch stainless steel pipe/protective case, loose, or bundled together. The UO_2 fuel rods may consist of 10x10, 9x9, or 8x8 fuel rod designs.

The calculations documented in Chapter 6.0 also demonstrate the 10x10 fuel assemblies may be transported with 8, 10, 12, or 14 part length fuel rods, and 9x9 fuel assemblies may be transported with 8, 10 and 12 part length fuel rods.

6.10 BENCHMARK EVALUATIONS

6.10.1 Applicability of Benchmark Experiments

The criticality calculation method is verified by comparison with critical experiment data which is sufficiently diverse to establish that the method bias and uncertainty will apply to conditions considered in the RAJ-II shipping container criticality analysis. A set of 27 critical experiments are analyzed using SCALE-PC to demonstrate its applicability to criticality analysis and to establish a set of Upper Subcritical Limits (USLs) that define acceptance criteria. Benchmark experiments are selected with compositions, configurations, and nuclear characteristics that are comparable to those encountered in the RAJ-II shipping container loaded with fuel as described in Table 6-1. The critical experiments are described in detail in References 2-5 and 9-12 and summarized in Section 6.11.10.

The critical experiments consisted of water moderated, oxide fuel arrays in square lattices. Fourteen experiments were 15x8 fuel rod lattices, with 4.31 weight percent (w/o) U-235 enrichment, and different absorber plates in the water gaps between rods. The absorber plates include aluminum, Type 304L stainless steel, Type 304L stainless steel with various boron enrichments, zircaloy-4, and Boral™. Thirteen experiments were 15x15 fuel rod lattices using multiple enrichments, no absorbers between rod clusters, and gadonium absorber integral to the fuel in most cases (9 cases). The lattice arrays in these experiments had enrichments of 2.46, 2.73, 2.74, 2.75, 2.76, 2.77, or 2.78 w/o U-235. Comparison with these experiments demonstrates the applicability of the criticality calculation method.

6.10.2 Bias Determination

A set of Upper Subcritical Limits is determined using the results from the 27 critical experiments and USL Method 1, Confidence Band with Administrative Margin, described in Section 4.0 of NUREG/CR-6361 (Reference 7). The USL Method 1 applies a statistical calculation of the method bias and its uncertainty plus an administrative margin (0.05 Δk) to a linear fit of the critical experiment benchmark data. The USLs are determined as a function of the critical experiment system parameters; enrichment, water-to-fuel ratio, hydrogen-to- U-235 ratio, pin pitch, average energy of the lethargy causing fission, and the average energy group causing fission.

- The following equation is determined for the USL as a function of enrichment:
  $USL = 0.9388 + (8.6824 \times 10^{-4})x$ for all x
  The variance of the equation fit is 3.6827×10^{-6}. The applicable range for enrichment is $2.46 \leq x \leq 4.31$.

- The following equation is determined for the USL as a function of water-to-fuel ratio:
  $USL = 0.9398 + (6.6864 \times 10^{-4})x$ for all x
  The variance of the equation fit is 3.8188×10^{-6}. The applicable range for water-to-fuel ratio is $1.8714 \leq x \leq 3.8832$.

- The following equation is determined for the USL as a function of hydrogen-to-U-235:
  $USL = 0.9380 + (1.4976 \times 10^{-5})x$ for all x
  The variance of the equation fit is 4.1692×10^{-6}. The applicable range for hydrogen-to-U-235 ratio is $200.56 \leq 255.92$.

- The following equation is determined for the USL as a function of pin pitch:
  $USL = 0.9387 + (1.4894 \times 10^{-3})x$ for all x
  The variance of the equation fit is 3.7993×10^{-6}. The applicable range for pin pitch is $1.6358 \leq x \leq 2.54$.

- The following equation is determined for the USL as a function of average energy of the lethargy causing fission:
  $USL = 0.9423 - (3.8725 \times 10^{-3})x$ for all x
  The variance of the equation fit is 4.1339×10^{-6}. The applicable range for average energy of the lethargy causing fission is $0.1127 \leq x \leq 0.3645$.

- The following equation is determined for the USL as a function of the average energy group causing fission:
  $USL = 0.9281 + (3.9834 \times 10^{-4})x$ for all x
  The variance of the equation fit is 4.0641×10^{-6}. The applicable range for the average energy group causing fission is $32.89 \leq x \leq 35.77$.

Of the preceding equations, the USL as a function of enrichment is the best correlated to the data since the variance of the equation fit is the smallest. Therefore, the USL as a function of enrichment is used to determine a minimum USL for each fuel assembly type considered for use

with the RAJ-II shipping container (Table 6-1). Figure 6-50 shows the USL as a function of enrichment. USL values are calculated as a function of enrichment for each candidate fuel design. All candidate fuel designs have the same maximum enrichment of 5.0 wt. percent U-235. Although the 5.0 wt. percent U-235 enrichment falls outside the range of applicability, ANSI/ANS-8.1 (Reference 6) allows the range of applicability to be extended beyond the range of conditions represented by the benchmarks, as long as that extrapolation is not large. As outlined in Reference 7, k(x)-w(x) is used to extend the USL curve beyond the range of applicability. Figure 6-50 displays the USL curve extrapolation using k(x)-w(x); the extrapolated USL value corresponding to the 5.0 wt. percent U-235 enrichment is 0.94323. Since the extrapolated value results in a higher USL than the maximum enrichment within the range of applicability would produce, the USL corresponding to the 4.31 wt. percent U-235 enrichment is conservatively selected. Therefore, the USL for the RAJ-II shipping container is 0.94254.

The following equation is used to develop the k_{eff} for the transportation of fuel in the RAJ-II shipping container:

$$k_{eff} = k_{case} + 2\sigma$$

where:

k_{case} = KENO V.a k_{eff} for a particular case of interest

σ = uncertainty in calculated KENO V.a k_{eff} for a particular case of interest

The k_{eff} for each container configuration analyzed in the RAJ-II shipping container criticality analysis is compared to the minimum USL (0.94254) to ensure subcriticality.

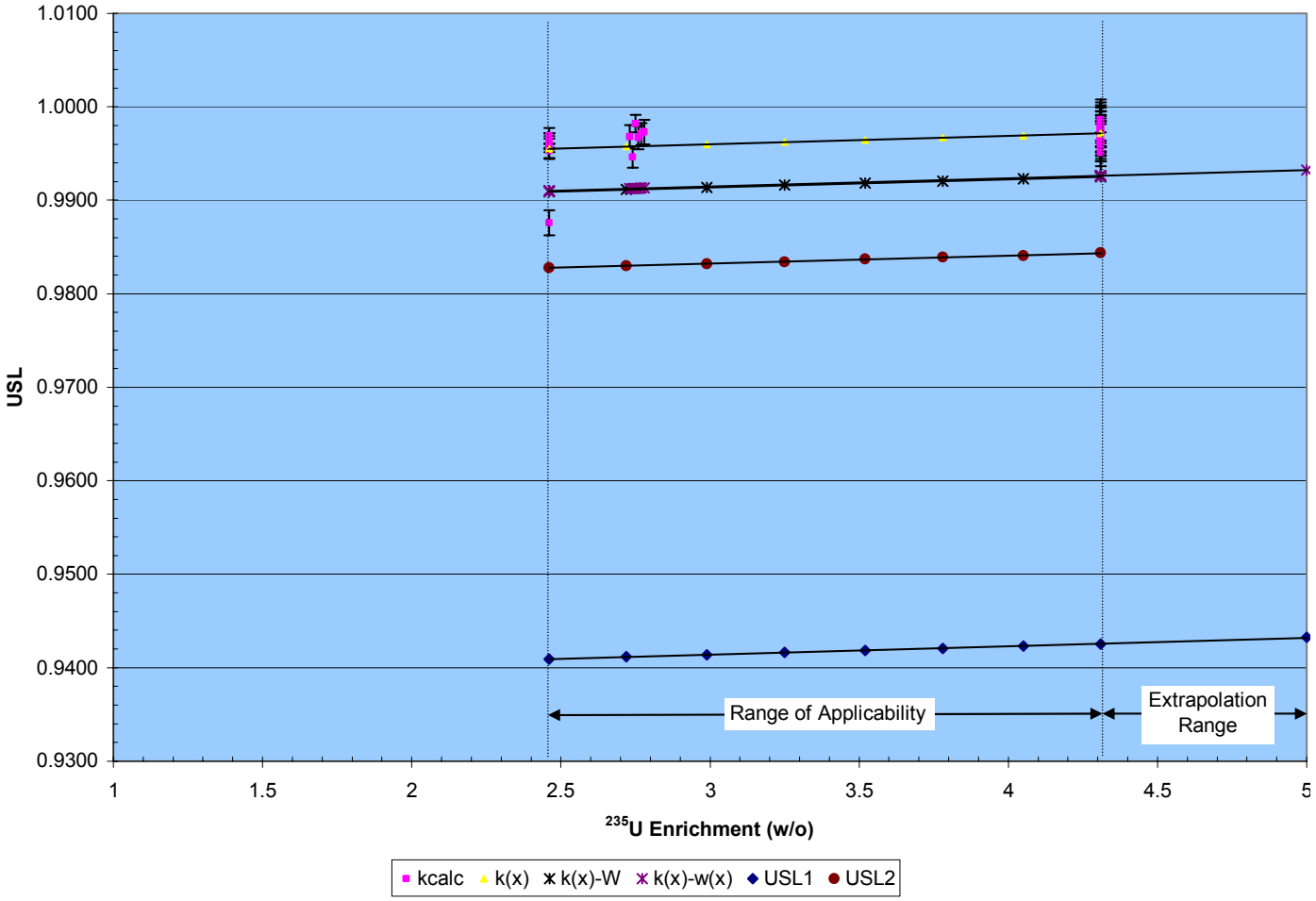


Figure 6-50 USL as a Function of Enrichment

6.11 APPENDIX

6.11.1 Single Package Normal Conditions of Transport Input

```
=CSAS25             PARM=SIZE=500000
RAJ-II CONTAINER, HAC, NO INTERSPERSED H2O, 100% INNER H2O DENSITY, 5.0 W/O
235U, 12 GAD RODS, SINGLE PACKAGE
44GROUPNDF5                 LATTICECELL
UO2            1  DEN=10.74    1.0  293 92235 5.0 92238 95.0   END
ZR             2  1.00             293                         END
H2O            3  1.00             293                         END
ARBMUO2        10.74 2 1 1 1 92000 1
                             8016 2 4 0.97840 293 92235  5.0
                                                  92238 95.0  END
ARBMGD2O3      7.407 2 0 1 1 64000 2
                             8016 3 4 0.02160 293            END
H2O            5  1.00             293                         END
SS304          6  1.00             293                         END
POLYETHYLENE   7  DEN=0.080000 1.0  293                         END
POLYETHYLENE   8  DEN=0.949 0.25405 293                         END
H2O            8  DEN=1.00  0.74595 293                         END
H2O            9  1.00             293                         END
ARBMAL2O3      0.25 2 0 1 0 13027 2 8016 3 10  0.49            END
ARBMSIO2       0.25 2 0 1 0 14000 1 8016 2 10  0.51            END
ZR             11 1.00             293                         END
END COMP
SQUAREPITCH 1.3500 0.8950 1 8 1.01000 2 0.9338 0               END
MORE DATA
RES=4 CYLINDER 0.4475  DAN(4)=2.3197146E-01
END MORE DATA
RAJ-II CONTAINER, HAC, NO INTERSPERSED H2O, 100% INNER H2O DENSITY, 5.0 W/O
235U, 12 GAD RODS, SINGLE PACKAGE
READ PARM TME=400 GEN=400 NPG=2500 NSK=50 NUB=YES RUN=YES END PARM
READ GEOM

UNIT  1
COM=!CONTAINER INNER BOX!
'DEFINE GEOMETRY FOR SEPARATOR PLATE BETWEEN ASSEMBLY COMPARTMENTS
CUBOID     6  1  2P0.0875   2P228.34  2P8.829
'DEFINE REGION FOR ASSEMBLY COMPARTMENTS WITHIN INNER BOX
CUBOID     9  1  2P17.713   2P228.34  2P8.829
'INSERT FOAM POLYETHYLENE
HOLE       4      -8.9003       0.00    0.00
HOLE       5       8.9003       0.00    0.00
'DEFINE WALLS FOR ASSEMBLY COMPARTMENTS WITHIN INNER BOX
CUBOID     6  1  2P17.800   2P228.34    8.829  -8.9165
'DEFINE REGION OUTSIDE THE WALLS OF THE ASSEMBLY COMPARTMENTS
CUBOID    10  1  2P22.798   2P228.34    8.829  -13.839
'DEFINE THE INNER WALLS OF THE BOX ENDS
CUBOID     6  1  2P22.798   2P228.48    8.829  -13.979
'DEFINE INNER CORE OF BOX ENDS
CUBOID    10  1  2P22.798   2P233.44    8.829  -13.979
'DEFINE OUTER WALLS OF THE INNER BOX
```

```
CUBOID     6  1  2P22.938   2P233.58    8.829  -13.979

UNIT 2
COM=!INNER BOX LID!
'DEFINE INNER CORE OF INNER BOX LID
CUBOID    10 1  2P22.798    2P233.44   2P2.48
'DEFINE WALLS FOR INNER BOX LID
CUBOID    6  1  2P22.938    2P233.58   2P2.62

UNIT 3
COM=!INNER BOX WITH ENDS AND LID!
ARRAY 1 3*0

UNIT 4
COM=!FOAM POLYETHYLENE FOR LEFT ASSEMBLY COMPARTMENT!
CUBOID     9  1  2P7.055   2P228.34  2P7.055
HOLE      70      -6.7500  -192.50  -6.750
'FOAM POLYETHYLENE FOR ASSEMBLY COMPARTMENTS
CUBOID     7  1  2P8.8126   2P228.34  2P8.829

UNIT 5
COM=!FOAM POLYETHYLENE FOR RIGHT ASSEMBLY COMPARTMENT!
CUBOID     9  1  2P7.055   2P228.34  2P7.055
HOLE      70      -6.7500  -192.50  -6.750
'FOAM POLYETHYLENE FOR ASSEMBLY COMPARTMENT
CUBOID     7  1  2P8.8126   2P228.34  2P8.829

UNIT 10
COM=!5 W/O FUEL PINS W/O GAD!
'DEFINE THE FUEL PELLET
YCYLINDER 1  1    0.4475   192.5  0
'DEFINE THE PELLET-CLAD GAP
YCYLINDER 0  1    0.4669   192.5  0
'DEFINE THE FUEL ROD CLADDING/POLY
YCYLINDER 2  1    0.5050   192.5  0
'DEFINE THE FUEL ROD PITCH FILLED WITH POLYETHYLENE
CUBOID    8  1  2P0.6750    192.5  0  2P0.6750

UNIT 20
COM=!SPACE WITHIN FUEL ASSEMBLY LATTICE!
CUBOID    8  1  2P0.6750   192.5  0  2P0.6750

UNIT 40
COM=!5 W/O FUEL PINS W (2.0 WT % X 0.75) GAD!
'DEFINE THE FUEL PELLET
YCYLINDER 4  1    0.4475   192.5  0
'DEFINE THE PELLET-CLAD GAP
YCYLINDER 0  1    0.4669   192.5  0
'DEFINE THE FUEL ROD CLADDING/POLY
YCYLINDER 2  1    0.5050   192.5  0
'DEFINE THE FUEL ROD PITCH FILLED WITH POLYETHYLENE
CUBOID    8  1  2P0.6750    192.5  0  2P0.6750

UNIT 50
COM=!LOWER HALF FUEL ASSEMBLY WITH CLUSTER SEPARATOR!
ARRAY 2 3*0
```

```
UNIT 60
COM=!UPPER HALF FUEL ASSEMBLY WITH CLUSTER SEPARATOR!
ARRAY 3 3*0

UNIT 70
COM=!COMPLETE FUEL ASSEMBLY!
ARRAY 4 3*0
REFLECTOR 11 1  2R0.3048 2R0.0  2R0.3048  1

GLOBAL
UNIT 400
COM=!OUTER CONTAINER BODY AND LID!
'DEFINE INNER REGION OF THE OUTER CONTAINER
CUBOID   3  1   2P35.788    2P253.188  2P31.900
'INNER CONTAINER PLACEMENT WITHIN OUTER CONTAINER
HOLE 3         -22.938      -233.58    -14.024
'DEFINE WALLS OF THE OUTER CONTAINER AND LID
CUBOID   6  1   2P35.963    2P253.363  2P32.075

'GLOBAL
'UNIT 500
'ARRAY 10 3*0
REFLECTOR  5  1  6R30.48  1
END GEOM

READ ARRAY
ARA=1 NUX=1 NUY=1 NUZ=2
FILL 1 2
END FILL
ARA=2 NUX=10 NUY=1 NUZ=10
FILL 10 10 10 10 10 10 10 10 40 40
     10 10 20 10 10 10 40 40 40 40
     10 20 10 10 10 10 40 40 40 10
     10 10 10 20 20 10 40 40 40 10
     10 20 10 20 20 10 10 10 10 10
     10 10 20 10 10 20 20 10 10 10
     10 20 10 20 10 20 20 10 10 10
     10 10 10 10 20 10 10 10 20 10
     10 20 10 20 10 20 10 20 10 10
     10 10 10 10 10 10 10 10 10 10
END FILL
ARA=3 NUX=10 NUY=1 NUZ=10
FILL 10 10 10 10 10 10 10 10 40 40
     10 10 10 10 10 10 40 40 40 40
     10 10 10 10 10 10 40 40 40 10
     10 10 10 20 20 10 40 40 40 10
     10 10 10 20 20 10 10 10 10 10
     10 10 10 10 10 20 20 10 10 10
     10 10 10 10 10 20 20 10 10 10
     10 10 10 10 10 10 10 10 10 10
     10 10 10 10 10 10 10 10 10 10
     10 10 10 10 10 10 10 10 10 10
END FILL
ARA=4  NUX=1  NUY=2  NUZ=1
FILL 50 60
END FILL
ARA=10 NUX=21 NUY=3 NUZ=24
```

```
FILL F400
END FILL
END ARRAY

READ BNDS ALL=VACUUM
END BNDS
END DATA
END
```

6.11.2 Single Package Hypothetical Accident Conditions Input

```
=CSAS25             PARM=SIZE=500000
RAJ-II CONTAINER, HAC, 12 PART LENGTH RODS, 12 GAD RODS, 1.350 CM PITCH,
PATTERN H, SINGLE PACKAGE
44GROUPNDF5                 LATTICECELL
UO2            1  DEN=10.74 1.0 293 92235 5.0 92238 95.0      END
ZR             2             0.26380  293                     END
POLYETHYLENE   2  DEN=0.949  0.73620  293                     END
H2O            3  0.01 293                                    END
ARBMUO2        10.74 2 1 1 1 92000 1
                              8016 2 4 0.97840 293 92235  5.0
                                                   92238 95.0 END
ARBMGD2O3      7.407 2 0 1 1 64000 2
                              8016 3 4 0.02160 293            END
H2O            5  1.00 293                                    END
SS304          6  1.00 293                                    END
H2O            7  1.00 293                                    END
H2O            8  1.00 293                                    END
ZR             9  1.00 293                                    END
ARBMAL2O3      0.25 2 0 1 0 13027 2 8016 3 10  0.49            END
ARBMSIO2       0.25 2 0 1 0 14000 1 8016 2 10  0.51            END
END COMP
SQUAREPITCH 1.3500 0.8950 1 7 1.19720 2 0.9338 0               END
MORE DATA
RES=4 CYLINDER 0.4475  DAN(4)=2.2023524E-01
END MORE DATA
RAJ-II CONTAINER, HAC, 12 PART LENGTH RODS, 12 GAD RODS, 1.350 CM PITCH,
PATTERN H, SINGLE PACKAGE
READ PARM TME=400 GEN=400 NPG=2500 NSK=50 NUB=YES RUN=YES END PARM
READ GEOM

UNIT  1
COM=!CONTAINER INNER BOX!
'DEFINE GEOMETRY FOR SEPARATOR PLATE BETWEEN ASSEMBLY COMPARTMENTS
CUBOID     6  1  2P0.0875   225.20  -228.34  2P8.829
'DEFINE REGION FOR ASSEMBLY COMPARTMENTS WITHIN INNER BOX
CUBOID     7  1  2P17.713   225.20  -228.34  2P8.829
'PLACE THE FUEL ASSEMBLIES INSIDE INNER BOX
HOLE       70     -15.290  -192.50  -6.477
HOLE       70       2.336  -192.50  -6.477
'DEFINE WALLS FOR ASSEMBLY COMPARTMENTS WITHIN INNER BOX
CUBOID     6  1  2P17.800   225.20  -228.34  8.829  -8.9165
'DEFINE REGION OUTSIDE THE WALLS OF THE ASSEMBLY COMPARTMENTS
CUBOID     10 1  2P22.798   225.20  -228.34  8.829  -13.839
'DEFINE THE INNER WALLS OF THE BOX ENDS
CUBOID     6  1  2P22.798   225.34  -228.48  8.829  -13.979
'DEFINE INNER CORE OF BOX ENDS -8.1CM IN Y FOR TOTAL DEFORMATION
CUBOID     10 1  2P22.798   225.34  -233.44  8.829  -13.979
'DEFINE OUTER WALLS OF THE INNER BOX -8.1CM IN Y FOR TOTAL DEFORMATION
CUBOID     6  1  2P22.938   225.48  -233.58  8.829  -13.979

UNIT 2
COM=!INNER BOX LID!
'DEFINE INNER CORE OF INNER BOX LID -8.1CM IN Y FOR TOTAL DEFORMATION
```

```
CUBOID    10 1  2P22.798    2P229.39   2P2.48
'DEFINE WALLS FOR INNER BOX LID -8.1CM IN Y FOR TOTAL DEFORMATION
CUBOID    6  1  2P22.938    2P229.53   2P2.62

UNIT 3
COM=!INNER BOX WITH ENDS AND LID!
ARRAY 1 3*0

UNIT 10
COM=!5 W/O FUEL PINS W/O GAD!
'DEFINE THE FUEL PELLET
YCYLINDER 1  1    0.4475   192.5  0
'DEFINE THE PELLET-CLAD GAP
YCYLINDER 0  1    0.4669   192.5  0
'DEFINE THE FUEL ROD CLADDING/POLY
YCYLINDER 2  1    0.5986   192.5  0
'DEFINE THE FUEL ROD PITCH FILLED WITH POLYETHYLENE
CUBOID    7  1  2P0.6750    192.5  0  2P0.6750

UNIT 20
COM=!SPACE WITHIN FUEL ASSEMBLY LATTICE!
CUBOID    7  1  2P0.6750   192.5  0  2P0.6750

UNIT 30
COM=!ARRAY FOR COMPLETE FUEL ASSEMBLY!
ARRAY 2 3*0
REFLECTOR 9  1  2R0.3048 2R0.0  2R0.3048  1

UNIT 40
COM=!5 W/O FUEL PINS W (2.0 WT % X 0.75) GAD!
'DEFINE THE FUEL PELLET
YCYLINDER 4  1    0.4475   192.5  0
'DEFINE THE PELLET-CLAD GAP
YCYLINDER 0  1    0.4669   192.5  0
'DEFINE THE FUEL ROD CLADDING/POLY
YCYLINDER 2  1    0.5986   192.5  0
'DEFINE THE FUEL ROD PITCH FILLED WITH POLYETHYLENE
CUBOID    7  1  2P0.6750    192.5  0  2P0.6750

UNIT 50
COM=!LOWER HALF FUEL ASSEMBLY WITH CLUSTER SEPARATOR!
ARRAY 2 3*0

UNIT 60
COM=!UPPER HALF FUEL ASSEMBLY WITH CLUSTER SEPARATOR!
ARRAY 3 3*0

UNIT 70
COM=!COMPLETE FUEL ASSEMBLY!
ARRAY 4 3*0
REFLECTOR 9  1  2R0.3048 2R0.0  2R0.3048  1

GLOBAL
UNIT 400
COM=!OUTER CONTAINER BODY AND LID!
'DEFINE INNER REGION OF THE OUTER CONTAINER
'MINUS 4.7CM IN Y AND -2.4CM IN Z FOR TOTAL DEFORMATION
```

```
CUBOID    0  1   2P35.788  247.960  -253.190  29.500  -31.900
'INNER CONTAINER PLACEMENT WITHIN OUTER CONTAINER
HOLE 3          -22.938      -229.53    -14.024
'DEFINE WALLS OF THE OUTER CONTAINER AND LID
CUBOID    6  1   2P35.963  248.135  -253.365  29.675  -32.075

'GLOBAL
'UNIT 500
'ARRAY 10 3*0
REFLECTOR  5  1  6R30.48  1
END GEOM

READ ARRAY
ARA=1 NUX=1 NUY=1 NUZ=2
FILL 1 2
END FILL
ARA=2 NUX=10 NUY=1 NUZ=10
FILL 10 10 10 10 10 10 10 10 40 40
     10 10 20 10 10 10 40 40 40 40
     10 20 10 10 10 10 40 40 40 10
     10 10 10 20 20 10 40 40 40 10
     10 20 10 20 20 10 10 10 10 10
     10 10 20 10 10 20 20 10 10 10
     10 20 10 20 10 20 20 10 10 10
     10 10 10 10 20 10 10 10 20 10
     10 20 10 20 10 20 10 20 10 10
     10 10 10 10 10 10 10 10 10 10
END FILL
ARA=3 NUX=10 NUY=1 NUZ=10
FILL 10 10 10 10 10 10 10 10 40 40
     10 10 10 10 10 10 40 40 40 40
     10 10 10 10 10 10 40 40 40 10
     10 10 10 20 20 10 40 40 40 10
     10 10 10 20 20 10 10 10 10 10
     10 10 10 10 10 20 20 10 10 10
     10 10 10 10 10 20 20 10 10 10
     10 10 10 10 10 10 10 10 10 10
     10 10 10 10 10 10 10 10 10 10
     10 10 10 10 10 10 10 10 10 10
END FILL
ARA=4  NUX=1  NUY=2  NUZ=1
FILL 50 60
END FILL
END ARRAY

READ BNDS ALL=VACUUM
END BNDS
END DATA
END
```

6.11.3 Package Array Normal Conditions of Transport Input

```
=CSAS25             PARM=SIZE=500000
RAJ-II CONTAINER, HAC, NO INTERSPERSED H2O, 100% INNER H2O DENSITY, 5.0 W/O
235U, 12 GAD RODS, 21 X 3 X 24 ARRAY
44GROUPNDF5                 LATTICECELL
UO2            1  DEN=10.74    1.0  293 92235 5.0 92238 95.0   END
ZR             2  1.00             293                         END
H2O            3  1.00             293                         END
ARBMUO2        10.74 2 1 1 1 92000 1
                             8016 2 4 0.97840 293 92235  5.0
                                                  92238 95.0  END
ARBMGD2O3      7.407 2 0 1 1 64000 2
                             8016 3 4 0.02160 293            END
H2O            5  1.00             293                         END
SS304          6  1.00             293                         END
POLYETHYLENE   7  DEN=0.080000 1.0  293                         END
POLYETHYLENE   8  DEN=0.949 0.25405 293                         END
H2O            8  DEN=1.00  0.74595 293                         END
H2O            9  1.00             293                         END
ARBMAL2O3      0.25 2 0 1 0 13027 2 8016 3 10  0.49            END
ARBMSIO2       0.25 2 0 1 0 14000 1 8016 2 10  0.51            END
ZR             11 1.00             293                         END
END COMP
SQUAREPITCH 1.3500 0.8950 1 8 1.01000 2 0.9338 0               END
MORE DATA
RES=4 CYLINDER 0.4475  DAN(4)=2.3197146E-01
END MORE DATA
RAJ-II CONTAINER, HAC, NO INTERSPERSED H2O, 100% INNER H2O DENSITY, 5.0 W/O
235U, 12 GAD RODS, 21 X 3 X 24 ARRAY
READ PARM TME=400 GEN=400 NPG=2500 NSK=50 NUB=YES RUN=YES END PARM
READ GEOM

UNIT  1
COM=!CONTAINER INNER BOX!
'DEFINE GEOMETRY FOR SEPARATOR PLATE BETWEEN ASSEMBLY COMPARTMENTS
CUBOID     6  1  2P0.0875   2P228.34  2P8.829
'DEFINE REGION FOR ASSEMBLY COMPARTMENTS WITHIN INNER BOX
CUBOID     9  1  2P17.713   2P228.34  2P8.829
'INSERT FOAM POLYETHYLENE
HOLE       4      -8.9003       0.00    0.00
HOLE       5       8.9003       0.00    0.00
'DEFINE WALLS FOR ASSEMBLY COMPARTMENTS WITHIN INNER BOX
CUBOID     6  1  2P17.800   2P228.34    8.829  -8.9165
'DEFINE REGION OUTSIDE THE WALLS OF THE ASSEMBLY COMPARTMENTS
CUBOID    10  1  2P22.798   2P228.34    8.829  -13.839
'DEFINE THE INNER WALLS OF THE BOX ENDS
CUBOID     6  1  2P22.798   2P228.48    8.829  -13.979
'DEFINE INNER CORE OF BOX ENDS
CUBOID    10  1  2P22.798   2P233.44    8.829  -13.979
'DEFINE OUTER WALLS OF THE INNER BOX
CUBOID     6  1  2P22.938   2P233.58    8.829  -13.979

UNIT 2
```

```
COM=!INNER BOX LID!
'DEFINE INNER CORE OF INNER BOX LID
CUBOID    10 1  2P22.798    2P233.44   2P2.48
'DEFINE WALLS FOR INNER BOX LID
CUBOID    6  1  2P22.938    2P233.58   2P2.62

UNIT 3
COM=!INNER BOX WITH ENDS AND LID!
ARRAY 1 3*0

UNIT 4
COM=!FOAM POLYETHYLENE FOR LEFT ASSEMBLY COMPARTMENT!
CUBOID     9  1  2P7.055   2P228.34  2P7.055
HOLE      70      -6.7500  -192.50  -6.750
'FOAM POLYETHYLENE FOR ASSEMBLY COMPARTMENTS
CUBOID     7  1  2P8.8126   2P228.34  2P8.829

UNIT 5
COM=!FOAM POLYETHYLENE FOR RIGHT ASSEMBLY COMPARTMENT!
CUBOID     9  1  2P7.055   2P228.34  2P7.055
HOLE      70      -6.7500  -192.50  -6.750
'FOAM POLYETHYLENE FOR ASSEMBLY COMPARTMENT
CUBOID     7  1  2P8.8126   2P228.34  2P8.829

UNIT 10
COM=!5 W/O FUEL PINS W/O GAD!
'DEFINE THE FUEL PELLET
YCYLINDER 1  1    0.4475   192.5  0
'DEFINE THE PELLET-CLAD GAP
YCYLINDER 0  1    0.4669   192.5  0
'DEFINE THE FUEL ROD CLADDING/POLY
YCYLINDER 2  1    0.5050   192.5  0
'DEFINE THE FUEL ROD PITCH FILLED WITH POLYETHYLENE
CUBOID    8  1  2P0.6750    192.5  0  2P0.6750

UNIT 20
COM=!SPACE WITHIN FUEL ASSEMBLY LATTICE!
CUBOID    8  1  2P0.6750   192.5  0  2P0.6750

UNIT 40
COM=!5 W/O FUEL PINS W (2.0 WT % X 0.75) GAD!
'DEFINE THE FUEL PELLET
YCYLINDER 4  1    0.4475   192.5  0
'DEFINE THE PELLET-CLAD GAP
YCYLINDER 0  1    0.4669   192.5  0
'DEFINE THE FUEL ROD CLADDING/POLY
YCYLINDER 2  1    0.5050   192.5  0
'DEFINE THE FUEL ROD PITCH FILLED WITH POLYETHYLENE
CUBOID    8  1  2P0.6750    192.5  0  2P0.6750

UNIT 50
COM=!LOWER HALF FUEL ASSEMBLY WITH CLUSTER SEPARATOR!
ARRAY 2 3*0

UNIT 60
COM=!UPPER HALF FUEL ASSEMBLY WITH CLUSTER SEPARATOR!
ARRAY 3 3*0
```

```
UNIT 70
COM=!COMPLETE FUEL ASSEMBLY!
ARRAY 4 3*0
REFLECTOR 11 1  2R0.3048 2R0.0  2R0.3048  1

UNIT 400
COM=!OUTER CONTAINER BODY AND LID!
'DEFINE INNER REGION OF THE OUTER CONTAINER
CUBOID   3  1   2P35.788    2P253.188  2P31.900
'INNER CONTAINER PLACEMENT WITHIN OUTER CONTAINER
HOLE 3         -22.938      -233.58    -14.024
'DEFINE WALLS OF THE OUTER CONTAINER AND LID
CUBOID   6  1   2P35.963    2P253.363  2P32.075

GLOBAL
UNIT 500
ARRAY 10 3*0
REFLECTOR  5  1  6R30.48  1
END GEOM

READ ARRAY
ARA=1 NUX=1 NUY=1 NUZ=2
FILL 1 2
END FILL
ARA=2 NUX=10 NUY=1 NUZ=10
FILL 10 10 10 10 10 10 10 10 40 40
     10 10 20 10 10 10 40 40 40 40
     10 20 10 10 10 10 40 40 40 10
     10 10 10 20 20 10 40 40 40 10
     10 20 10 20 20 10 10 10 10 10
     10 10 20 10 10 20 20 10 10 10
     10 20 10 20 10 20 20 10 10 10
     10 10 10 10 20 10 10 10 20 10
     10 20 10 20 10 20 10 20 10 10
     10 10 10 10 10 10 10 10 10 10
END FILL
ARA=3 NUX=10 NUY=1 NUZ=10
FILL 10 10 10 10 10 10 10 10 40 40
     10 10 10 10 10 10 40 40 40 40
     10 10 10 10 10 10 40 40 40 10
     10 10 10 20 20 10 40 40 40 10
     10 10 10 20 20 10 10 10 10 10
     10 10 10 10 10 20 20 10 10 10
     10 10 10 10 10 20 20 10 10 10
     10 10 10 10 10 10 10 10 10 10
     10 10 10 10 10 10 10 10 10 10
     10 10 10 10 10 10 10 10 10 10
END FILL
ARA=4  NUX=1  NUY=2  NUZ=1
FILL 50 60
END FILL
ARA=10 NUX=21 NUY=3 NUZ=24
FILL F400
END FILL
END ARRAY
```

```
READ BNDS ALL=VACUUM
END BNDS
END DATA
END
```

6.11.4 Package Array Hypothetical Accident Conditions Input

6.11.4.1 GNF 10x10

```
=CSAS25             PARM=SIZE=500000
RAJ-II CONTAINER, HAC, 100% H2O DENSITY, WORSTCASE, GNF 10x10, 10 X 1 X 10
ARRAY
44GROUPNDF5                 LATTICECELL
UO2            1  DEN=10.74 1.0 293 92235 5.0 92238 95.0      END
ZR             2             0.26380  293                     END
POLYETHYLENE   2  DEN=0.949  0.73620  293                     END
H2O            3  0.01 293                                    END
ARBMUO2        10.74 2 1 1 1 92000 1
                              8016 2 4 0.97840 293 92235  5.0
                                                   92238 95.0 END
ARBMGD2O3      7.407 2 0 1 1 64000 2
                              8016 3 4 0.02160 293            END
H2O            5  1.00 293                                    END
SS304          6  1.00 293                                    END
H2O            7  1.00 293                                    END
POLYETHYLENE   8  DEN=0.080000 1.0  293                       END
ZR             9  1.00 293                                    END
ARBMAL2O3      0.25 2 0 1 0 13027 2 8016 3 10  0.49            END
ARBMSIO2       0.25 2 0 1 0 14000 1 8016 2 10  0.51            END
END COMP
SQUAREPITCH 1.3500 0.8950 1 7 1.19720 2 0.9338 0               END
MORE DATA
RES=4 CYLINDER 0.4475  DAN(4)=2.2023524E-01
END MORE DATA
RAJ-II CONTAINER, HAC, 100% H2O DENSITY, WORSTCASE, GNF 10x10, 10 X 1 X 10
ARRAY
READ PARM TME=400 GEN=400 NPG=2500 NSK=50 NUB=YES RUN=YES END PARM
READ GEOM

UNIT  1
COM=!CONTAINER INNER BOX!
'DEFINE GEOMETRY FOR SEPARATOR PLATE BETWEEN ASSEMBLY COMPARTMENTS
CUBOID     6  1  2P0.0875   225.20  -228.34  2P8.829
'DEFINE REGION FOR ASSEMBLY COMPARTMENTS WITHIN INNER BOX
CUBOID     7  1  2P17.713   225.20  -228.34  2P8.829
'INSERT FOAM POLYETHYLENE AND FUEL
HOLE       4      -8.9001     0.00      0.00
HOLE       5       8.9001     0.00      0.00
'DEFINE WALLS FOR ASSEMBLY COMPARTMENTS WITHIN INNER BOX
CUBOID     6  1  2P17.800   225.20  -228.34  8.829  -8.9165
'DEFINE REGION OUTSIDE THE WALLS OF THE ASSEMBLY COMPARTMENTS
CUBOID     10 1  2P22.798   225.20  -228.34  8.829  -13.839
'DEFINE THE INNER WALLS OF THE BOX ENDS
CUBOID     6  1  2P22.798   225.34  -228.48  8.829  -13.979
'DEFINE INNER CORE OF BOX ENDS -8.1CM IN Y FOR TOTAL DEFORMATION
CUBOID     10 1  2P22.798   225.34  -233.44  8.829  -13.979
'DEFINE OUTER WALLS OF THE INNER BOX -8.1CM IN Y FOR TOTAL DEFORMATION
CUBOID     6  1  2P22.938   225.48  -233.58  8.829  -13.979
```

```
UNIT 2
COM=!INNER BOX LID!
'DEFINE INNER CORE OF INNER BOX LID -8.1CM IN Y FOR TOTAL DEFORMATION
CUBOID    10 1  2P22.798    2P229.39   2P2.48
'DEFINE WALLS FOR INNER BOX LID -8.1CM IN Y FOR TOTAL DEFORMATION
CUBOID    6  1  2P22.938    2P229.53   2P2.62

UNIT 3
COM=!INNER BOX WITH ENDS AND LID!
ARRAY 1 3*0

UNIT 4
COM=!FOAM POLYETHYLENE FOR LEFT ASSEMBLY COMPARTMENT!
CUBOID     7  1  2P7.055   225.20  -228.34  2P7.055
HOLE      70      -6.7500 -192.50   -6.750
'FOAM POLYETHYLENE FOR ASSEMBLY COMPARTMENTS
CUBOID     8  1  2P8.8126  225.20  -228.34  2P8.829

UNIT 5
COM=!FOAM POLYETHYLENE FOR RIGHT ASSEMBLY COMPARTMENT!
CUBOID     7  1  2P7.055   225.20  -228.34  2P7.055
HOLE      70      -6.7500 -192.50   -6.750
'FOAM POLYETHYLENE FOR ASSEMBLY COMPARTMENT
CUBOID     8  1  2P8.8126  225.20  -228.34  2P8.829

UNIT 10
COM=!5 W/O FUEL PINS W/O GAD!
'DEFINE THE FUEL PELLET
YCYLINDER 1  1    0.4475   192.5  0
'DEFINE THE PELLET-CLAD GAP
YCYLINDER 0  1    0.4669   192.5  0
'DEFINE THE FUEL ROD CLADDING/POLY
YCYLINDER 2  1    0.5986   192.5  0
'DEFINE THE FUEL ROD PITCH FILLED WITH POLYETHYLENE
CUBOID    7  1  2P0.6750    192.5  0  2P0.6750

UNIT 20
COM=!SPACE WITHIN FUEL ASSEMBLY LATTICE!
CUBOID    7  1  2P0.6750   192.5  0  2P0.6750

UNIT 30
COM=!ARRAY FOR COMPLETE FUEL ASSEMBLY!
ARRAY 2 3*0
REFLECTOR 9  1  2R0.3048 2R0.0  2R0.3048  1

UNIT 40
COM=!5 W/O FUEL PINS W (2.0 WT % X 0.75) GAD!
'DEFINE THE FUEL PELLET
YCYLINDER 4  1    0.4475   192.5  0
'DEFINE THE PELLET-CLAD GAP
YCYLINDER 0  1    0.4669   192.5  0
'DEFINE THE FUEL ROD CLADDING/POLY
YCYLINDER 2  1    0.5986   192.5  0
'DEFINE THE FUEL ROD PITCH FILLED WITH POLYETHYLENE
CUBOID    7  1  2P0.6750    192.5  0  2P0.6750

UNIT 50
```

```
COM=!LOWER HALF FUEL ASSEMBLY WITH CLUSTER SEPARATOR!
ARRAY 2 3*0

UNIT 60
COM=!UPPER HALF FUEL ASSEMBLY WITH CLUSTER SEPARATOR!
ARRAY 3 3*0

UNIT 70
COM=!COMPLETE FUEL ASSEMBLY!
ARRAY 4 3*0
REFLECTOR 9  1  2R0.3048 2R0.0  2R0.3048  1

UNIT 400
COM=!OUTER CONTAINER BODY AND LID!
'DEFINE INNER REGION OF THE OUTER CONTAINER
'MINUS 4.7CM IN Y AND -2.4CM IN Z FOR TOTAL DEFORMATION
CUBOID    0  1   2P35.788  247.960  -253.190  29.500  -31.900
'INNER CONTAINER PLACEMENT WITHIN OUTER CONTAINER
HOLE 3          -22.938      -229.53    -14.024
'DEFINE WALLS OF THE OUTER CONTAINER AND LID
CUBOID    6  1   2P35.963  248.135  -253.365  29.675  -32.075

GLOBAL
UNIT 500
ARRAY 10 3*0
REFLECTOR  5  1  6R30.48  1
END GEOM

READ ARRAY
ARA=1 NUX=1 NUY=1 NUZ=2
FILL 1 2
END FILL
ARA=2 NUX=10 NUY=1 NUZ=10
FILL 10 10 10 10 10 10 10 10 40 40
     10 10 20 10 10 10 40 40 40 40
     10 20 10 10 10 10 40 40 40 10
     10 10 10 20 20 10 40 40 40 10
     10 20 10 20 20 10 10 10 10 10
     10 10 20 10 10 20 20 10 10 10
     10 20 10 20 10 20 20 10 10 10
     10 10 10 10 20 10 10 10 20 10
     10 20 10 20 10 20 10 20 10 10
     10 10 10 10 10 10 10 10 10 10
END FILL
ARA=3 NUX=10 NUY=1 NUZ=10
FILL 10 10 10 10 10 10 10 10 40 40
     10 10 10 10 10 10 40 40 40 40
     10 10 10 10 10 10 40 40 40 10
     10 10 10 20 20 10 40 40 40 10
     10 10 10 20 20 10 10 10 10 10
     10 10 10 10 10 20 20 10 10 10
     10 10 10 10 10 20 20 10 10 10
     10 10 10 10 10 10 10 10 10 10
     10 10 10 10 10 10 10 10 10 10
     10 10 10 10 10 10 10 10 10 10
END FILL
ARA=4  NUX=1  NUY=2  NUZ=1
```

```
FILL 50 60
END FILL
ARA=10 NUX=10 NUY=1 NUZ=10
FILL F400
END FILL
END ARRAY

READ BNDS ALL=VACUUM
END BNDS
END DATA
END
```

6.11.5 Single Package Loose Rods Normal Conditions of Transport Input

```
=CSAS25             PARM=SIZE=500000
RAJ-II CONTAINER, 8, NTC, 100% H20, 2.8150 CM PITCH, LOOSE FUEL RODS, SINGLE
PACKAGE
44GROUPNDF5                 LATTICECELL
UO2            1  DEN=10.74    1.0  293 92235 5.0 92238 95.0   END
POLYETHYLENE   2  DEN=0.925    1.0  293                        END
H2O            3  1.00              293                        END
UO2            4  DEN=10.4799  1.0  293 92235 3.25 92238 96.75 END
GD             4  DEN=0.17374  1.0  293                        END
O              4  DEN=0.026514 1.0  293                        END
H2O            5  1.00              293                        END
SS304          6  1.00              293                        END
H2O            8  1.00              293                        END
H2O            9  1.00              293                        END
ARBMAL2O3      0.25 2 0 1 0 13027 2 8016 3 10  0.49            END
ARBMSIO2       0.25 2 0 1 0 14000 1 8016 2 10  0.51            END
ZR             11 1.00              293                        END
END COMP
SQUAREPITCH 2.8150 1.0500 1 8 1.13048 2 1.100 0               END
RAJ-II CONTAINER, 8, NTC, 100% H20, 2.8150 CM PITCH, LOOSE FUEL RODS, SINGLE
PACKAGE
READ PARM TME=400 GEN=400 NPG=2500 NSK=50 NUB=YES END PARM
READ GEOM

UNIT  1
COM=!CONTAINER INNER BOX!
'DEFINE GEOMETRY FOR SEPARATOR PLATE BETWEEN ASSEMBLY COMPARTMENTS
CUBOID     6  1  2P0.0875   2P228.34  2P8.829
'DEFINE REGION FOR ASSEMBLY COMPARTMENTS WITHIN INNER BOX
CUBOID     3  1  2P17.713   2P228.34  2P8.829
'INSERT FOAM POLYETHYLENE
HOLE       4      -8.9003       0.00    0.00
HOLE       5       8.9003       0.00    0.00
'DEFINE WALLS FOR ASSEMBLY COMPARTMENTS WITHIN INNER BOX
CUBOID     6  1  2P17.800   2P228.34    8.829  -8.9165
'DEFINE REGION OUTSIDE THE WALLS OF THE ASSEMBLY COMPARTMENTS
CUBOID    10  1  2P22.798   2P228.34    8.829  -13.839
'DEFINE THE INNER WALLS OF THE BOX ENDS
CUBOID     6  1  2P22.798   2P228.48    8.829  -13.979
'DEFINE INNER CORE OF BOX ENDS
CUBOID    10  1  2P22.798   2P233.44    8.829  -13.979
'DEFINE OUTER WALLS OF THE INNER BOX
CUBOID     6  1  2P22.938   2P233.58    8.829  -13.979

UNIT 2
COM=!INNER BOX LID!
'DEFINE INNER CORE OF INNER BOX LID
CUBOID    10 1  2P22.798    2P233.44   2P2.48
'DEFINE WALLS FOR INNER BOX LID
CUBOID    6  1  2P22.938    2P233.58   2P2.62

UNIT 3
```

```
COM=!INNER BOX WITH ENDS AND LID!
ARRAY 1 3*0

UNIT 4
COM=!FOAM POLYETHYLENE FOR LEFT ASSEMBLY COMPARTMENT!
CUBOID     3  1  2P7.0378   2P228.34  2P7.054
HOLE      30      -7.0376  -191.77   -7.0376
'FOAM POLYETHYLENE FOR ASSEMBLY COMPARTMENTS
CUBOID     7  1  2P8.8126   2P228.34  2P8.829

UNIT 5
COM=!FOAM POLYETHYLENE FOR RIGHT ASSEMBLY COMPARTMENT!
CUBOID     3  1  2P7.0378   2P228.34  2P7.054
HOLE      30      -7.0376  -191.77   -7.0376
'FOAM POLYETHYLENE FOR ASSEMBLY COMPARTMENT
CUBOID     7  1  2P8.8126   2P228.34  2P8.829

UNIT 10
COM=!5 W/O FUEL PINS W/O GAD!
'DEFINE THE FUEL PELLET
YCYLINDER 1  1    0.52500  381  0
'DEFINE THE PELLET-CLAD GAP
YCYLINDER 0  1    0.55000  381  0
'DEFINE THE FUEL ROD CLADDING
YCYLINDER 2  1    0.56524  381  0
'DEFINE THE FUEL ROD PITCH FILLED WITH WATER
CUBOID    8  1  2P1.40750  381  0  2P1.40750

UNIT 20
COM=!SPACE WITHIN FUEL ASSEMBLY LATTICE!
CUBOID    8  1  2P1.40750  381  0  2P1.40750

UNIT 30
COM=!ARRAY FOR COMPLETE FUEL ASSEMBLY!
ARRAY 2 3*0

UNIT 400
COM=!OUTER CONTAINER BODY AND LID!
'DEFINE INNER REGION OF THE OUTER CONTAINER
CUBOID   3  1   2P35.788    2P253.188  2P31.900
'INNER CONTAINER PLACEMENT WITHIN OUTER CONTAINER
HOLE 3         -22.938      -233.58    -14.024
'DEFINE WALLS OF THE OUTER CONTAINER AND LID
CUBOID   6  1   2P35.963    2P253.363  2P32.075

GLOBAL
UNIT 500
ARRAY 10 3*0
REFLECTOR  5  1  6R30.48  1
END GEOM

READ ARRAY
ARA=1 NUX=1 NUY=1 NUZ=2
FILL 1 2
END FILL
ARA=2 NUX=5  NUY=1 NUZ=5
FILL 10 10 10 10 10
```

```
     10 10 10 10 10
     10 10 10 10 10
     10 10 10 10 10
     10 10 10 10 10
END FILL
ARA=10 NUX=21 NUY=3  NUZ=24
FILL F400
END FILL
END ARRAY

READ BNDS ALL=VACUUM
END BNDS
END DATA
END
```

6.11.6 Single Package Loose Fuel Rods Hypothetical Accident Conditions Input

```
=CSAS25             PARM=SIZE=500000
RAJ-II CONTAINER, 8, HAC, 100% H2O, WORST CASE MODEL, 3.0056 CM PITCH, LOOSE
FUEL RODS, SINGLE PACKAGE
44GROUPNDF5                 LATTICECELL
UO2            1  DEN=10.74 1.0 293 92235 5.0 92238 95.0      END
POLYETHYLENE   2  DEN=0.925    1.0    293                     END
H2O            3  1.00               293                     END
UO2            4  DEN=10.4799  1.0 293 92235 3.25 92238 96.75 END
GD             4  DEN=0.17374  1.0 293                        END
O              4  DEN=0.026514 1.0 293                        END
H2O            5  1.00 293                                    END
SS304          6  1.00 293                                    END
H2O            7  DEN=1.00  1.0 293                           END
H2O            8  DEN=1.00     1.0    293                     END
ZR             9  1.00 293                                    END
ARBMAL2O3      0.25 2 0 1 0 13027 2 8016 3 10  0.49           END
ARBMSIO2       0.25 2 0 1 0 14000 1 8016 2 10  0.51           END
END COMP
SQUAREPITCH 3.0056 1.0500 1 8 1.13048 2 1.100 0               END
RAJ-II CONTAINER, 8, HAC, 100% H2O, WORST CASE MODEL, 3.0056 CM PITCH, LOOSE
FUEL RODS, SINGLE PACKAGE
READ PARM TME=400 GEN=400 NPG=2500 NSK=50 NUB=YES END PARM
READ GEOM

UNIT  1
COM=!CONTAINER INNER BOX!
'DEFINE GEOMETRY FOR SEPARATOR PLATE BETWEEN ASSEMBLY COMPARTMENTS
CUBOID     6  1  2P0.0875   225.20  -228.34  2P8.829
'DEFINE REGION FOR ASSEMBLY COMPARTMENTS WITHIN INNER BOX
CUBOID     7  1  2P17.713   225.20  -228.34  2P8.829
'PLACE THE FUEL ASSEMBLIES INSIDE INNER BOX
HOLE       30     -16.413  -190.50  -7.514
HOLE       30       1.386  -190.50  -7.514
'DEFINE WALLS FOR ASSEMBLY COMPARTMENTS WITHIN INNER BOX
CUBOID     6  1  2P17.800   225.20  -228.34  8.829  -8.9165
'DEFINE REGION OUTSIDE THE WALLS OF THE ASSEMBLY COMPARTMENTS
CUBOID     10 1  2P22.798   225.20  -228.34  8.829  -13.839
'DEFINE THE INNER WALLS OF THE BOX ENDS
CUBOID     6  1  2P22.798   225.34  -228.48  8.829  -13.979
'DEFINE INNER CORE OF BOX ENDS -8.1CM IN Y FOR TOTAL DEFORMATION
CUBOID     10 1  2P22.798   225.34  -233.44  8.829  -13.979
'DEFINE OUTER WALLS OF THE INNER BOX -8.1CM IN Y FOR TOTAL DEFORMATION
CUBOID     6  1  2P22.938   225.48  -233.58  8.829  -13.979

UNIT 2
COM=!INNER BOX LID!
'DEFINE INNER CORE OF INNER BOX LID -8.1CM IN Y FOR TOTAL DEFORMATION
CUBOID    10 1  2P22.798    2P229.39   2P2.48
'DEFINE WALLS FOR INNER BOX LID -8.1CM IN Y FOR TOTAL DEFORMATION
CUBOID    6  1  2P22.938    2P229.53   2P2.62

UNIT 3
```

```
COM=!INNER BOX WITH ENDS AND LID!
ARRAY 1 3*0

UNIT 10
COM=!5 W/O FUEL PINS W/O GAD!
'DEFINE THE FUEL PELLET
YCYLINDER 1  1    0.52500  381  0
'DEFINE THE PELLET-CLAD GAP
YCYLINDER 0  1    0.55000  381  0
'DEFINE THE FUEL ROD CLADDING
YCYLINDER 2  1    0.56524  381  0
'DEFINE THE FUEL ROD PITCH FILLED WITH WATER
CUBOID    8  1  2P1.50280  381  0  2P1.50280

UNIT 20
COM=!SPACE WITHIN FUEL ASSEMBLY LATTICE!
CUBOID    8  1  2P1.50280  381  0  2P1.50280

UNIT 30
COM=!ARRAY FOR COMPLETE FUEL ASSEMBLY!
ARRAY 2 3*0

GLOBAL
UNIT 400
COM=!OUTER CONTAINER BODY AND LID!
'DEFINE INNER REGION OF THE OUTER CONTAINER
'MINUS 4.7CM IN Y AND -2.4CM IN Z FOR TOTAL DEFORMATION
CUBOID    0  1   2P35.788  247.960  -253.190  29.500  -31.900
'INNER CONTAINER PLACEMENT WITHIN OUTER CONTAINER
HOLE 3          -22.938      -229.53    -14.024
'DEFINE WALLS OF THE OUTER CONTAINER AND LID
CUBOID    6  1   2P35.963  248.135  -253.365  29.675  -32.075

'GLOBAL
'UNIT 500
'ARRAY 10 3*0
REFLECTOR  5  1  6R30.48  1
END GEOM

READ ARRAY
ARA=1 NUX=1 NUY=1 NUZ=2
FILL 1 2
END FILL
ARA=2 NUX=5  NUY=1 NUZ=5
FILL 10 10 10 10 10
     10 10 10 10 10
     10 10 10 10 10
     10 10 10 10 10
     10 10 10 10 10
END FILL
ARA=10 NUX=14 NUY=2 NUZ=16
FILL F400
END FILL
END ARRAY

READ BNDS ALL=VACUUM
END BNDS
END DATA
```

6.11.7 Package Array Loose Fuel Rods Normal Conditions of Transport Input

```
=CSAS25             PARM=SIZE=500000
RAJ-II CONTAINER, 8, NTC, 100% H20, 2.8150 CM PITCH, LOOSE FUEL RODS, 21 x 3
x 24
44GROUPNDF5                 LATTICECELL
UO2            1  DEN=10.74    1.0  293 92235 5.0 92238 95.0   END
POLYETHYLENE   2  DEN=0.925    1.0  293                        END
H2O            3  1.00              293                        END
UO2            4  DEN=10.4799  1.0  293 92235 3.25 92238 96.75 END
GD             4  DEN=0.17374  1.0  293                        END
O              4  DEN=0.026514 1.0  293                        END
H2O            5  1.00              293                        END
SS304          6  1.00              293                        END
POLYETHYLENE   7  DEN=0.067967 1.0  293                        END
H2O            8  1.00              293                        END
H2O            9  1.00              293                        END
ARBMAL2O3      0.25 2 0 1 0 13027 2 8016 3 10  0.49            END
ARBMSIO2       0.25 2 0 1 0 14000 1 8016 2 10  0.51            END
ZR             11 1.00              293                        END
END COMP
SQUAREPITCH 2.8150 1.0500 1 8 1.13048 2 1.100 0               END
RAJ-II CONTAINER, 8, NTC, 100% H20, 2.8150 CM PITCH, LOOSE FUEL RODS, 21 x 3
x 24
READ PARM TME=400 GEN=400 NPG=2500 NSK=50 NUB=YES END PARM
READ GEOM

UNIT  1
COM=!CONTAINER INNER BOX!
'DEFINE GEOMETRY FOR SEPARATOR PLATE BETWEEN ASSEMBLY COMPARTMENTS
CUBOID     6  1  2P0.0875   2P228.34  2P8.829
'DEFINE REGION FOR ASSEMBLY COMPARTMENTS WITHIN INNER BOX
CUBOID     3  1  2P17.713   2P228.34  2P8.829
'INSERT FOAM POLYETHYLENE
HOLE       4      -8.9003       0.00    0.00
HOLE       5       8.9003       0.00    0.00
'DEFINE WALLS FOR ASSEMBLY COMPARTMENTS WITHIN INNER BOX
CUBOID     6  1  2P17.800   2P228.34    8.829  -8.9165
'DEFINE REGION OUTSIDE THE WALLS OF THE ASSEMBLY COMPARTMENTS
CUBOID    10  1  2P22.798   2P228.34    8.829  -13.839
'DEFINE THE INNER WALLS OF THE BOX ENDS
CUBOID     6  1  2P22.798   2P228.48    8.829  -13.979
'DEFINE INNER CORE OF BOX ENDS
CUBOID    10  1  2P22.798   2P233.44    8.829  -13.979
'DEFINE OUTER WALLS OF THE INNER BOX
CUBOID     6  1  2P22.938   2P233.58    8.829  -13.979

UNIT 2
COM=!INNER BOX LID!
'DEFINE INNER CORE OF INNER BOX LID
CUBOID    10 1  2P22.798    2P233.44   2P2.48
'DEFINE WALLS FOR INNER BOX LID
CUBOID    6  1  2P22.938    2P233.58   2P2.62
```

```
UNIT 3
COM=!INNER BOX WITH ENDS AND LID!
ARRAY 1 3*0

UNIT 4
COM=!FOAM POLYETHYLENE FOR LEFT ASSEMBLY COMPARTMENT!
CUBOID     3  1  2P7.0378   2P228.34  2P7.054
HOLE      30      -7.0376  -191.77   -7.0376
'FOAM POLYETHYLENE FOR ASSEMBLY COMPARTMENTS
CUBOID     7  1  2P8.8126   2P228.34  2P8.829

UNIT 5
COM=!FOAM POLYETHYLENE FOR RIGHT ASSEMBLY COMPARTMENT!
CUBOID     3  1  2P7.0378   2P228.34  2P7.054
HOLE      30      -7.0376  -191.77   -7.0376
'FOAM POLYETHYLENE FOR ASSEMBLY COMPARTMENT
CUBOID     7  1  2P8.8126   2P228.34  2P8.829

UNIT 10
COM=!5 W/O FUEL PINS W/O GAD!
'DEFINE THE FUEL PELLET
YCYLINDER 1  1    0.52500  381  0
'DEFINE THE PELLET-CLAD GAP
YCYLINDER 0  1    0.55000  381  0
'DEFINE THE FUEL ROD CLADDING
YCYLINDER 2  1    0.56524  381  0
'DEFINE THE FUEL ROD PITCH FILLED WITH WATER
CUBOID    8  1  2P1.40750  381  0  2P1.40750

UNIT 20
COM=!SPACE WITHIN FUEL ASSEMBLY LATTICE!
CUBOID    8  1  2P1.40750  381  0  2P1.40750

UNIT 30
COM=!ARRAY FOR COMPLETE FUEL ASSEMBLY!
ARRAY 2 3*0

UNIT 400
COM=!OUTER CONTAINER BODY AND LID!
'DEFINE INNER REGION OF THE OUTER CONTAINER
CUBOID   3  1   2P35.788    2P253.188  2P31.900
'INNER CONTAINER PLACEMENT WITHIN OUTER CONTAINER
HOLE 3         -22.938      -233.58    -14.024
'DEFINE WALLS OF THE OUTER CONTAINER AND LID
CUBOID   6  1   2P35.963    2P253.363  2P32.075

GLOBAL
UNIT 500
ARRAY 10 3*0
REFLECTOR  5  1  6R30.48  1
END GEOM

READ ARRAY
ARA=1 NUX=1 NUY=1 NUZ=2
FILL 1 2
END FILL
ARA=2 NUX=5  NUY=1 NUZ=5
```

```
FILL 10 10 10 10 10
     10 10 10 10 10
     10 10 10 10 10
     10 10 10 10 10
     10 10 10 10 10
END FILL
ARA=10 NUX=21 NUY=3  NUZ=24
FILL F400
END FILL
END ARRAY

READ BNDS ALL=VACUUM
END BNDS
END DATA
END
```

6.11.8 Package Array Loose Fuel Rods Hypothetical Accident Conditions Input

```
=CSAS25             PARM=SIZE=500000
RAJ-II CONTAINER, 8, HAC, 100% H2O, WORST CASE MODEL, 3.0056 CM PITCH, LOOSE
FUEL RODS, 10 X 1 X 10 ARRAY
44GROUPNDF5                 LATTICECELL
UO2            1  DEN=10.74 1.0 293 92235 5.0 92238 95.0      END
POLYETHYLENE   2  DEN=0.925    1.0    293                     END
H2O            3  1.00               293                     END
H2O            5  1.00 293                                    END
SS304          6  1.00 293                                    END
POLYETHYLENE   7  DEN=0.08000  1.0  293                       END
H2O            8  DEN=1.00     1.0    293                     END
ZR             9  1.00 293                                    END
ARBMAL2O3      0.25 2 0 1 0 13027 2 8016 3 10  0.49           END
ARBMSIO2       0.25 2 0 1 0 14000 1 8016 2 10  0.51           END
END COMP
SQUAREPITCH 3.0056 1.0500 1 8 1.13048 2 1.100 0               END
RAJ-II CONTAINER, 8, HAC, 100% H2O, WORST CASE MODEL, 3.0056 CM PITCH, LOOSE
FUEL RODS, 10 X 1 X 10 ARRAY
READ PARM TME=400 GEN=400 NPG=2500 NSK=50 NUB=YES END PARM
READ GEOM

UNIT  1
COM=!CONTAINER INNER BOX!
'DEFINE GEOMETRY FOR SEPARATOR PLATE BETWEEN ASSEMBLY COMPARTMENTS
CUBOID     6  1  2P0.0875   225.20  -228.34  2P8.829
'DEFINE REGION FOR ASSEMBLY COMPARTMENTS WITHIN INNER BOX
CUBOID     7  1  2P17.713   225.20  -228.34  2P8.829
'PLACE THE FUEL ASSEMBLIES INSIDE INNER BOX
HOLE       30     -15.913  -190.50  -7.014
HOLE       30       1.886  -190.50  -7.014
'DEFINE WALLS FOR ASSEMBLY COMPARTMENTS WITHIN INNER BOX
CUBOID     6  1  2P17.800   225.20  -228.34  8.829  -8.9165
'DEFINE REGION OUTSIDE THE WALLS OF THE ASSEMBLY COMPARTMENTS
CUBOID     10 1  2P22.798   225.20  -228.34  8.829  -13.839
'DEFINE THE INNER WALLS OF THE BOX ENDS
CUBOID     6  1  2P22.798   225.34  -228.48  8.829  -13.979
'DEFINE INNER CORE OF BOX ENDS -8.1CM IN Y FOR TOTAL DEFORMATION
CUBOID     10 1  2P22.798   225.34  -233.44  8.829  -13.979
'DEFINE OUTER WALLS OF THE INNER BOX -8.1CM IN Y FOR TOTAL DEFORMATION
CUBOID     6  1  2P22.938   225.48  -233.58  8.829  -13.979

UNIT 2
COM=!INNER BOX LID!
'DEFINE INNER CORE OF INNER BOX LID -8.1CM IN Y FOR TOTAL DEFORMATION
CUBOID    10 1  2P22.798    2P229.39   2P2.48
'DEFINE WALLS FOR INNER BOX LID -8.1CM IN Y FOR TOTAL DEFORMATION
CUBOID    6  1  2P22.938    2P229.53   2P2.62

UNIT 3
COM=!INNER BOX WITH ENDS AND LID!
ARRAY 1 3*0
```

```
UNIT 10
COM=!5 W/O FUEL PINS W/O GAD!
'DEFINE THE FUEL PELLET
YCYLINDER 1  1    0.52500  381  0
'DEFINE THE PELLET-CLAD GAP
YCYLINDER 0  1    0.55000  381  0
'DEFINE THE FUEL ROD CLADDING
YCYLINDER 2  1    0.56524  381  0
'DEFINE THE FUEL ROD PITCH FILLED WITH WATER
CUBOID    8  1  2P1.50280  381  0  2P1.50280

UNIT 20
COM=!SPACE WITHIN FUEL ASSEMBLY LATTICE!
CUBOID    8  1  2P1.50280  381  0  2P1.50280

UNIT 30
COM=!ARRAY FOR COMPLETE FUEL ASSEMBLY!
ARRAY 2 3*0

UNIT 40
COM=!5 W/O FUEL PINS W/O GAD LEFT SIDE FOAM!
'DEFINE THE FUEL PELLET
YCYLINDER 1  1    0.52500  381  0
'DEFINE THE PELLET-CLAD GAP
YCYLINDER 0  1    0.55000  381  0
'DEFINE THE FUEL ROD CLADDING
YCYLINDER 2  1    0.56524  381  0
'DEFINE THE FUEL ROD PITCH FILLED WITH WATER
CUBOID    8  1    1.50280  -1.00280 381  0  2P1.50280

UNIT 46
COM=!5 W/O FUEL PINS W/O GAD LEFT SIDE TOP FOAM!
'DEFINE THE FUEL PELLET
YCYLINDER 1  1    0.52500  381  0
'DEFINE THE PELLET-CLAD GAP
YCYLINDER 0  1    0.55000  381  0
'DEFINE THE FUEL ROD CLADDING
YCYLINDER 2  1    0.56524  381  0
'DEFINE THE FUEL ROD PITCH FILLED WITH WATER
CUBOID    8  1    1.50280  -1.00280 381  0    1.00280  -1.50280

UNIT 47
COM=!5 W/O FUEL PINS W/O GAD LEFT SIDE BOTTOM FOAM!
'DEFINE THE FUEL PELLET
YCYLINDER 1  1    0.52500  381  0
'DEFINE THE PELLET-CLAD GAP
YCYLINDER 0  1    0.55000  381  0
'DEFINE THE FUEL ROD CLADDING
YCYLINDER 2  1    0.56524  381  0
'DEFINE THE FUEL ROD PITCH FILLED WITH WATER
CUBOID    8  1    1.50280  -1.00280 381  0    1.50280  -1.00280

UNIT 50
COM=!5 W/O FUEL PINS W/O GAD RIGHT SIDE FOAM!
'DEFINE THE FUEL PELLET
YCYLINDER 1  1    0.52500  381  0
'DEFINE THE PELLET-CLAD GAP
```

```
YCYLINDER 0  1    0.55000  381  0
'DEFINE THE FUEL ROD CLADDING
YCYLINDER 2  1    0.56524  381  0
'DEFINE THE FUEL ROD PITCH FILLED WITH WATER
CUBOID    8  1    1.00280  -1.50280 381  0  2P1.50280

UNIT 56
COM=!5 W/O FUEL PINS W/O GAD RIGHT SIDE TOP FOAM!
'DEFINE THE FUEL PELLET
YCYLINDER 1  1    0.52500  381  0
'DEFINE THE PELLET-CLAD GAP
YCYLINDER 0  1    0.55000  381  0
'DEFINE THE FUEL ROD CLADDING
YCYLINDER 2  1    0.56524  381  0
'DEFINE THE FUEL ROD PITCH FILLED WITH WATER
CUBOID    8  1    1.00280  -1.50280 381  0    1.00280  -1.50280

UNIT 57
COM=!5 W/O FUEL PINS W/O GAD RIGHT BOTTOM SIDE FOAM!
'DEFINE THE FUEL PELLET
YCYLINDER 1  1    0.52500  381  0
'DEFINE THE PELLET-CLAD GAP
YCYLINDER 0  1    0.55000  381  0
'DEFINE THE FUEL ROD CLADDING
YCYLINDER 2  1    0.56524  381  0
'DEFINE THE FUEL ROD PITCH FILLED WITH WATER
CUBOID    8  1    1.00280  -1.50280 381  0    1.50280  -1.00280

UNIT 60
COM=!5 W/O FUEL PINS W/O GAD TOP SIDE FOAM!
'DEFINE THE FUEL PELLET
YCYLINDER 1  1    0.52500  381  0
'DEFINE THE PELLET-CLAD GAP
YCYLINDER 0  1    0.55000  381  0
'DEFINE THE FUEL ROD CLADDING
YCYLINDER 2  1    0.56524  381  0
'DEFINE THE FUEL ROD PITCH FILLED WITH WATER
CUBOID    8  1  2P1.50280  381  0    1.00280  -1.50280

UNIT 70
COM=!5 W/O FUEL PINS W/O GAD BOTTOM SIDE FOAM!
'DEFINE THE FUEL PELLET
YCYLINDER 1  1    0.52500  381  0
'DEFINE THE PELLET-CLAD GAP
YCYLINDER 0  1    0.55000  381  0
'DEFINE THE FUEL ROD CLADDING
YCYLINDER 2  1    0.56524  381  0
'DEFINE THE FUEL ROD PITCH FILLED WITH WATER
CUBOID    8  1  2P1.50280  381  0    1.50280  -1.00280

UNIT 400
COM=!OUTER CONTAINER BODY AND LID!
'DEFINE INNER REGION OF THE OUTER CONTAINER
'MINUS 4.7CM IN Y AND -2.4CM IN Z FOR TOTAL DEFORMATION
CUBOID    0  1   2P35.788  247.960  -253.190  29.500  -31.900
'INNER CONTAINER PLACEMENT WITHIN OUTER CONTAINER
HOLE 3          -22.938      -229.53    -14.024
```

```
'DEFINE WALLS OF THE OUTER CONTAINER AND LID
CUBOID    6  1   2P35.963  248.135  -253.365  29.675  -32.075

GLOBAL
UNIT 500
ARRAY 10 3*0
REFLECTOR  5  1  6R30.48  1
END GEOM

READ ARRAY
ARA=1 NUX=1 NUY=1 NUZ=2
FILL 1 2
END FILL
ARA=2 NUX=5  NUY=1 NUZ=5
FILL 47 70 70 70 57
     40 10 10 10 50
     40 10 10 10 50
     40 10 10 10 50
     46 60 60 60 56
END FILL
ARA=10 NUX=10 NUY=1 NUZ=10
FILL F400
END FILL
END ARRAY

READ BNDS ALL=VACUUM
END BNDS
END DATA
END
```

6.11.9 Data Tables for Figures in RAJ-II CSE

Table 6-24 Data for Figure 6-25 RAJ-II Array HAC Polyethylene Sensitivity

Output File Name	Case Description	Interspersed Moderator Density (g/cm^3)	Polyethylene Mass (kg)	k_{eff}	σ	$k_{eff} + 2\sigma$
rajII_hac_a10_no interspersedh2o_ polyethylenesens itivity_1.284cmpit ch_14X2X16	Atrium 10XP+	0.00	0	0.8715	0.0008	0.8731
"	Atrium 10XP+	0.00	10.9	0.8774	0.0009	0.8792
"	Atrium 10XP+	0.00	17.1	0.8813	0.0009	0.8831
"	Atrium 10XP+	0.00	20.4	0.8810	0.0008	0.8826
"	Atrium 10XP+	0.00	22.9	0.8822	0.0009	0.8840
"	Atrium 10XP+	0.00	25.4	0.8847	0.0008	0.8863
"	Atrium 10XP+	0.00	27.9	0.8860	0.001	0.8880
rajII_hac_g10_no interspersedh2o_ polyethylenesens itivity_pitch1.295 4cm_14X2X16	GNF 10 x 10	0.00	0	0.8863	0.0007	0.8877
"	GNF 10 x 10	0.00	10.9	0.8923	0.0008	0.8939
"	GNF 10 x 10	0.00	17.1	0.8940	0.0008	0.8956
"	GNF 10 x 10	0.00	20.4	0.8955	0.0007	0.8969
"	GNF 10 x 10	0.00	22.9	0.8975	0.0009	0.8993
"	GNF 10 x 10	0.00	25.4	0.8994	0.0008	0.9010
"	GNF 10 x 10	0.00	27.9	0.9001	0.0008	0.9017
rajII_hac_f9_10g adrods_refassy_ 14x2x16_polysen s	FANP 9x9	0.00	0	0.8728	0.0009	0.8746
rajII_hac_f9_10g adrods_refassy_ 14x2x16_polysen s	FANP 9x9	0.00	20	0.8756	0.0009	0.8774

rajII_hac_f9_10gadrods_refassy_14x2x16_channels	FANP 9x9	0.00	22	0.8755	0.0009	0.8773
rajII_hac_f9_10gadrods_refassy_14x2x16_polysens	FANP 9x9	0.00	24	0.8769	0.0007	0.8783
rajII_hac_f9_10gadrods_refassy_14x2x16_polysens	FANP 9x9	0.00	26	0.8758	0.0008	0.8774
rajII_hac_f9_10gadrods_refassy_14x2x16_polysens	FANP 9x9	0.00	28	0.8766	0.0008	0.8782
rajII_hac_f9_10gadrods_refassy_14x2x16_polysens	FANP 9x9	0.00	30	0.8776	0.0009	0.8794
rajII_hac_g9_10gadrods_refassy_14X2X16_polysens	GNF 9x9	0.00	0	0.8612	0.0008	0.8628
rajII_hac_g9_10gadrods_refassy_14X2X16_polysens	GNF 9x9	0.00	20	0.8661	0.0009	0.8679
rajII_hac_g9_10gadrods_refassy_14X2X16_channels	GNF 9x9	0.00	22	0.8659	0.0008	0.8676
rajII_hac_g9_10gadrods_refassy_14X2X16_polysens	GNF 9x9	0.00	24	0.8676	0.0007	0.8690
rajII_hac_g9_10gadrods_refassy_14X2X16_polysens	GNF 9x9	0.00	26	0.8670	0.0009	0.8688
rajII_hac_g9_10gadrods_refassy_14X2X16_polysens	GNF 9x9	0.00	28	0.8656	0.0009	0.8674
rajII_hac_g9_10gadrods_refassy_14X2X16_polysens	GNF 9x9	0.00	30	0.8702	0.0008	0.8718

rajII_hac_g8_nointerspersedh2o_polyethylenesensitivity_1.6256cm_14X2X16	GNF 8x8	0.00	0	0.8795	0.0009	0.8813
“	GNF 8x8	0.00	19	0.8865	0.0009	0.8883
“	GNF 8x8	0.00	22	0.8900	0.0009	0.8918
“	GNF 8x8	0.00	24	0.8892	0.0008	0.8908
“	GNF 8x8	0.00	26	0.8924	0.0008	0.8940
“	GNF 8x8	0.00	28	0.8915	0.0009	0.8933
“	GNF 8x8	0.00	30	0.8942	0.0009	0.8960

Table 6-25 Data for Figure 6-26 RAJ-II Fuel Rod Pitch Sensitivity Study

Output File Name	Interspersed Moderator Density (g/cm^3)	Polyethylene Mass (kg)	Pitch (cm)	k_{eff}	σ	$k_{eff} + 2\sigma$
rajII_hac_a10_nointerspersedh2o_pitchsensitivity_14X2X16	0.00	20.4	1.210	0.8301	0.0010	0.8321
"	0.00	20.4	1.284	0.8810	0.0008	0.8826
"	0.00	20.4	1.350	0.9245	0.0009	0.9263
"	0.00	20.4	1.376	0.9391	0.0008	0.9407
rajII_hac_g10_nointerspersedh2o_pitchsensitivity_14X2X16	0.00	20.4	1.1960	0.8394	0.0009	0.8412
"	0.00	20.4	1.2954	0.8955	0.0007	0.8969
"	0.00	20.4	1.350	0.9241	0.0008	0.9257
"	0.00	20.4	1.3760	0.9328	0.0008	0.9344
rajII_hac_f9_10gadrods_refassy_14x2x16_pitch	0.00	22	1.3389	0.8219	0.0008	0.8235
"	0.00	22	1.4478	0.8755	0.0009	0.8773
"	0.00	22	1.5028	0.8998	0.0008	0.9014
rajII_hac_f9_10gadrods_refassy_14x2x16_channels	0.00	22	1.5376	0.9126	0.0009	0.9144
rajII_hac_g9_10gadrods_refassy_14X2X16_pitchsens	0.00	22	1.3260	0.8073	0.0008	0.8089
"	0.00	22	1.4376	0.8659	0.0008	0.8676
"	0.00	22	1.5028	0.8929	0.0008	0.8944
rajII_hac_g9_10gadrods_refassy_14X2X16_channels	0.00	22	1.5376	0.9076	0.0009	0.9095
rajII_hac_g8_nointerspersedh2o_pitchsensitivity_14X2X16	0.00	22	1.4603	0.7968	0.0009	0.7986
"	0.00	22	1.6256	0.8900	0.0009	0.8918
"	0.00	22	1.6923	0.9216	0.0008	0.9232
"	0.00	22	1.7264	0.9384	0.0008	0.9400

Table 6-26 Data for Figure 6-27 RAJ-II Array HAC Pellet Diameter Sensitivity Study

Output File Name	Interspersed Moderator Density (g/cm^3)	Pellet Diameter (cm)	k_{eff}	σ	$k_{eff} + 2\sigma$
rajII_hac_a10_nointerspersedh2o_pelletodsensitivity_14X2X16	0	0.8000	0.8560	0.0008	0.8576
"	0	0.8400	0.8680	0.0009	0.8698
"	0	0.8882	0.8810	0.0008	0.8826
"	0	0.8941	0.8839	0.0008	0.8855
"	0	0.9200	0.8906	0.0008	0.8922
rajII_hac_g10_nointerspersedh2o_pelletodsensitivity_14X2X16	0	0.8000	0.8641	0.0009	0.8659
"	0	0.8400	0.8796	0.0009	0.8814
"	0	0.8882	0.8941	0.0008	0.8957
"	0	0.8941	0.8955	0.0007	0.8969
"	0	0.9200	0.9050	0.0008	0.9066
rajII_hac_f9_10gadrods_refassy_14x2x16_pelletod	0	0.8882	0.8600	0.0008	0.8616
"	0	0.9000	0.8633	0.0009	0.8651
rajII_hac_f9_10gadrods_refassy_14x2x16_channels	0	0.9398	0.8755	0.0009	0.8773
rajII_hac_f9_10gadrods_refassy_14x2x16_pelletod	0	0.9550	0.8799	0.0008	0.8815
"	0	0.9600	0.8817	0.0007	0.8831
rajII_hac_g9_10gadrods_refassy_14X2X16_pelletodsens	0	0.8882	0.8462	0.0008	0.8478
"	0	0.9000	0.8509	0.0009	0.8527
"	0	0.9398	0.8609	0.0008	0.8625
rajII_hac_g9_10gadrods_refassy_14X2X16_channels	0	0.9550	0.8659	0.0008	0.8676
rajII_hac_g9_10gadrods_refassy_14X2X16_pelletodsens	0	0.9600	0.8678	0.0008	0.8694
rajII_hac_g8_nointerspersedh2o_pelletodsensitivity_14X2X16	0	0.9200	0.8566	0.0008	0.8582
"	0	0.9550	0.8648	0.0008	0.8664
"	0	1.0000	0.8783	0.0008	0.8799
"	0	1.0439	0.8900	0.0009	0.8918
"	0	1.0700	0.8940	0.0009	0.8958

Table 6-27 Data for Figure 6-28 RAJ-II Array HAC Fuel Rod Clad ID Sensitivity Study

Output File Name	Moderator Density (g/cm^3)	Clad Inner Diameter (cm)	k_{eff}	σ	$k_{eff} + 2\sigma$
rajII_hac_a10_nointersperseedh2o_cladidsensitivity_14X2X16	0	0.8800	0.8760	0.0009	0.8778
"	0	0.8900	0.8805	0.0009	0.8823
"	0	0.9218	0.8810	0.0008	0.8826
"	0	0.9322	0.8813	0.0008	0.8829
"	0	1.0330	0.8855	0.0010	0.8875
rajII_hac_g10_nointersperseedh2o_cladidsensitivity_14X2X16	0	0.9000	0.8937	0.0010	0.8957
"	0	0.9218	0.8956	0.0008	0.8972
"	0	0.9322	0.8955	0.0007	0.8969
"	0	1.0185	0.8999	0.0008	0.9015
rajII_hac_f9_10gadrods_refassy_14x2x16_cladid	0	0.9400	0.8742	0.0009	0.8759
rajII_hac_f9_10gadrods_refassy_14x2x16_channels	0	0.9601	0.8755	0.0009	0.8773
rajII_hac_f9_10gadrods_refassy_14x2x16_cladid	0	0.9750	0.8760	0.0009	0.8777
"	0	0.9830	0.8768	0.0009	0.8786
"	0	1.0998	0.8789	0.0008	0.8804
rajII_hac_g9_10gadrods_refassy_14X2X16_cladid	0	0.9560	0.8641	0.0008	0.8657
"	0	0.9600	0.8643	0.0008	0.8659
"	0	0.9750	0.8660	0.0009	0.8678
rajII_hac_g9_10gadrods_refassy_14X2X16_channels	0	0.9830	0.8659	0.0008	0.8676
rajII_hac_g9_10gadrods_refassy_14X2X16_cladid	0	1.1100	0.8702	0.0008	0.8718
rajII_hac_g8_nointersperseedh2o_cladidsensitivity_14X2X16	0	1.0440	0.8894	0.001	0.8914
"	0	1.0719	0.8900	0.0009	0.8918
"	0	1.1000	0.8900	0.0009	0.8918
"	0	1.1500	0.8918	0.0008	0.8934
"	0	1.2192	0.8917	0.0008	0.8933

Table 6-28 Data for Figure 6-29 RAJ-II Array HAC Fuel Rod Clad OD Sensitivity Study

Output File Name	Moderator Density (g/cm^3)	Clad Outer Diameter (cm)	k_{eff}	σ	$k_{eff} + 2\sigma$
rajII_hac_a10_nointerspersedh2o_cladodsensitivity_14X2X16	0	0.9218	0.9051	0.0008	0.9067
"	0	1.0185	0.8858	0.0009	0.8876
"	0	1.0330	0.8810	0.0008	0.8826
"	0	1.1000	0.8647	0.0008	0.8663
"	0	1.1210	0.8604	0.0009	0.8622
rajII_hac_g10_nointerspersedh2o_cladodsensitivity_14X2X16	0	0.9322	0.9118	0.0008	0.9134
"	0	1.0185	0.8955	0.0007	0.8969
"	0	1.0330	0.8935	0.0008	0.8951
"	0	1.1000	0.8790	0.0008	0.8806
"	0	1.1210	0.8742	0.0009	0.8760
rajII_hac_f9_10gadrods_refassy_14x2x16_cladod	0	0.9601	0.8967	0.0008	0.8984
"	0	1.0330	0.8876	0.0008	0.8892
"	0	1.0998	0.8792	0.0008	0.8808
rajII_hac_f9_10gadrods_refassy_14x2x16_channels	0	1.1200	0.8755	0.0009	0.8773
rajII_hac_g9_10gadrods_refassy_14X2X16_cladod	0	0.9830	0.8857	0.0008	0.8873
"	0	1.0330	0.8791	0.0009	0.8809
rajII_hac_g9_10gadrods_refassy_14X2X16_channels	0	1.1100	0.8659	0.0008	0.8676
rajII_hac_g9_10gadrods_refassy_14X2X16_cladod	0	1.1200	0.8644	0.0010	0.8664
rajII_hac_g8_nointerspersedh2o_cladodsensitivity_14X2X16	0	1.0719	0.9120	0.0008	0.9136
"	0	1.1500	0.9030	0.0008	0.9046
"	0	1.2192	0.8900	0.0009	0.8918
"	0	1.2500	0.8832	0.0008	0.8848

Table 6-29 Data For Figure 6-37 Moderator Density Sensitivity Study for the RAJ-II HAC Worst Case Parameter Fuel Design

Output File Name	Moderator Density (g/cm^3)	Clad Inner Diameter (cm)	Clad Outer Diameter (cm)	k_{eff}	σ	$k_{eff} + 2\sigma$
rajII_hac_g10_worstcase_moderatordensity_14X2X16	0.00	0.9338	1.010	0.7154	0.0006	0.7166
“	0.02	0.9338	1.010	0.7349	0.0007	0.7363
“	0.04	0.9338	1.010	0.7526	0.0007	0.7540
“	0.06	0.9338	1.010	0.7686	0.0006	0.7698
“	0.08	0.9338	1.010	0.7820	0.0007	0.7834
“	0.10	0.9338	1.010	0.7933	0.0008	0.7949
“	0.20	0.9338	1.010	0.8383	0.0007	0.8397
“	0.40	0.9338	1.010	0.8908	0.0007	0.8922
“	0.60	0.9338	1.010	0.9182	0.0009	0.9200
“	0.80	0.9338	1.010	0.9319	0.0008	0.9335
“	1.00	0.9338	1.010	0.9404	0.0007	0.9418

Table 6-30 Data for Figure 6-39 RAJ-II Single Package Normal Conditions of Transport Results

Output File Name	Fuel Assembly Type	Moderator Density (g/cm^3)	Gadolinia Rod (#)	Pitch (cm)	Pellet OD (cm)	Clad Inner Diameter (cm)	Clad Outer Diameter (cm)	k_{eff}	σ	$k_{eff}+2\sigma$
rajII_normal_g10_5.0wtpct235u_h2odensitysensitivity_12gadrods_singlepackage	GNF 10 x 10	0.00	12	1.35	0.895	0.9338	1.010	0.2833	0.0005	0.2843
“	GNF 10 x 10	0.02	12	1.35	0.895	0.9338	1.010	0.2899	0.0005	0.2909
“	GNF 10 x 10	0.04	12	1.35	0.895	0.9338	1.010	0.2966	0.0006	0.2978
“	GNF 10 x 10	0.06	12	1.35	0.895	0.9338	1.010	0.3071	0.0006	0.3083
“	GNF 10 x 10	0.08	12	1.35	0.895	0.9338	1.010	0.3178	0.0006	0.3190
“	GNF 10 x 10	0.10	12	1.35	0.895	0.9338	1.010	0.3297	0.0005	0.3307
“	GNF 10 x 10	0.20	12	1.35	0.895	0.9338	1.010	0.3899	0.0006	0.3911
“	GNF 10 x 10	0.40	12	1.35	0.895	0.9338	1.010	0.4848	0.0008	0.4864
“	GNF 10 x 10	0.60	12	1.35	0.895	0.9338	1.010	0.5597	0.0008	0.5613
“	GNF 10 x 10	0.80	12	1.35	0.895	0.9338	1.010	0.6180	0.0007	0.6194
“	GNF 10 x 10	1.00	12	1.35	0.895	0.9338	1.010	0.6673	0.0008	0.6689

Table 6-31 Data for Figure 6-40 RAJ-II Single Package HAC Results

Output File Name	Fuel Assembly Type	Inner Container Moderator Density (g/cm^3)	Gadolinia Fuel Rods (#)	Pitch (cm)	Pellet OD (cm)	Clad Inner Diameter (cm)	Clad Outer Diameter (cm)	k_{eff}	σ	$k_{eff} + 2\sigma$
rajII_hac_g10__worstcase_moderatordensity_singlepackage	GNF 10 x 10	0.00	12	1.35	0.895	0.9338	1.010	0.2794	0.0005	0.2804
“	GNF 10 x 10	0.02	12	1.35	0.895	0.9338	1.010	0.2850	0.0005	0.2860
“	GNF 10 x 10	0.04	12	1.35	0.895	0.9338	1.010	0.2902	0.0005	0.2912
“	GNF 10 x 10	0.06	12	1.35	0.895	0.9338	1.010	0.2967	0.0006	0.2979
“	GNF 10 x 10	0.08	12	1.35	0.895	0.9338	1.010	0.3041	0.0006	0.3053
“	GNF 10 x 10	0.10	12	1.35	0.895	0.9338	1.010	0.3111	0.0005	0.3121
“	GNF 10 x 10	0.20	12	1.35	0.895	0.9338	1.010	0.3546	0.0006	0.3558
“	GNF 10 x 10	0.40	12	1.35	0.895	0.9338	1.010	0.4526	0.0007	0.4540
“	GNF 10 x 10	0.60	12	1.35	0.895	0.9338	1.010	0.5468	0.0008	0.5484
“	GNF 10 x 10	0.80	12	1.35	0.895	0.9338	1.010	0.6274	0.0008	0.6290
rajII_hac_g10_100pcth20density_worstcase_singlepackage	GNF 10 x 10	1.00	12	1.35	0.895	0.9338	1.010	0.6931	0.0010	0.6951

Table 6-32 Data for Figure 6-41 RAJ-II Package Array Under Normal Conditions of Transport Results

Output File Name	Fuel Assembly Type	Interspersed Moderator Density (g/cm^3)	Part Length Fuel Rods (#)	Pitch (cm)	Pellet OD (cm)	Clad Inner Diameter (cm)	Clad Outer Diameter (cm)	k_{eff}	σ	$k_{eff} + 2\sigma$
rajII_normal_g10_5.0wtpct235u_h2odensitysensitivity_12gadrods_21X3X24	GNF 10 x 10	0.00	12	1.35	0.895	0.9338	1.010	0.8519	0.0008	0.8535
“	GNF 10 x 10	0.02	12	1.35	0.895	0.9338	1.010	0.7962	0.0007	0.7976
“	GNF 10 x 10	0.04	12	1.35	0.895	0.9338	1.010	0.7441	0.0007	0.7455
“	GNF 10 x 10	0.06	12	1.35	0.895	0.9338	1.010	0.7054	0.0008	0.7070
“	GNF 10 x 10	0.08	12	1.35	0.895	0.9338	1.010	0.6726	0.0008	0.6742
“	GNF 10 x 10	0.10	12	1.35	0.895	0.9338	1.010	0.6427	0.0008	0.6443
“	GNF 10 x 10	0.20	12	1.35	0.895	0.9338	1.010	0.5500	0.0008	0.5516
“	GNF 10 x 10	0.40	12	1.35	0.895	0.9338	1.010	0.5254	0.0007	0.5268
“	GNF 10 x 10	0.60	12	1.35	0.895	0.9338	1.010	0.5690	0.0007	0.5704
“	GNF 10 x 10	0.80	12	1.35	0.895	0.9338	1.010	0.6206	0.0007	0.6220
“	GNF 10 x 10	1.00	12	1.35	0.895	0.9338	1.010	0.6683	0.0008	0.6699

Table 6-33 Data for Figure 6-42 RAJ-II Package Array Hypothetical Accident Condition Results

Output File Name	Fuel Assembly Type	Inner Container Moderator Density (g/cm^3)	Gadolinia-urania Fuel Rods (#)	Pitch (cm)	Pellet OD (cm)	Clad Inner Diameter (cm)	Clad Outer Diameter (cm)	k_{eff}	σ	$k_{eff} + 2\sigma$
rajII_hac_g10_12partlengthrods_worstcase_moderatordensity_10X1X10	GNF 10 x 10	0.00	12	1.35	0.895	0.9338	1.010	0.6375	0.0007	0.6389
“	GNF 10 x 10	0.02	12	1.35	0.895	0.9338	1.010	0.6470	0.0007	0.6484
“	GNF 10 x 10	0.04	12	1.35	0.895	0.9338	1.010	0.6567	0.0007	0.6581
“	GNF 10 x 10	0.06	12	1.35	0.895	0.9338	1.010	0.6648	0.0007	0.6662
“	GNF 10 x 10	0.08	12	1.35	0.895	0.9338	1.010	0.6734	0.0007	0.6748
“	GNF 10 x 10	0.10	12	1.35	0.895	0.9338	1.010	0.6822	0.0007	0.6836
“	GNF 10 x 10	0.20	12	1.35	0.895	0.9338	1.010	0.7226	0.0007	0.7240
“	GNF 10 x 10	0.40	12	1.35	0.895	0.9338	1.010	0.7976	0.0007	0.7990
“	GNF 10 x 10	0.60	12	1.35	0.895	0.9338	1.010	0.8561	0.0009	0.8579
“	GNF 10 x 10	0.80	12	1.35	0.895	0.9338	1.010	0.9005	0.0008	0.9021
“	GNF 10 x 10	1.00	12	1.35	0.895	0.9338	1.010	0.9378	0.0009	0.9396

Table 6-34 Data for Figure 6-45 RAJ-II Fuel Rod Transport in Stainless Steel Pipe

Output File Name	Fuel Assembly Type	Interspersed Moderator Density (g/cm^3)	Pitch (cm)	Fuel Rod (#)	Pellet OD (cm)	Clad Inner Diameter (cm)	Clad Outer Diameter (cm)	k_{eff}	σ	$k_{eff} + 2\sigma$
rajII_hac_8_worstcase_sspipe_14x2x16	8x8	1.000	1.1305	110	1.05	1.1000	1.1000	0.8793	0.0007	0.8807
“	8x8	1.000	1.6662	52	1.05	1.1000	1.1000	1.0235	0.0009	1.0253
“	8x8	1.000	1.9035	43	1.05	1.1000	1.1000	1.0440	0.0008	1.0456
rajII_hac_8_worstcase_sspipe_22fuelrods_14x2x16	8x8	1.000	2.5	22	1.05	1.1000	1.1000	0.8823	0.0008	0.8839
rajII_hac_8_worstcase_sspipe_14x2x16	8x8	1.000	2.937	14	1.05	1.1000	1.1000	0.7294	0.0008	0.7310
rajII_hac_9_worstcase_sspipe_14x2x16	9x9	1.000	1.0505	140	0.9600	1.0200	1.0200	0.8701	0.0006	0.8713
“	9x9	1.000	1.4770	72	0.9600	1.0200	1.0200	1.0515	0.0008	1.0531
“	9x9	1.000	2	38	0.9600	1.0200	1.0200	1.0056	0.0009	1.0074
rajII_hac_9_worstcase_sspipe_26fuelrods_14x2x16	9x9	1.000	2.25	26	0.9600	1.0200	1.0200	0.8900	0.0008	0.8916
rajII_hac_9_worstcase_sspipe_14x2x16	9x9	1.000	2.5432	22	0.9600	1.0200	1.0200	0.8416	0.0010	0.8436

Output File Name	Fuel Assembly Type	Interspersed Moderator Density (g/cm^3)	Pitch (cm)	Fuel Rod (#)	Pellet OD (cm)	Clad Inner Diameter (cm)	Clad Outer Diameter (cm)	k_{eff}	σ	$k_{eff} + 2\sigma$
rajII_hac_10_worstcase_sspipe_14x2x16	10x10	1.000	1.0305	144	0.9	1.000	1.000	0.8666	0.0007	0.8680
“	10x10	1.000	1.3213	84	0.9	1.000	1.000	1.0070	0.0008	1.0086
“	10x10	1.000	1.6416	56	0.9	1.000	1.000	1.0310	0.0011	1.0332
“	10x10	1.000	2.0484	30	0.9	1.000	1.000	0.8863	0.0008	0.8879

Table 6-35 Data for Figure 6-46 RAJ-II Fuel Rod Single Package Under Normal Conditions of Transport

Output File Name	Fuel Assembly Type	Interspersed Moderator Density (g/cm^3)	Pitch (cm)	Fuel Rod Number (#)	Pellet OD (cm)	Clad Inner Diameter (cm)	Clad Outer Diameter (cm)	k_{eff}	σ	$k_{eff} + 2\sigma$
rajII_normal_8_worstcasefuel_fuelrodtransport_moderatordensitysensitivity_singlepackage	8x8	0.00	2.815	25	1.05	1.1000	1.1000	0.1675	0.0004	0.1683
“	8x8	0.01	2.815	25	1.05	1.1000	1.1000	0.1675	0.0004	0.1683
“	8x8	0.02	2.815	25	1.05	1.1000	1.1000	0.1672	0.0004	0.1680
“	8x8	0.04	2.815	25	1.05	1.1000	1.1000	0.1702	0.0004	0.1710
“	8x8	0.06	2.815	25	1.05	1.1000	1.1000	0.1757	0.0005	0.1767
“	8x8	0.08	2.815	25	1.05	1.1000	1.1000	0.1845	0.0005	0.1855
“	8x8	0.10	2.815	25	1.05	1.1000	1.1000	0.1949	0.0004	0.1957
“	8x8	0.20	2.815	25	1.05	1.1000	1.1000	0.2567	0.0005	0.2577
“	8x8	0.40	2.815	25	1.05	1.1000	1.1000	0.3890	0.0007	0.3904
“	8x8	0.60	2.815	25	1.05	1.1000	1.1000	0.4967	0.0007	0.4981
“	8x8	0.80	2.815	25	1.05	1.1000	1.1000	0.5783	0.0009	0.5801
“	8x8	1.00	2.815	25	1.05	1.1000	1.1000	0.6365	0.0008	0.6381

Table 6-36 Data for Figure 6-47 RAJ-II Fuel Rod Transport Single Package HAC

Output File Name	Fuel Assembly Type	Interspersed Moderator Density (g/cm^3)	Pitch (cm)	Fuel Rod Number (#)	Pellet OD (cm)	Clad Inner Diameter (cm)	Clad Outer Diameter (cm)	k_{eff}	σ	$k_{eff} + 2\sigma$
rajII_hac_8_worstcase_fuelrod transport_moderatordensitysensitivity_singlepackage	8x8	0.00	3.0056	25	1.05	1.1000	1.1000	0.1769	0.0004	0.1777
“	8x8	0.01	3.0056	25	1.05	1.1000	1.1000	0.1761	0.0004	0.1769
“	8x8	0.02	3.0056	25	1.05	1.1000	1.1000	0.1767	0.0004	0.1775
“	8x8	0.04	3.0056	25	1.05	1.1000	1.1000	0.1778	0.0005	0.1788
“	8x8	0.06	3.0056	25	1.05	1.1000	1.1000	0.1794	0.0004	0.1802
“	8x8	0.08	3.0056	25	1.05	1.1000	1.1000	0.1829	0.0004	0.1837
“	8x8	0.10	3.0056	25	1.05	1.1000	1.1000	0.1876	0.0004	0.1884
“	8x8	0.20	3.0056	25	1.05	1.1000	1.1000	0.2306	0.0005	0.2316
“	8x8	0.40	3.0056	25	1.05	1.1000	1.1000	0.3718	0.0007	0.3732
“	8x8	0.60	3.0056	25	1.05	1.1000	1.1000	0.5062	0.0007	0.5076
“	8x8	0.80	3.0056	25	1.05	1.1000	1.1000	0.5980	0.0008	0.5996
“	8x8	1.00	3.0056	25	1.05	1.1000	1.1000	0.6532	0.0008	0.6548

Table 6-37 Data for Figure 6-48 RAJ-II Package Array Under Normal Conditions of Transport with Loose Fuel Rods

Output File Name	Fuel Assembly Type	Interspersed Moderator Density (g/cm^3)	Pitch (cm)	Fuel Rod Number (#)	Pellet OD (cm)	Clad Inner Diameter (cm)	Clad Outer Diameter (cm)	k_{eff}	σ	$k_{eff} + 2\sigma$
rajII_normal_8_worstcasefuel_fuelrodtransport_moderatordensitysensitivity_21X3X24	8x8	0.00	2.815	25	1.05	1.1000	1.1000	0.5055	0.0006	0.5067
“	8x8	0.01	2.815	25	1.05	1.1000	1.1000	0.5827	0.0006	0.5839
“	8x8	0.02	2.815	25	1.05	1.1000	1.1000	0.5931	0.0007	0.5945
“	8x8	0.04	2.815	25	1.05	1.1000	1.1000	0.5891	0.0007	0.5905
“	8x8	0.06	2.815	25	1.05	1.1000	1.1000	0.5719	0.0007	0.5733
“	8x8	0.08	2.815	25	1.05	1.1000	1.1000	0.5523	0.0009	0.5541
“	8x8	0.10	2.815	25	1.05	1.1000	1.1000	0.5291	0.0007	0.5305
“	8x8	0.20	2.815	25	1.05	1.1000	1.1000	0.4383	0.0006	0.4395
“	8x8	0.40	2.815	25	1.05	1.1000	1.1000	0.4300	0.0007	0.4314
“	8x8	0.60	2.815	25	1.05	1.1000	1.1000	0.5079	0.0008	0.5095
“	8x8	0.80	2.815	25	1.05	1.1000	1.1000	0.5817	0.0008	0.5833
“	8x8	1.00	2.815	25	1.05	1.1000	1.1000	0.6365	0.0008	0.6381

Table 6-38 Data for

Figure 6-49 RAJ-II Fuel Rod Transport Under HAC

Output File Name	Fuel Assembly Type	Interspersed Moderator Density (g/cm^3)	Pitch (cm)	Fuel Rod Number (#)	Pellet OD (cm)	Clad Inner Diameter (cm)	Clad Outer Diameter (cm)	k_{eff}	σ	$k_{eff} + 2\sigma$
rajII_hac_8_worstcase_fuelrodtransport_100pcth2odensity_10x1x10	8x8	0.00	3.0056	25	1.05	1.1000	1.1000	0.3230	0.0005	0.3240
“	8x8	0.01	3.0056	25	1.05	1.1000	1.1000	0.3479	0.0005	0.3489
“	8x8	0.02	3.0056	25	1.05	1.1000	1.1000	0.3752	0.0007	0.3766
“	8x8	0.04	3.0056	25	1.05	1.1000	1.1000	0.4007	0.0006	0.4019
“	8x8	0.06	3.0056	25	1.05	1.1000	1.1000	0.4287	0.0006	0.4299
“	8x8	0.08	3.0056	25	1.05	1.1000	1.1000	0.4556	0.0006	0.4568
“	8x8	0.10	3.0056	25	1.05	1.1000	1.1000	0.5743	0.0009	0.5761
“	8x8	0.20	3.0056	25	1.05	1.1000	1.1000	0.7416	0.0009	0.7434
“	8x8	0.40	3.0056	25	1.05	1.1000	1.1000	0.8264	0.0008	0.8280
“	8x8	0.60	3.0056	25	1.05	1.1000	1.1000	0.8660	0.0008	0.8676
“	8x8	0.80	3.0056	25	1.05	1.1000	1.1000	0.8731	0.0007	0.8745
“	8x8	1.00	3.0056	25	1.05	1.1000	1.1000	0.3752	0.0007	0.3766

6.11.10 Summary of Experiments

This document provides a summary of the experiments used in Reference 3 to determine the SCALE 4.4a bias. Trending data is either from the original experiments or calculated herein, i.e., H/U values, have been added to the data. Note that in most cases the experimental $k_{eff} \pm \sigma$ from Reference 3 do not have a reference. If data from the original experiment and/or data from the International Handbook of Evaluated Criticality Safety Benchmark Experiments (see Reference 4) provided these values, it was so noted or additional values provided.

The USL method of NUREG/CR-6361 (Reference 7) has the tacit assumption that the experimental k is 1.0000. Likewise, it does not account for the uncertainty in the experimental values. It is recommended that the procedure discussed in NUREG/CR-6698, "Guide for Validation of Nuclear Criticality Safety Calculational Methodology," be considered. The document has the following definitions for the calculated' values used for the bias evaluation:

$$k_{norm} = k_{calc}/k_{exp} \text{ and}$$

$$\sigma_{norm} = [(\sigma_{calc})^2 + (\sigma_{exp})^2]^{1/2}$$

This will normalize the calculated to experimental to account for uncertainties in the experimental values.

Note: The reference numbers quoted in the following sections are references listed in each section, rather than those listed in Section 6.11.

6.11.10.1 Critical Configurations

6.11.10.1.1 Water-Moderated U(4.31)O2 Fuel Rods in 2.54-cm Square-Pitched Arrays

References:

1. "Critical Separation Between Subcritical Clusters of 4.29 Wt% U-235 Enriched UO_2 Rods in Water With Fixed Neutron Poisons," S.R. Bierman, B. M. Durst, E.D. Clayton, Battelle Pacific Northwest Laboratories, NUREG/CR-0073(PNL-2695).
2. "Water-Moderated U(4.31)O_2 Fuel Rods in 2.54-cm Square-Pitched Arrays," V.F. Dean, Evaluator, International Handbook of Evaluated Criticality Safety Benchmark Experiments," NEA/NSC/DOC(95)03, Sept 2001, Nuclear Energy Agency.
3. "Software Validation Document, EMF-2670, PC-SCALE 4.4a V&V", C.D. Manning, EMF-2670, Rev. 1, 11/26/2002, Framatome ANP.

Reference 3 uses the data from this set of experiments as part of a heterogeneous uranium oxide set of benchmark calculations. Table 6 of that reference provides some information on the experimental configuration and Tables 7 and 9 provide results for the 238 and 44 group Scale

4.4a cross-sections, respectively. Table 6-39 Summary of Information for Experiment below provides a summary of the benchmark information from References 1 and 2. The rod and oxide dimensional and material information came from Reference 1. The enrichment quoted in Reference 1 was changed in Reference 2 due to a later chemical analysis of the fuel rods used in the experiment. Thus, the table uses the 4.31 value from Reference 2 rather than 4.29 quoted in Reference 1. The temperatures of the experiments were not included in Reference 1 and were not explicitly noted at the time of the experiment. The authors of Reference 2 obtained log books from similar experiments at PNL that showed temperatures ranging from ~18°C to ~25°C. From these data Reference 2 inferred an average value of ~22°C which is listed here. The value used in the calculations of Reference 3 is not currently known. The temperature value is used to calculate the hydrogen atom density and a deviation of a few degrees will not significantly change the results. The U and H atom densities used a value of Avogadro's number of 0.6022142E-24. The H/U value applies only to the fuel cluster. Table 6-42 Urania Gadolinia Experiment Summary[a] contains cases using cell-weighted models, 'x' added to case ID. These are included for completeness and should not be included in the normal benchmarking trending.

Table 6-39 Summary of Information for Experiment

Pellet OD, cm	1.2649	Enrichment, wt%	4.31[a]	V_{H2O}/V_{oxide}	3.883228
Rod OD, cm	1.2827	Oxide Density, g/cm^3	94.9	U-235 Atom Density	1.0125E-03
Rod OD, cm	1.4147	Temperature, ^{o}C	22[b]	H Atom Density	0.066724
Rod Pitch, cm	2.54	Water Density, g/cm^3	0.9978	H/U	255.92
Clad Material	Aluminum	Boron, ppm	0.0		

a) Redefined from 4.29 in Reference 2 due to fuel evaluation after publication of Reference 1.
b) Not defined in Reference 1, assumed in Reference 2 based upon inference from data notebooks of experiments.

Table 6-40 Parameters for Benchmark Cases for SCALE 4.4a 44 Group Cross-Section Set

Case ID[c]	Lattice[a]	Spacing[a] between clusters, cm		Experimental k_{eff} and σ				SCALE 4.4a 44 Group Cross-Section Calculated k_{eff} and σ				Absorber Plates in Water Gap
		Rod-rod	Cell-cell	k_{eff}[b]	σ[b]	k_{eff}[c]	σ[c]	k_{eff}[d]	σ[d]	AFG[d]	EALF[d] (ev)	
c004.out	15x8	11.72	10.62	1.0000	0.0020	0.9997	0.0020	0.9971	0.0008	35.772	0.112667	None
c005b.out	15x8	10.77	9.64	1.0000	0.0180	0.9997	0.0020	0.9960	0.0008	35.763	0.112942	0.625 cm Al plates
c006b.out	15x8	10.72	9.59	1.0000	0.0019	0.9997	0.0020	0.9960	0.0008	35.768	0.112841	0.625 cm Al plates
c007a.out	15x8	9.76	8.63	1.0000	0.0021	0.9997	0.0020	0.9966	0.0008	35.768	0.112705	0.302 cm SS 304L plates
c008b.out	15x8	9.22	8.09	1.0000	0.0021	0.9997	0.0020	0.9948	0.0008	35.755	0.113485	0.302 cm SS 304L plates
c009b.out	15x8	8.08	6.95	1.0000	0.0021	0.9997	0.0020	0.9963	0.0008	35.748	0.113698	0.298 cm 304L plates with 1.05 wt% B
c010b.out	15x8	6.60	5.47	1.0000	0.0021	0.9997	0.0020	0.9980	0.0008	35.728	0.114519	0.298 cm 304L plates with 1.05 wt% B
c011b.out	15x8	7.90	6.77	1.0000	0.0021	0.9997	0.0020	0.9983	0.0009	35.750	0.113450	0.298 cm 304L plates with 1.62 wt% B
c012b.out	15x8	5.76	4.63	1.0000	0.0021	0.9997	0.0020	0.9975	0.0007	35.729	0.114508	0.298 cm 304L plates with 1.62 wt% B
c013b.out	15x8	9.65	8.52	1.0000	0.0021	0.9997	0.0020	0.9956	0.001	35.768	0.112832	0.485 cm, SS 304L plates
c014b.out	15x8	8.58	7.45	1.0000	0.0021	0.9997	0.0020	0.9970	0.0009	35.745	0.113819	0.485 cm, SS 304L plates
c029b.out	15x8	10.90	9.77	1.0000	0.0021	0.9997	0.0020	0.9967	0.0008	35.770	0.112874	0.652 cm, Zircaloy-4 plates
c030b.out	15x8	10.86	9.73	1.0000	0.0021	0.9997	0.0020	0.9977	0.0009	35.767	0.112860	0.652 cm, Zircaloy-4 plates
c031b.out	15x8	7.672	6.55	1.0000	0.0021	0.9997	0.0020	0.9975	0.0008	35.727	0.114536	0.723 cm, Boral plates, 28.7 wt% B

a) From Reference 1. The 'rod surface-to-rod' surface spacing is reported in Reference 1. Reference 2 (p. 9) provides the cell-to-cell spacing for selected experiments from Reference 1 as: (rod-rod) – (pitch) + (rod diameter). This formula was applied to all above values even though some 'rod-rod' may be 'array plate-to-plate'.

b) Values from Reference 3, Table 6, p. 42. Source of σ values is not listed in this reference.

c) Values from Reference 2, p. 23 based upon calculational uncertainties in parameters and assumptions in the benchmark models of the reference. Note that Reference 2 only includes 4 of the cases from Reference 1 listed above. Here it is assumed that the values listed above apply to all cases.

d) From Reference 3, Table 9, p. 61 for 44 group cross-sections. Table 7 in this reference has values for 238 group cross-sections.

Table 6-41 Parameters for Benchmark Cases for SCALE 4.4a 238 Group Cross-Section Set

Case ID[c]	Lattice[a]	Cluster Spacing[a], cm		Experimental k_{eff} and σ				SCALE 4.4a 238 Group Cross-Section Calculated k_{eff} and σ				Absorber Plates in Water Gap
		Rod-rod	Cell-cell	k_{eff}[b]	σ[b]	k_{eff}[c]	σ[c]	k_{eff}[d]	σ[d]	AFG[d]	EALF[d] (ev)	
c001x.out[e]	10x11.51	0.0	0.0	1.0000	0.0021	0.9997	0.0020	0.9987	0.0008	208.112	0.108721	--
c002x.out	8x16.37	0.0	0.0	1.0000	0.0021	0.9997	0.0020	0.9993	0.0008	208.157	0.108277	--
c003x.out	9x13.35	0.0	0.0	1.0000	0.0021	0.9997	0.0020	1.0015	0.0010	208.136	0.108496	--
c004.out	15x8	11.72	10.62	1.0000	0.0020	0.9997	0.0020	0.9930	0.0010	207.568	0.114058	None
c005b.out	15x8	10.77	9.64	1.0000	0.0180	0.9997	0.0020	0.9931	0.0008	207.550	0.114504	0.625 cm Al plates
c006b.out	15x8	10.72	9.59	1.0000	0.0019	0.9997	0.0020	0.9941	0.0009	207.508	0.114748	0.625 cm Al plates
c007a.out	15x8	9.76	8.63	1.0000	0.0021	0.9997	0.0020	0.9944	0.0008	207.547	0.114468	0.302 cm SS 304L plates
c007x.out	15x8	9.76	8.63	1.0000	0.0021	0.9997	0.0020	1.0010	0.0008	208.273	0.107285	0.302 cm SS 304L plates
c008b.out	15x8	9.22	8.09	1.0000	0.0021	0.9997	0.0020	0.9931	0.0007	207.487	0.114939	0.302 cm SS 304L plates
c008x.out	15x8	9.22	8.09	1.0000	0.0021	0.9997	0.0020	0.9981	0.0008	208.220	0.107758	0.302 cm SS 304L plates
c009b.out	15x8	8.08	6.95	1.0000	0.0021	0.9997	0.0020	0.9928	0.0008	207.472	0.114907	0.298 cm 304L plates with 1.05 wt% B
c010b.out	15x8	6.60	5.47	1.0000	0.0021	0.9997	0.0020	0.9952	0.0009	207.373	0.115896	0.298 cm 304L plates with 1.05 wt% B
c011b.out	15x8	7.90	6.77	1.0000	0.0021	0.9997	0.0020	0.9964	0.0008	207.507	0.114703	0.298 cm 304L plates with 1.62 wt% B
c012b.out	15x8	5.76	4.63	1.0000	0.0021	0.9997	0.0020	0.9938	0.0009	207.364	0.116224	0.298 cm 304L plates with 1.62 wt% B
c013b.out	15x8	9.65	8.52	1.0000	0.0021	0.9997	0.0020	0.9953	0.0008	207.495	0.114944	0.485 cm, SS 304L plates
c013x.out	15x8	9.65	8.52	1.0000	0.0021	0.9997	0.0020	1.0002	0.0009	208.270	0.107272	0.485 cm, SS 304L plates
c014b.out	15x8	8.58	7.45	1.0000	0.0021	0.9997	0.0020	0.9942	0.0009	207.484	0.115038	0.485 cm, SS 304L plates
c014x.out	15x8	8.580	7.45	1.0000	0.0021	0.9997	0.0020	1.0018	0.0008	208.211	0.107849	0.485 cm, SS 304L plates
c029b.out	15x8	10.90	9.77	1.0000	0.0021	0.9997	0.0020	0.9942	0.0008	207.549	0.114428	0.652 cm, Zircaloy-4 plates
c030b.out	15x8	10.86	9.73	1.0000	0.0021	0.9997	0.0020	0.9946	0.0008	207.508	0.114783	0.652 cm, Zircaloy-4 plates
c031b.out	15x8	7.672	6.55	1.0000	0.0021	0.9997	0.0020	0.9951	0.0008	207.387	0.115885	0.723 cm, Boral plates, 28.7 wt% B

a) From Reference 1. The 'rod surface-to-rod' surface spacing is reported in Reference 1. Reference 2 (p. 9) provides the cell-to-cell spacing for selected experiments from Reference 1 as: (rod-rod) – (pitch) + (rod diameter). This formula was applied to all above values even though some 'rod-rod' may be 'array plate-to-plate'.
b) Values from Reference 3, Table 6, p. 42. Source of σ values is not listed in this reference.
c) Values from Reference 2, p. 23 based upon calculational uncertainties in parameters and assumptions in the benchmark models of the reference. Note that Reference 2 only includes 4 of the cases from Reference 1 listed above. Here it is assumed that the values listed above apply to all cases.
d) From Reference 3, Table 9, p. 61 for 44 group cross-sections. Table 7 in this reference has values for 238 group cross-sections.
e) From Reference 3, Table 6. The 'x' before '.out' means the case is a cell weighted model.

6.11.10.1.2 Urania Gadolinia Experiments

References:

4. FANP Doc: 32-5012895-00, "Validation Report – SCALEPC-44A Urania-Gadolinia Experiments," R.S. Harding.
5. "Urania Gadolinia: Nuclear Model Development and Critical Experiment Benchmark," L.W. Newman, Babcock & Wilcox for DOE, DOE/ET/34212-41, BAW-1910, April 1984.
6. "Development and Demonstration of An Advanced Extended-Burnup Fuel Assembly Design Incorporating Urania-Gadolinia," L.W. Newman, Babcock & Wilcox for DOE, DOE/ET/34212-41, BAW-1681-2, August 1982.

Reference 4 uses the experimental data from References 5 and 6 to construct benchmark cases for SCALE 4.4a. Table 6-42 Urania Gadolinia Experiment Summary[a] summarizes the experimental configuration data that form the basis for the KENO V.a models. Table 6-44 Urania Gadolinia Critical Experiment Trending Data provides trending parameters for this set of experiments. Table 6-43 Experimental Parameters for Calculating U-235 and H Atom Densities lists the basis for the H/U values tabulated in Table 6-44 Urania Gadolinia Critical Experiment Trending Data. Table 6-45 Urania Gadolinia Benchmark k_{eff} Data provides the experimental and calculated results for the 44 and 238 group SCALE 4.4a cross-section sets from Reference 3.

Table 6-42 Urania Gadolinia Experiment Summary[a]

Parameter	Rod 1	Rod 2	Rod 3
U-235 wt%	4.02	2.459	1.944
Gadolinia Wt%	-	-	4
Pellet density[b], g/cm^3	9.46	10.218	10.328
Pellet OD, cm	1.1265	1.03	1.0296
Rod OD, cm	1.1265	1.044	1.0439
Rod OD, cm	1.2078	1.206	1.2065
Rod Pitch, cm	1.6358	1.6358	1.6358
Clad Material	SS	Al	Al
$V_{fuel/cell}$	0.996654	0.833229	0.832582
$V_{H2O/cell}$	1.530044	1.533399	1.532452
Water boron factor[c]		0.99928	
Temperature[d], °C		22	
Water density, g/cm^3		0.99777	

a) From Reference 4.
b) Based upon rod mass and fuel volume in rod.
c) A factor to correct water density from 25 °C to 20 °C. Boron ppm is based upon 25 °C measurements. See Reference 4, p. 9.
d) Not specified explicitly for this set of experiments. This value is inferred from temperature data in Reference 7.

Table 6-43 Experimental Parameters for Calculating U-235 and H Atom Densities

Case ID	Number of Different Type Rods in each Critical Configuration(Reference 1 Table 1))						Core Volume[a]		Atom Density[a]	
	2.46 Wt%	4.02 Wt%	1.94 Wt% (Gd)	Water	Misc	Core Total	Fuel	Water	U-235	H
core01.out	4808	-	-	153	-	4961	4006.16	7765.83	5.67711E-04	0.066676
core03.out	4788	-	-	137	16	4941	3989.50	7692.42	5.67711E-04	0.066676
core05.out	4780	-	28	153	-	4961	4006.15	7765.90	5.67061E-04	0.066676
core5a.out	4776	-	32	153	-	4961	4006.14	7765.91	5.66968E-04	0.066676
core5b.out	4780	-	28	153	-	4961	4006.15	7765.90	5.67061E-04	0.066676
core08.out	4772	-	36	153	-	4961	4006.14	7765.92	5.66875E-04	0.066676
core10.out	4772	-	36	137	16	4961	4006.14	7723.11	5.66875E-04	0.066676
core12a.out	3920	888	-	153	-	4961	4151.29	7768.81	6.21492E-04	0.066676
core14.out	3920	860	28	153	-	4961	4146.69	7768.79	6.19146E-04	0.066676
core16.out	3920	852	36	153	-	4961	4145.38	7768.78	6.18475E-04	0.066676
core18.out	3676	944	-	180	-	4800	4003.79	7553.60	6.27210E-04	0.066676
core19.out	3676	928	16	180	-	4800	4001.17	7553.58	6.25815E-04	0.066676
core20.out	3676	912	32	180	-	4800	3998.54	7553.57	6.24420E-04	0.066676

a) Calculated values. Atom densities based upon Avogadro's number of 0.6022142E-24

Table 6-44 Urania Gadolinia Critical Experiment Trending Data

Case Name	Clad[a]	Lattice[a]	wt% 235[a]	Boron, ppm[a]	Vh2o/Vfuel[b]	H/U[b]	k_{eff}[c]	Sigma[c]	Rod Configurations[a]
core01.out	Al	15x15	2.46	1337.9	1.9385	227.67	1.0002	0.0005	0
core03.out	Al	15x15	2.46/1.94	1239.3	1.9282	226.46	1.0000	0.0006	20-4%Gd
core05.out	Al	15x15	2.46/1.94	1208.0	1.9385	227.93	0.9999	0.0006	28-4%Gd
core5a.out	Al	15x15	2.46/1.94	1191.3	1.9385	227.97	0.9999	0.0006	32-4%Gd
core5b.out	Al	15x15	2.46/1.94	1207.1	1.9385	227.93	0.9999	0.0006	28-4%Gd
core08.out	Al	15x15	2.46/1.94	1170.7	1.9385	228.01	1.0083	0.0012	36-4%Gd
core10.out	Al	15x15	2.46/1.94	1177.1	1.9278	226.75	1.0001	0.0009	36-4%Gd+3 void rods
core12a.out	SS/Al	15x15	4.02/2.46	1899.3	1.8714	200.77	1.0000	0.0007	4.02 inner/2.456 outer
core14.out	SS/Al	15x15	4.02/2.46/1.94	1653.8	1.8735	201.76	1.0030	0.0009	28-4%Gd
core16.out	SS/Al	15x15	4.02/2.46/1.94	1579.4	1.8741	202.04	1.0001	0.0010	36-4%Gd
core18.out	SS/Al	16x16	4.02/2.46	1776.8	1.8866	200.56	1.0002	0.0011	CE Large Guide Tubes
core19.out	SS/Al	16x16	4.02/2.46/1.94	1628.3	1.8878	201.14	1.0002	0.0010	16-4%Gd
core20.out	SS/Al	16x16	4.02/2.46/1.94	1499.0	1.8891	201.72	1.0002	0.0010	Zone + 32-4%

a) Reference 4.
b) Calculated values from Table 5.
c) Reference 3, Table 6. The source of these values is not documented in the reference.

Table 6-45 Urania Gadolinia Benchmark k_{eff} Data

Case ID	Experimental k_{eff} and σ		SCALE 4.4a 44 Group Cross-Section Calculated k_{eff} and σ				SCALE 4.4a 238 Group Cross-Section Calculated k_{eff} and σ			
	k_{eff}[a]	σ[a]	k_{eff}[b]	σ[b]	AFG[b]	EALF[b] (ev)	k_{eff}[b]	σ[b]	AFG[b]	EALF[b] (ev)
core01.out	1.0002	0.0005	0.9955	0.0006	33.8930	0.2530	0.9952	0.0007	197.6190	0.2567
core03.out	1.0000	0.0006	0.9963	0.0006	33.9190	0.2499	0.9943	0.0006	197.6810	0.2547
core05.out	0.9999	0.0006	0.9968	0.0006	33.9280	0.2493	0.9935	0.0006	197.6840	0.2543
core5a.out	0.9999	0.0006	0.9963	0.0005	33.9270	0.2494	0.9940	0.0006	197.6850	0.2547
core5b.out	0.9999	0.0006	0.9959	0.0006	33.9160	0.2504	0.9941	0.0007	197.6280	0.2558
core08.out	1.0083	0.0012	0.9958	0.0006	33.9200	0.2503	0.9928	0.0005	197.7470	0.2534
core10.out	1.0001	0.0009	0.9956	0.0006	33.9130	0.2512	0.9922	0.0007	197.6080	0.2562
core12a.out	1.0000	0.0007	0.9982	0.0006	32.8910	0.3644	0.9950	0.0006	193.1960	0.3697
core14.out	1.0030	0.0009	0.9976	0.0007	33.0670	0.3421	0.9942	0.0007	193.8910	0.3488
core16.out	1.0001	0.0010	0.9969	0.0007	33.1010	0.3376	0.9941	0.0007	194.1570	0.3412
core18.out	1.0002	0.0011	0.9975	0.0007	32.8960	0.3645	0.9950	0.0007	193.2390	0.3684
core19.out	1.0002	0.0010	0.9973	0.0006	33.0140	0.3489	0.9941	0.0007	193.6610	0.3553
core20.out	1.0002	0.0010	0.9969	0.0007	33.1050	0.3382	0.9950	0.0006	194.0850	0.3425

a) Values from Reference 3, Table 6, p. 42. Source of σ values is not documented in this reference.
b) From Reference 3, Table 9, p. 61 for 44 group cross-sections. Table 7 in this reference has values for 238 group cross-sections.

6.11.10.1.3 Critical Experiments Supporting Close Proximity Water Storage of Power Reactor Fuel

References:

7. FANP Doc. 32-5012896-00, "Validation Report – SCALEPC-44A Close Proximity Experiments," R.S. Harding.
8. "Critical Experiments Supporting Close Proximity Water Storage of Power Reactor Fuel," M.N. Baldwin, etal., BAW-1484-7, July 1979.

Reference 7 uses the experimental data from Reference 8 to construct benchmark cases for SCALE 4.4a. Table 6-46 Close Proximity Experiment Summary[a] summarizes the experimental configuration data that form the basis for the KENO V.a models. Table 6-47 Close Proximity Experiment Trending Data provides trending parameters for this set of experiments. Table 6-48 Close Proximity Experiment k_{eff} Data provides the experimental and calculated results for the 44 and 238 group SCALE 4.4a cross-section sets from Reference 3.

Table 6-46 Close Proximity Experiment Summary[a]

U-235 wt%	2.459	Fuel Lattice	14x14
Pellet Density[b], g/cm^3	10.218	Clad Material	Al
Pellet OD, cm	1.030	Vfuel/cell	0.8332
Rod OD, cm	1.044	Vh2o/cell	1.5342
Rod OD, cm	1.206	Vh2o/Vf	1.8413
Rod Pitch, cm	1.636		

a) From Reference 7.
b) Based upon rod mass and fuel volume in rod.

Table 6-47 Close Proximity Experiment Trending Data

Case ID	Cluster Spacing[a], cm	Temp[a], °C	Boron[a], ppm	Boron Factors[b]	Water density[b], g/cm^3	Atom Density[c]		H/U[c]	Absorbers[a]
						U-235	H		
aclp1.out	--	21	0	0.999788	0.99799	5.6991E-04	0.066725	215.57	--
aclp2.out	0.000	18.5	1037	1.000298	0.99850	5.6991E-04	0.066793	215.79	--
aclp3.out	1.636	18	764	1.000392	0.99860	5.6991E-04	0.066806	215.83	H2O
aclp4.out	1.636	17	0	1.000572	0.99878	5.6991E-04	0.066830	215.91	84 B4C pins/H2O
aclp5.out	3.272	17.5	0	1.000483	0.99869	5.6991E-04	0.066818	215.87	64 B4C pins/H2O
aclp6.out	3.272	17.5	0	1.000483	0.99869	5.6991E-04	0.066818	215.87	64 B4C pins/H2O
aclp7.out	4.908	17.5	0	1.000483	0.99869	5.6991E-04	0.066818	215.87	34 B4C pins/H2O
aclp8.out	4.908	17.5	0	1.000483	0.99869	5.6991E-04	0.066818	215.87	34 B4C pins/H2O
aclp9.out	6.544	17.5	0	1.000483	0.99869	5.6991E-04	0.066818	215.87	H2O
aclp10.out	6.544	24.5	143	0.998967	0.99718	5.6991E-04	0.066616	215.22	H2O
acp11a.out	1.636	25.5	510	0.999712	0.99692	5.6991E-04	0.066648	215.32	0.462 cm, SS 304/H2O
acp11b.out	1.636	26	514	0.998578	0.99992	5.6991E-04	0.066773	215.73	0.462 cm, SS 304/H2O
acp11c.out	1.636	25.5	501	0.999712	0.99692	5.6991E-04	0.066648	215.32	0.462 cm, SS 304/H2O
acp11d.out	1.636	25.5	493	0.998840	0.99692	5.6991E-04	0.066590	215.14	0.462 cm, SS 304/H2O
acp11e.out	1.636	25	474	0.999712	0.99404	5.6991E-04	0.066456	214.70	0.462 cm, SS 304/H2O
acp11f.out	1.636	25	462	0.998840	0.99404	5.6991E-04	0.066398	214.52	0.462 cm, SS 304/H2O
acp11g.out	1.636	25.5	432	0.999712	0.99992	5.6991E-04	0.066849	215.97	0.462 cm, SS 304/H2O
aclp12.out	3.272	26	217	0.998578	0.99679	5.6991E-04	0.066564	215.05	0.462 cm, SS 304/H2O
aclp13.out	1.636	20	15	1.000000	0.99821	5.6991E-04	0.066754	215.67	0.645 cm, BAl 1.614 wt% B/H2O
acp13a.out	1.636	17	28	1.000572	0.99878	5.6991E-04	0.066830	215.91	0.645 cm, BAl 1.614 wt% B/H2O
aclp14.out	1.636	18	92	1.000392	0.99860	5.6991E-04	0.066806	215.83	0.645 cm, BAl 1.614 wt% B/H2O
aclp15.out	1.636	18	395	1.000392	0.99860	5.6991E-04	0.066806	215.83	0.645 cm, BAl 1.614 wt% B/H2O
aclp16.out	3.272	17.5	121	1.000483	0.99878	5.6991E-04	0.066824	215.89	0.645 cm, BAl 1.614 wt% B/H2O
aclp17.out	1.636	17.5	487	1.000483	0.99878	5.6991E-04	0.066824	215.89	0.645 cm, BAl 1.614 wt% B/H2O
aclp18.out	3.272	18	197	1.000392	0.99860	5.6991E-04	0.066806	215.83	0.645 cm, BAl 1.614 wt% B/H2O
aclp19.out	1.636	17.5	634	1.000483	0.99878	5.6991E-04	0.066824	215.89	0.645 cm, BAl 1.614 wt% B/H2O
aclp20.out	3.272	17.5	320	1.000483	0.99878	5.6991E-04	0.066824	215.89	0.645 cm, BAl 1.614 wt% B/H2O
aclp21.out	6.544	16.5	72	1.000740	0.99992	5.6991E-04	0.066918	216.19	0.645 cm, BAl 1.614 wt% B/H2O

a) Reference 8.
b) Boron factors to correct water density from 25°C to 20°C. Boron ppm is based upon 25°C measurements. See Reference 7, Table 3.0-1, p. 46. Water density from standard tables.
c) Calculated values based upon Avogadro's number of 0.6022142E-24

Table 6-48 Close Proximity Experiment k_{eff} Data

Case ID	Experimental k_{eff} and σ		SCALE 4.4a 44 Group Cross-Section Calculated k_{eff} and σ				SCALE 4.4a 238 Group Cross-Section Calculated k_{eff} and σ			
	k_{eff}[a]	σ[a]	k_{eff}[b]	σ[b]	AFG[b]	EALF[b] (ev)	k_{eff}[b]	σ[b]	AFG[b]	EALF[b] (ev)
aclp1.out	1.0002	0.0005	0.9931	0.0008	34.8710	0.1712	0.9889	0.0009	201.9510	0.1761
aclp2.out	1.0001	0.0005	0.9956	0.0008	33.9420	0.2484	0.9939	0.0008	197.6580	0.2540
aclp3.out	1.0000	0.0006	0.9963	0.0006	34.5210	0.1960	0.9934	0.0007	200.5280	0.2002
aclp4.out	0.9999	0.0006	0.9897	0.0008	34.6110	0.1910	0.9875	0.0008	200.7350	0.1946
aclp5.out	1.0000	0.0007	0.9883	0.0008	34.9500	0.1662	0.9873	0.0008	202.4670	0.1689
aclp6.out	1.0097	0.0012	0.9884	0.0007	34.8840	0.1716	0.9872	0.0007	201.9760	0.1760
aclp7.out	0.9998	0.0009	0.9900	0.0007	35.2100	0.1496	0.9867	0.0008	203.6900	0.1527
aclp8.out	1.0083	0.0012	0.9906	0.0008	35.1720	0.1526	0.9874	0.0007	203.3420	0.1573
aclp9.out	1.0030	0.0009	0.9906	0.0006	35.3620	0.1411	0.9879	0.0007	204.4120	0.1438
aclp10.out	1.0001	0.0009	0.9913	0.0007	35.2090	0.1494	0.9883	0.0008	203.7410	0.1528
acp11a.out	1.0000	0.0006	0.9955	0.0007	34.4600	0.2001	0.9919	0.0006	200.2820	0.2046
acp11b.out	1.0007	0.0007	0.9942	0.0007	34.4640	0.1997	0.9916	0.0009	200.2900	0.2043
acp11c.out	1.0007	0.0006	0.9943	0.0008	34.4550	0.2007	0.9915	0.0008	200.1800	0.2060
acp11d.out	1.0007	0.0006	0.9939	0.0006	34.4290	0.2035	0.9920	0.0009	200.1670	0.2063
acp11e.out	1.0007	0.0006	0.9952	0.0007	34.4350	0.2030	0.9918	0.0006	200.0830	0.2078
acp11f.out	1.0007	0.0006	0.9947	0.0008	34.4360	0.2033	0.9916	0.0006	200.0020	0.2089
acp11g.out	1.0007	0.0006	0.9941	0.0007	34.4200	0.2054	0.9908	0.0007	199.9760	0.2096
aclp12.out	1.0000	0.0007	0.9911	0.0007	34.8740	0.1702	0.9889	0.0008	202.2960	0.1727
aclp13.out	1.0000	0.0010	0.9922	0.0007	34.5220	0.1963	0.9906	0.0009	200.3490	0.2013
acp13a.out	1.0000	0.0010	0.9901	0.0008	34.5020	0.1979	0.9884	0.0007	200.2550	0.2031
aclp14.out	1.0001	0.0010	0.9905	0.0007	34.4720	0.2005	0.9891	0.0009	200.1840	0.2045
aclp15.out	0.9998	0.0016	0.9881	0.0008	34.4020	0.2057	0.9823	0.0007	199.8980	0.2102
aclp16.out	1.0001	0.0006	0.9860	0.0007	34.8250	0.1737	0.9841	0.0007	202.0010	0.1769
aclp17.out	1.0007	0.0019	0.9897	0.0007	34.3970	0.2061	0.9874	0.0007	199.9490	0.2097
aclp18.out	1.0002	0.0011	0.9869	0.0007	34.8410	0.1728	0.9859	0.0008	202.0310	0.1759
aclp19.out	1.0002	0.0010	0.9910	0.0007	34.4010	0.2052	0.9888	0.0006	199.9530	0.2096
aclp20.out	1.0003	0.0011	0.9889	0.0006	34.8410	0.1726	0.9869	0.0008	202.0440	0.1758
aclp21.out	0.9997	0.0013	0.9868	0.0008	35.1290	0.1544	0.9854	0.0007	203.3850	0.1570

a) Values from Reference 3, Table 6, p. 42. Generally obtained from Tables 8 and 9 of Reference 8; acp11 series of values not documented in Reference 3.
b) From Reference 3, Table 9, p. 61 for 44 group cross-sections. Table 7 in this reference has values for 238 group cross-sections.

6.11.10.1.4 Critical Experiments Supporting Underwater Storage of Tightly Packed Configurations of Spent Fuel Pins

References:

9. FANP Doc. 32-5012897-00, "Validation Report – SCALEPC-44A Consolidation Experiments," R.S. Harding
10. "Critical Experiments Supporting Underwater Storage of Tightly Packed Configurations of Spent Fuel Pins," G.S. Hoovler, etal., BAW-1645-4, November, 1981.

Reference 9 uses the experimental data from Reference 10 to construct benchmark cases for SCALE 4.4a. Table 6-49 Tightly Packed Configuration Experiment Summary[a] summarizes the experimental configuration data that form the basis for the KENO V.a models. Table 6-50 Tightly Packed Configuration Experiment Trending Data provides trending parameters for this set of experiments. Table 6-51 Tightly Packed Configuration Experiment k_{eff} Data provides the experimental and calculated results for the 44 and 238 group SCALE 4.4a cross-section sets from Reference 3.

Table 6-49 Tightly Packed Configuration Experiment Summary[a]

U-235 wt%	2.459	Fuel Volume, cm^3	0.833229
Pellet Density[b], g/cm^3	10.233	Pitch, cm	Vh20/Ffuel
U-235 atom density[c]	5.7075E-04	1.2093	0.149022
Pellet OD, cm	1.0300	1.2090	0.383292
Rod OD, cm	1.0440	1.4097	1.014058
Rod OD, cm	1.2060		
Clad Material	Al		

a) From Reference 9.
b) Based upon rod mass and fuel volume in rod, note this is the same 2.459 wt% fuel used in the previous 2 benchmark cases. The difference in densities has not been discussed.
c) Calculated values based upon Avogadro's number of 0.6022142E-24.

Table 6-50 Tightly Packed Configuration Experiment Trending Data

Case ID	Rod Pitch[a], cm	Lattice[a]	Cluster Spacing[a], cm	Temp[a], °C	Boron[a], ppm	Boron Factor[b]	Water density[b]	V_{h2o}/V_{fuel}[c]	H atom density[c]	H/U_l[c]
rcon01.out	1.2093	15x17 tria[d]	1.778x1.945	22.5	435	0.999451	0.99767	0.1490	0.066681	17.41
rcon02.out	1.2093	15x17 tria	1.778x1.945	23.5	426	0.999214	0.99742	0.1490	0.066648	17.40
rcon03.out	1.2093	15x17 tria	1.778x1.945	24.0	406	0.999091	0.99730	0.1490	0.066632	17.40
rcon04.out	1.2093	15x17 tria	1.778x1.945	22.5	383	0.999451	0.99767	0.1490	0.066681	17.41
rcon05.out	1.2093	15x17 tria	1.778x1.945	23.0	354	0.999334	0.99754	0.1490	0.066665	17.41
rcon06.out	1.2093	15x17 tria	1.778x1.945	23.0	335	0.999334	0.99754	0.1490	0.066665	17.41
rcon07.out	1.2093	15x17 tria	2.539x2.709	20.0	361	1.000000	0.99821	0.1490	0.066754	17.43
rcon09.out	1.2090	15x15 sq	1.7780	21.0	886	0.999788	0.99799	0.3833	0.066725	44.81
rcon10.out	1.2090	15x15 sq	1.7780	21.0	871	0.999788	0.99799	0.3833	0.066725	44.81
rcon11.out	1.2090	15x15 sq	1.7780	22.0	852	0.999566	0.99777	0.3833	0.066695	44.79
rcon12.out	1.2090	15x15 sq	1.7780	21.0	834	0.999788	0.99799	0.3833	0.066725	44.81
rcon13.out	1.2090	15x15 sq	1.7780	21.0	815	0.999788	0.99799	0.3833	0.066725	44.81
rcon14.out	1.2090	15x15 sq	1.7780	22.0	781	0.999566	0.99777	0.3833	0.066695	44.79
rcon15.out	1.2090	15x15 sq	1.7780	22.0	746	0.999566	0.99777	0.3833	0.066695	44.79
rcon16.out	1.4097	13x13 sq	1.7920	22.5	1156	0.999451	0.99767	1.0141	0.066681	118.47
rcon17.out	1.4097	13x13 sq	1.7920	22.5	1141	0.999451	0.99767	1.0141	0.066681	118.47
rcon18.out	1.4097	13x13 sq	1.7920	23.0	1123	0.999334	0.99754	1.0141	0.066665	118.44
rcon19.out	1.4097	13x13 sq	1.7920	23.0	1107	0.999334	0.99754	1.0141	0.066665	118.44
rcon20.out	1.4097	13x13 sq	1.7920	23.0	1093	0.999334	0.99754	1.0141	0.066665	118.44
rcon21.out	1.4097	13x13 sq	1.7920	23.0	1068	0.999334	0.99754	1.0141	0.066665	118.44
rcon28.out	1.4097	15x17 tria	3.807x2.976	18.5	121	1.000298	0.99850	1.0141	0.066793	17.44

a) Reference 9.
b) Boron factors to correct water density from 25°C to 20°C. Boron ppm is based upon 25 °C measurements. See Reference 10, Table 3.0-1, p. 46. Water density from standard tables.
c) Calculated values based upon Avogadro's number of 0.6022142E-24.
d) Triangular pitch for array.

Table 6-51 Tightly Packed Configuration Experiment k_{eff} Data

Case ID	Experimental k_{eff} and σ		SCALE 4.4a 44 Group Cross-Section Calculated k_{eff} and σ				SCALE 4.4a 238 Group Cross-Section Calculated k_{eff} and σ			
	k_{eff}[a]	σ[a]	k_{eff}[b]	σ[b]	AFG[b]	EALF[b] (ev)	k_{eff}[b]	σ[b]	AFG[b]	EALF[b] (ev)
rcon01.out	1.0007	0.0006	0.9999	0.0008	28.9400	2.4011	0.9910	0.0007	170.1330	2.4368
rcon02.out	1.0007	0.0006	1.0009	0.0007	28.9020	2.4444	0.9909	0.0008	169.9770	2.4688
rcon03.out	1.0007	0.0006	0.9973	0.0008	28.8680	2.4872	0.9882	0.0007	169.6020	2.5454
rcon04.out	1.0007	0.0006	1.0008	0.0007	28.8990	2.4644	0.9899	0.0007	169.6960	2.5284
rcon05.out	1.0007	0.0006	0.9995	0.0008	28.8970	2.4706	0.9899	0.0008	169.6200	2.5435
rcon06.out	1.0007	0.0006	0.9980	0.0007	28.8900	2.4915	0.9906	0.0008	169.5520	2.5553
rcon07.out	1.0007	0.0006	0.9982	0.0008	29.8910	1.6259	0.9904	0.0008	175.2760	1.6431
rcon09.out	1.0007	0.0006	0.9977	0.0006	29.8930	1.4607	1.0092	0.0007	180.0400	1.1271
rcon10.out	1.0007	0.0006	0.9966	0.0008	29.8760	1.4759	0.9884	0.0006	176.1470	1.4891
rcon11.out	1.0007	0.0006	0.9959	0.0007	29.8450	1.4982	0.9909	0.0008	176.1150	1.4922
rcon12.out	1.0007	0.0006	0.9980	0.0008	29.8490	1.4979	0.9876	0.0007	175.8550	1.5240
rcon13.out	1.0007	0.0006	0.9969	0.0007	29.8430	1.5074	0.9897	0.0007	175.8220	1.5280
rcon14.out	1.0007	0.0006	0.9963	0.0007	29.8310	1.5207	0.9894	0.0007	175.7230	1.5402
rcon15.out	1.0007	0.0006	0.9975	0.0008	29.8450	1.5180	0.9915	0.0007	175.7200	1.5399
rcon16.out	1.0007	0.0006	0.9948	0.0007	32.7100	0.4216	0.9892	0.0007	175.7140	1.5415
rcon17.out	1.0007	0.0006	0.9952	0.0006	32.6820	0.4276	0.9894	0.0006	191.3680	0.4309
rcon18.out	1.0007	0.0006	0.9939	0.0006	32.6400	0.4370	0.9909	0.0007	191.2180	0.4360
rcon19.out	1.0007	0.0006	0.9965	0.0006	32.6540	0.4344	0.9897	0.0007	191.0430	0.4426
rcon20.out	1.0007	0.0006	0.9967	0.0007	32.6370	0.4391	0.9915	0.0007	190.9880	0.4447
rcon21.out	1.0007	0.0006	0.9959	0.0008	32.6220	0.4427	0.9903	0.0007	190.8780	0.4485
rcon28.out	1.0007	0.0006	0.9968	0.0008	31.0790	1.0062	0.9915	0.0008	190.7670	0.4529

a) Values from Reference 3, Table 6, p. 42. Source of value not documented in this reference.
b) From Reference 3, Table 9, p. 61 for 44 group cross-sections. Table 7 in this reference has values for 238 group cross-sections

6.11.10.1.5 Reduced Density Moderation Between Fuel Clusters with 4.738 Wt% Fuel

References:

11. FANP Doc. 32-5012894-00, "Validation Report – SCALEPC-44A Dissolution Experiments," R.S. Harding.
12. "Dissolution and Storage Experimental Program with U[4.75]O_2 Rods," Transactions of the American Nuclear Society, Vol. 33, pg. 362.

Reference 11 uses the experimental data from Reference 12 to construct benchmark cases for SCALE 4.4a. Table 6-52 Reduced Density Moderation Experiments Summary and Trending Parameters[a] summarizes the experimental configuration data that form the basis for the KENO V.a models and provides trending parameters that are constant for the series of experiments. Table 6-53 Reduced Density Moderation Experiments Trending Data and k_{eff} Data provides trending parameters for this set of experiments. It also provides the experimental and calculated results for the 44 and 238 group SCALE 4.4a cross-section sets from Reference 3.

Table 6-52 Reduced Density Moderation Experiments Summary and Trending Parameters[a]

U-235 wt%	4.738	Temperature, °C	22
Pellet Density, g/cm^3	10.38	Water density, g/cm^3	0.99777
Pellet OD, cm	0.7900	Fuel Volume, cm^3	0.49017
Rod OD, cm	0.8200	Water Volume, cm^3	1.12852
Rod OD, cm	0.9400	V_{h2o}/V_{fuel}	2.30232
Rod Pitch, cm	1.3500	U-235 atom density[b]	1.1155E-03
Clad Material	Al alloy	H atom density[b]	0.066676
Lattice	18x18	H/U	1.3761E+02

a) From Reference 11.
b) Calculated values based upon Avogadro's number of 0.6022142E-24.

Table 6-53 Reduced Density Moderation Experiments Trending Data and k_{eff} Data

Case ID	Cluster Spacing[a], cm	Spacing Material[a] [Material (density)]	Experimental k_{eff} and σ		SCALE 4.4a 44 Group Cross-Section Calculated k_{eff} and σ				SCALE 4.4a 238 Group Cross-Section Calculated k_{eff} and σ			
			k_{eff}[b]	σ[b]	k_{eff}[c]	σ[c]	AFG[c]	EALF[c] (ev)	k_{eff}[c]	σ[c]	AFG[c]	EALF[c] (ev)
mdis01.out	0.0	-	1.0000	0.0014	0.9914	0.0008	33.5390	0.2824	0.9885	0.0010	195.994	0.2879
mdis02.out	2.5	H2O	1.0000	0.0014	0.9871	0.0009	33.6720	0.2644	0.9862	0.0008	196.836	0.2685
mdis03.out	2.5	Air/Box	1.0000	0.0014	0.9841	0.0011	33.6720	0.2647	0.9805	0.0008	196.750	0.2702
mdis04.out	2.5	Polystr(0.0323)/Box	1.0000	0.0014	0.9902	0.0008	33.8040	0.2514	0.9884	0.0008	197.439	0.2559
mdis05.out	2.5	Polyeth(0.2879)/Box	1.0000	0.0014	0.9908	0.0010	33.9160	0.2407	0.9891	0.0009	198.001	0.2442
mdis06.out	2.5	Polyeth(0.5540)/Box	1.0000	0.0014	1.0008	0.0010	34.0370	0.2295	0.9963	0.0008	198.539	0.2344
mdis07.out	2.5	H2O/Box	1.0000	0.0014	0.9917	0.0009	34.1100	0.2242	0.9886	0.0008	198.827	0.2288
mdis08.out	5.0	H2O	1.0000	0.0014	0.9873	0.0010	33.8000	0.2497	0.9840	0.0009	197.504	0.2545
mdis09.out	5.0	Air/Box	1.0000	0.0014	0.9869	0.0010	33.8110	0.2485	0.9861	0.0009	197.586	0.2524
mdis10.out	5.0	Polystr(0.0323)/Box	1.0000	0.0014	0.9938	0.0008	34.0940	0.2225	0.9912	0.0008	198.934	0.2267
mdis11.out	5.0	Polyeth(0.2879)/Box	1.0000	0.0014	1.0031	0.0010	34.3010	0.2048	0.9997	0.0008	200.018	0.2076
mdis12.out	5.0	Polyeth(0.0.5540)/Box	1.0000	0.0014	-	-	-	-	1.0027	0.0009	200.577	0.1984
mdis13.out	5.0	H2O/Box	1.0000	0.0014	0.9907	0.0008	34.4280	0.1951	0.9878	0.0008	200.547	0.1988
mdis14.out	10.0	H2O	1.0000	0.0014	0.9890	0.0008	33.9850	0.2294	0.9854	0.0009	198.552	0.2333
mdis15.out	10.0	Air/Box	1.0000	0.0014	0.9894	0.0009	34.0150	0.2266	0.9842	0.0008	198.647	0.2315
mdis16.out	10.0	Polystr(0.0323)/Box	1.0000	0.0014	1.0013	0.0008	34.4450	0.1907	0.9970	0.0009	200.792	0.1948
mdis17.out	10.0	Polyeth(0.2879)/Box	1.0000	0.0014	0.9985	0.0008	34.5970	0.1788	0.9951	0.0009	201.537	0.1831
mdis18.out	10.0	Polyeth(0.0.5540)/Box	1.0000	0.0014	0.9965	0.0008	34.6430	0.1740	0.9923	0.0009	201.894	0.1774
mdis19.out	10.0	H2O/Box	1.0000	0.0014	0.9931	0.0009	34.6530	0.1737	0.9888	0.0008	201.908	0.1772

a) References 11 and 12.
b) Values from Reference 3, Table 6, p. 42. Source of value not documented in this reference.
c) From Reference 3, Table 9, p. 61 for 44 group cross-sections. Table 7 in this reference has values for 238 group cross-sections.

6.12 References

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10. Hovler, G.S. et al., Critical Experiments Supporting Underwater Storage of Tightly Packed Configurations of Spent Fuel Pins, BAW-1645-4, November, 1981.
11. Transactions of the American Nuclear Society, Dissolution and Storage Experimental Program with U[4.75]O_2 Rods, Vol. 33, pg. 362.
12. Harding, R.S., Validation Report – SCALEPC-44A Consolidation Experiments, FANP Doc. 32-5012897-00

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Glossary of Terms and Acronyms

ASME – American Society of Mechanical Engineers
ASME B&PVC – ASME Boiler and Pressure Vessel Code
ASNT – American Society for Non-destructive Testing
CG – Center of Gravity
CTU – Certification Test Unit
BWR – Boiling Water Reactor
HAC – Hypothetical Accident Condition
IC – Inner Container
IC Inner Thermal Insulator (Aluminum Silicate) – The Alumina Silicate thermal insulation between the inner and outer walls of IC container to provide added margin to criteria set forth for HAC fire condition in 10 CFR 71.73(c)(4)
IC Lid – The lid of the inner container
IC Body – The body of the inner container consisting of the outer wall the thermal insulation, the inner wall, the polyethylene liner and the shock absorbing system along with the fuel securement system
JIS – Japanese Industrial Standards
JSNDI – Japanese Society for Non-destructive Inspection
LDPE – Low Density Polyethylene
NCT – Normal Conditions of Transport
NDIS – Non-destructive Inspection Society
OC – Outer Container
OC Body – The assembly consisting of the OC lower wall, and the internal shock absorbing material
OC Lid – The lid for the outer container.
Packaging – The assembly of components necessary to ensure compliance with packaging requirements as defined in 10 CFR 71.4. Within this SAR, the packaging is denoted as the RAJ-II packaging
Package – The packaging with its radioactive contents, as presented for transportation as defined in 10 CFR 71.4. Within this SAR, the package is denoted as the RAJ-II package.
Payload – Unirradiated fuel assemblies and fuel rods.
RAM – Radioactive Material
SAR – Safety Analysis Report (this document)
TI – Transport Index
USL – Upper Safety Limit