Chapter 4 Appendix 4A
Criticality Models

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1.0 INTRODUCTION

The purpose of this appendix is to provide a summary of criticality calculations performed for the ISF Facility to demonstrate compliance with the ISF SAR Table 3.3-5, "Control Methods for Prevention of Criticality."

This appendix covers the fuel handling process as it flows through the ISF. The fuel is received in a DOE transfer cask and is moved to the fuel packaging area (FPA). In the FPA the fuel is removed from the transfer cask and placed in ISF containers that ultimately end up in the storage tubes of the storage area (SA) portion of the facility. Analyses are performed for the credible events within the ISF Facility. There are also normal fuel handling events that are analyzed such as loading a cask or placement of fuel canisters into storage tubes.

There are three basic fuel types analyzed: TRIGA fuel, Peach Bottom Fuel, and Shippingport reflectors. The analyses are developed such that the double contingency principle is not violated.

Sections 2 through 4 summarize key information from the criticality calculations performed for the ISF. Section 2 covers the six criticality calculations written for TRIGA fuel, Section 3 addresses five calculations for the Peach Bottom Fuel and Section 4 covers the single calculation written for the Shippingport reflector fuel. Each calculation is contained in a separate subsection for the section addressing that fuel type. For example, key information from the calculation for "TRIGA ISF Baskets Side-by-Side" is summarized in Section 2.2 because Section 2 addresses TRIGA fuel.

Both credible and non-credible scenarios were analyzed. Credible scenarios were explicitly modeled to determine k_{eff} for comparison against the design basis multiplication factor of 0.95. As discussed in Sections 5.2 and 5.3, upper limits ranging from ≤ 0.9130 to ≤ 0.9304 for calculated k_{eff} were established to account for bias and uncertainty, depending on the fuel type and code used for analysis. These cases included routine handling, packaging, transfer and storage scenarios. Non-credible scenarios were analyzed to determine the bounding quantity of fissile material that results in an effective multiplication factor of 0.95. These non-credible scenarios included:

- TRIGA elements with three sides of concrete reflection
- Crushed Peach Bottom fuel assemblies moderated with graphite
- Reflector rods in an infinite array

Each subsection consists of the following information which was extracted from the criticality calculations:

1) Purpose of the calculation
2) Summary of results
3) Description of the spent fuel loading
4) Description of the model
5) Material densities used in the models
6) Summary of calculation methodology

7) Description of fuel loading and other contents optimization
8) Detailed summary of the criticality calculation results
9) List of references applicable to that calculation.

2.0 TRIGA FUEL

2.1 TRIGA, PEACH BOTTOM, AND SHIPPINGPORT FUELS IN THE PEACH BOTTOM TRANSFER CASK

The TRIGA, Peach Bottom, and Shippingport fuels are transferred to the ISF Facility by the DOE. The Peach Bottom Transfer Cask is used for these transfers. Information pertinent to the Peach Bottom transfer cask delivery system (fuels, internal packaging for the fuels, transfer cask) may be found in Appendix A to the Safety Analysis Report.

Section 4.7.3.4 Criticality Evaluation for Spent Fuel Handling Operations of Appendix A discusses the criticality evaluations for the respective fuels while they are inside the closed Peach Bottom transfer cask.

2.2 TRIGA ISF BASKETS SIDE-BY-SIDE

2.2.1 Criticality Evaluation

An MCNP analysis was performed to show that two TRIGA fuel baskets, each containing 54 TRIGA elements, positioned side-by-side in the Fuel Packaging Area would remain subcritical. For purposes of this analysis, each fuel element and basket was explicitly modeled, including all fixtures, adapters, and hardware, to confirm that these items did not adversely impact the neutronics.

2.2.2 Discussion and Results

TRIGA fuel will be received and handled in the Fuel Packaging Area of the ISF facility. In the FPA the TRIGA fuel elements will be packaged into ISF baskets each holding 54 TRIGA fuel elements.

MCNP4C calculations were performed to demonstrate that two TRIGA fuel baskets side-by-side would remain subcritical. The configuration is non-credible because only one fuel-handling machine is present in the FPA. Correspondingly, only one TRIGA fuel basket could be moving in the FPA at any given time. Two baskets would not pass side-by-side due to engineering controls and administrative practices. However, because the TRIGA canister contains two TRIGA baskets this analysis was performed to substantiate the inherent safety of fuel handling practices in the FPA.

The k_{eff} result for two TRIGA baskets passing by side-by-side in air is given in Table 2.2-1.

2.2.3 Spent Fuel Loading

Stainless steel clad TRIGA fuel containing a ^{235}U loading of 43.875 grams was used in these calculations. A basket of stainless steel clad fuel elements thus contains 2.37 kg of ^{235}U and two baskets full of fuel would contain 4.74 kg of ^{235}U.

2.2.4 Model Specification

2.2.4.1 Description of Calculation Model

The model was developed using one full TRIGA basket with a reflecting surface beside it to simulate an adjacent second basket. Figures 2.2-1 and 2.2-2 provide graphical representation of the side-by-side basket configuration.

Table 2.2-2 summarizes the modeled properties of the significant components used in this calculation. Modeled properties are derived from DOE fuels reference documents and ISF design documents for the specific components (basket, canister, etc).

TRIGA fuel as modeled contained approximately 9-weight percent uranium enriched to 20% in ^{235}U, resulting in uranium loadings of 43.875 grams for ^{235}U and approximately 176 grams for ^{238}U. Each element has 2,088 grams of zirconium and a hydrogen-to-zirconium ratio of 1.70.

2.2.4.2 Regional Densities

Table 2.2-3 summarizes the material atom density compositions used in this calculation.

2.2.5 Criticality Calculations

2.2.5.1 Calculation Methodology

MCNP4C was used to calculate k_{eff} to demonstrate that two baskets of TRIGA fuel passed side-by-side in the Fuel Packaging Area would remain safely subcritical. A basket of TRIGA fuel was modeled in air and a reflective surface inserted to simulate another TRIGA fuel basket passing by resulting in a side-by-side configuration. Water moderation was not included in the model as the lag storage areas and the fuel handling equipment are all above the maximum expected flood elevation. Although the TRIGA fuel basket is designed to contain a gadolinium phosphate neutron poison in the center position, this neutron poison was omitted from the calculation.

2.2.5.2 Fuel Loading and Other Contents Optimization

Baskets were loaded with stainless steel clad TRIGA fuel that contained a 43.875-gram ^{235}U fuel loading. Each element had approximately 9-weight % total uranium enriched to 20% in ^{235}U.

2.2.5.3 Criticality Results

The side-by-side configuration would not present any nuclear safety concern in that the computed $k_{eff} + 2\sigma$ was 0.5681, well below any upper safety levels. This configuration remains safely subcritical.

2.2.6 References

Characterization of TRIGA Fuel, N. Tomsio, ORNL/Sub/86-22047/3, GA-C18542, October 1986.

2.3 STORAGE VAULT FULL OF TRIGA FUEL

2.3.1 Criticality Evaluation

An analysis was performed to show that a Storage Area vault fully loaded with TRIGA fuel would be critically safe.

2.3.2 Discussion and Results

The Storage Area is composed of two independent vaults. Vault 1 contains a total of 102 storage tubes, 72 18-inch tubes and 30 24-inch tubes. Vault 2 contains a total of 144 tubes, all of them 18-inch tubes.

MCNP4C calculations were performed to determine the k_{eff} of vault 2 of the Storage Area completely filled with TRIGA fuel canisters. Vault 2 can hold a total of 144 ISF TRIGA canisters (15,552 fuel elements). This approach is conservative since current plans are to place only 15 canisters of TRIGA fuel in the Storage Area, with the remaining positions filled with less reactive fuel.

For conservatism, a fully flooded vault calculation was included in the analysis. Additionally, an evaluation was conducted in which the water density was altered from full density down to 0.2 g/cc in increments of 0.2 g/cc. The highest value for $k_{eff} + 2\sigma$ of 0.8153 was obtained in the fully flooded condition. Table 2.3-1 summarizes the results of all the calculations performed in this evaluation.

2.3.3 Spent Fuel Loading

Stainless steel clad TRIGA fuel containing a ^{235}U loading of 43.875 grams was used in these calculations. A basket of stainless steel clad fuel elements thus contains 2.37 kg of ^{235}U and a canister 4.74 kg of ^{235}U. Vault 2 of the ISF Facility when fully loaded with TRIGA fuel would contain approximately 683 kg of ^{235}U.

2.3.4 Model

2.3.4.1 Description of Calculation Model

For the purposes of modeling the actual configuration of the Storage Area, Vault 2 was selected because the configuration contains more canister locations for TRIGA fuel, the most reactive fuel type to be stored in the facility. The MCNP model was a stainless steel canister inserted in each of the 144 tube locations, with each canister containing two TRIGA fuel baskets one atop the other. Figures 2.3-1 through 2.3-3 provide graphical representation of the baskets, canister, and configuration within the storage tube.

Table 2.3-2 summarizes the modeled properties of the significant components used in this calculation. Modeled configurations are derived from reference documents and ISF project references for the specific components (basket, canister, etc).

TRIGA fuel as modeled contained approximately 9-weight percent uranium enriched to 20% in ^{235}U, resulting in uranium loadings of 43.875 grams for ^{235}U and approximately 176 grams for ^{238}U. Each element has 2,088 grams of zirconium and a hydrogen-to-zirconium ration of 1.70.

A dry basket, canister, and storage tube were used as a baseline calculation based on the assumption that water is not able to penetrate the confinement boundaries as the canister-storage tube interface or the basket-canister interface. For conservatism, the Storage Area was modeled with the most reactive fuel type (TRIGA) and the vault, storage tubes, and canisters flooded.

2.3.4.2 Regional Densities

The material atom density compositions used in this calculation are the same as those used in the calculations described in Section 2.2 and are summarized in Table 2.2-3.

2.3.5 Criticality Calculations

2.3.5.1 Calculation Methodology

The MCNP4C code was used to determine the effective multiplication factor for a fully loaded vault (Vault 2) of TRIGA fuel. A total of 144 storage tubes were modeled each holding 1 canister of 2 TRIGA baskets.

The vault was modeled in a dry configuration followed by a fully flooded condition included the storage tubes and canisters. Variable moderator density was input into the model to evaluate the sensitivity of k_{eff} to these changes. Full density water was used first and then lowered to a density of 0.2 g/cc in 0.2 g/cc increments.

2.3.5.2 Fuel Loading and Other Contents Optimization

Canisters were loaded with stainless steel clad TRIGA fuel that contained a 43.875-gram ^{235}U fuel loading. Each element had approximately 9-weight % total uranium enriched to 20% in ^{235}U.

A water moderator and reflector were added to the baseline dry model to demonstrate that in the presence of a moderator the vault would remain subcritical. Sensitivity to the moderator density is discussed in Section 2.3.5.1.

2.3.5.3 Criticality Results

In all cases the storage configuration was shown to remain subcritical regardless of the presence of water or the water density. Water penetration into the ISF storage tubes and ISF canisters is not considered a viable scenario due to both being sealed containers which have undergone weld inspections and leak testing per ASME Boiler & Pressure Vessel Code Section III. The flooded cases were run strictly to demonstrate the inherent safety of the Storage Area configuration fully loaded with the most reactive fuel under varying moderator conditions.

2.3.6 References

Characterization of TRIGA Fuel, N. Tomsio, ORNL/Sub/86-22047/3, GA-C18542, October 1986.

2.4 TRIGA CANISTERS

2.4.1 Criticality Evaluation

This evaluation was made with MCNP (MCNP4B2) to determine whether a single ISF canister containing TRIGA fuel elements is safely subcritical and if two TRIGA canisters will remain subcritical if they are passed side-by-side or end-to-end.

2.4.2 Discussion and Results

MCNP4B2 calculations show that a single dry ISF canister loaded with 108 TRIGA fuel elements with a 1-inch water reflector is subcritical, with a $k_{eff} + 2\sigma$ equal to 0.5741. The use of nominal reflection (equivalent to one inch of water) to allow for minor reflection from the building surfaces and equipment is standard practice. If a single dry canister is reflected with 12-inches of water, the $k_{eff} + 2\sigma$ value increases to 0.6063, which is also subcritical. A 12-inch water reflector was used to represent the maximum standard practice reflection for the canister.

Two dry canisters loaded with 108 TRIGA fuel elements each and passed side-by-side will remain safely subcritical, with a $k_{eff} + 2\sigma$ equal to 0.6056 for a 1-inch water reflector. Two dry canisters passed end-to-end with a 1-inch water reflector also remain subcritical, with a $k_{eff} + 2\sigma$ value of 0.5755. If two dry canisters passed end-to-end are reflected with 12 inches of water, the $k_{eff} + 2\sigma$ value increases to 0.6060, which is also subcritical.

If two canisters passed side-by-side are assumed to be flooded and reflected with 12 inches of water, the $k_{eff} + 2\sigma$ value increases to 0.8405, which is still subcritical. The SA and FPA design minimizes the possibility for any appreciable amount of water to enter these areas. Therefore, conditions analyzed in the flooded and reflected scenario are considered unlikely events to occur in either the SA or the FPA.

The results of these calculations are summarized in Table 2.4-1.

2.4.3 Spent Fuel Loading

The nominal TRIGA fuel element fissile material content specified in the ISF Contract (39g ^{235}U) was adjusted to account for variations in post-1964 fuel elements to provide the most reactive and bounding source term for criticality analysis. Manufacturing variations resulted in a higher uranium content and a greater H:Zr atom ratio. A single TRIGA ISF canister contains 108 TRIGA fuel elements for a total of 4.74 kilograms of ^{235}U. Two canisters passed side-by-side or end-to-end contains a total of 9.48 kilograms of ^{235}U for each configuration.

2.4.4 Model Specification

2.4.4.1 Description of Calculational Model

The MCNP model for a single dry TRIGA ISF canister with a 1-inch water reflector is shown in Figures 2.4-1 and 2.4-2. The MCNP model for a single dry TRIGA canister with a 12-inch water reflector is shown in Figures 2.4-3 and 2.4-4. The MCNP model for 2 dry TRIGA canisters passed side-by-side with a 1-inch water reflector is shown in Figures 2.4-5 and 2.4-6. Note that a reflective surface was used on one side of the canister to simulate 2 canisters side-by-side. The MCNP model for 2 flooded TRIGA

canisters passed side-by-side with a 12-inch water reflector is shown in Figures 2.4-7 and 2.4-8. Figure 2.4-9 shows an axial view of the model for 2 dry TRIGA canisters passed end-to-end with a 1-inch water reflector. The radial view for this model is identical to Figure 2.4-1, and is therefore not repeated as a separate figure. An axial view of the MCNP model for 2 dry TRIGA canisters passed end-to-end with a 12-inch water reflector is shown in Figure 2.4-10. The radial view for this model is identical to Figure 2.4-3, and is therefore not repeated as a separate figure. Table 2.4-2 summarizes the modeled configuration.

2.4.4.2 Regional Densities

Table 2.4-3 summarizes the material atom density compositions used in this calculation.

2.4.5 Criticality Calculations

2.4.5.1 Calculational Methodology

The MCNP4B2 code (Monte Carlo N-Particle Transport Code System) was used to determine the k_{eff} for a single dry canister loaded with 108 TRIGA fuel elements, for two loaded canisters placed side-by-side and for two loaded canisters placed end-to-end. The dry canisters were nominally reflected with one inch of water as a standard practice to allow for minor reflection from the building surfaces and equipment. A single canister and two canisters placed end-to-end were also reflected by 12 inches of water. In addition, two flooded canisters placed side-by-side were reflected by 12 inches of water. The MCNP models used are depicted in Figure 2.4-1 through Figure 2.4-10.

2.4.5.2 Fuel Loading and Other Contents Optimization

A single TRIGA ISF canister contained 108 TRIGA fuel elements for a total of 4.74 kilograms of ^{235}U. Two canisters passed side-by-side or end-to-end contained a total of 9.48 kilograms of ^{235}U for each configuration. These fuel loadings and configurations address the maximum reactivity conditions for the TRIGA canister. The nominal TRIGA fuel element fissile material content specified in the ISF Contract (39g ^{235}U) was adjusted to account for variations in post-1964 fuel elements to provide the most reactive and bounding source term for criticality analysis. Manufacturing variations resulted in a higher uranium content and a greater H:Zr atom ratio.

2.4.5.3 Criticality Results

The results of these calculations are summarized in Table 2.4-1. These calculations show that a single dry ISF canister loaded with 108 TRIGA fuel elements with a 1-inch water reflector is subcritical, with a k_{eff} $+2\sigma$ equal to 0.5741 (Case 9-1). The use of nominal reflection (equivalent to one inch of water) to allow for minor reflection from the building surfaces and equipment is standard practice. If a single dry canister is reflected with 12 inches of water, the k_{eff} $+2\sigma$ value increases to 0.6063 (Case 9-2), which is also safely subcritical. A 12-inch water reflector was used to represent a maximum reflection for the canister.

Two dry canisters loaded with 108 TRIGA fuel elements each and passed side-by-side with a 1-inch water reflector will remain safely subcritical, with a k_{eff} $+2\sigma$ equal to 0.6056 (Case 9-3). Two dry canisters passed end-to-end with a 1-inch water reflector also remain subcritical, with a k_{eff} $+2\sigma$ value of 0.5755 (Case 9-5). If two dry canisters passed end-to-end are reflected with 12 inches of water, the k_{eff}

+2σ value increases to 0.6060 (Case 9-6), which is also safely subcritical. Cases 9-5 and 9-6 provide an indication of the sensitivity of the effective neutron multiplication to the water reflector thickness.

If two canisters passed side-by-side are assumed to be flooded and reflected with 12 inches of water, the k_{eff} +2σ value increases to 0.8405, which is still safely subcritical. The SA and FPA design minimizes the possibility for any appreciable amount of water to enter these areas. Therefore, conditions analyzed in the flooded and reflected scenario are considered unlikely events to occur in either the SA or the FPA.

2.4.6 References

Characterization of TRIGA Fuel, N Tomsio, ORNL/Sub/86-22047/3, GA-C18542, October 1986.

2.5 TRIGA WITH THREE SIDES OF CONCRETE REFLECTION

2.5.1 Criticality Evaluation

A criticality evaluation was performed to determine the maximum number of TRIGA fuel elements that can safely be handled in an uncontrolled, unconfined, and unmoderated condition in the ISF facility without exceeding criticality limits. In determining the maximum number of TRIGA fuel elements needed for critical conditions, the fuel was assumed to be reflected on three sides with concrete and reflected on three sides with one inch of water to account for minor reflection from the building surfaces and equipment. As described in the *Accident Analysis* subsection of SAR Section 8.2.5.3, Flood, the FPA is designed to prevent the ingress of floodwater. Additional design features that ensure the FPA is free of water include no water systems located in the FPA and the work bench (operating deck) elevation (4938.5 feet) positioned above the maximum probable flood elevation (4920.71 feet).

2.5.2 Discussion and Results

These calculations show that the subcritical k_{eff} + 2σ upper safety limit of 0.9130 will be reached with 45 TRIGA fuel elements in a hexagonal array and more than 53 elements in a square pitch array. The results of these calculations are summarized in Table 2.5-1 and Figure 2.5-1.

2.5.3 Spent Fuel Loading

Each TRIGA fuel with SS cladding assembly used in these calculations contained 43.875 grams of ^{235}U. The nominal TRIGA fuel element fissile material content specified in the ISF Contract (39g ^{235}U) was adjusted to account for variations in post-1964 fuel elements to provide the most reactive and bounding source term for criticality analysis. Manufacturing variations resulted in a higher uranium content and a greater H:Zr atom ratio.

2.5.4 Model Specification

2.5.4.1 Description of Calculational Model

Typical MCNP models of the unmoderated and reflected fuel assemblies are shown in Figures 2.5-2 through 2.5-4. Table 2.5-2 summarizes the modeled configuration. The number of assemblies was varied from problem to problem.

One model used was a hexagonal array of fuel elements that is as closely packed as possible. The other used a square pitch array with fuel packed as closely as possible. The dry array models were placed in the corner of 36-inch thick concrete walls and were closely reflected with one inch of water on the other boundaries of the array. The use of nominal reflection (equivalent to one inch of water) to allow for minor reflection from the building surfaces and equipment is standard practice.

2.5.4.2 Regional Densities

Table 2.5-3 summarizes the material atom density compositions used in this calculation.

2.5.5 Criticality Calculations

2.5.5.1 Calculational Methodology

The MCNP4B2 code was used to determine the k_{eff} for various numbers of unmoderated and reflected arrays of TRIGA fuel elements. These values were used to determine the maximum number of assemblies that may be safely handled without presenting a criticality problem.

2.5.5.2 Fuel Loading and Other Contents Optimization

Each TRIGA fuel assembly used in these calculations contained 43.875 grams of ^{235}U. The nominal TRIGA fuel element fissile material content specified in the ISF Contract (39g ^{235}U) was adjusted to account for variations in post-1964 fuel elements to provide the most reactive and bounding source term for criticality analysis. Manufacturing variations resulted in a higher uranium content and a greater H:Zr atom ratio.

Since there is no restriction on the geometry of the pile of fuel it was assumed that the fuel could collect in a corner of the cell, which would provide full concrete reflection on three sides. The reflection on the other three sides was taken to be nominal, equivalent to one inch of water, as is standard practice to allow for minor reflections from the building surfaces and equipment. Therefore, analyses were made with TRIGA fuel in a concrete corner, unmoderated, and reflected on the other three sides by one inch of water. Calculations were made for the fuel with a hexagonal pitch. This was expected to be the most reactive configuration, but calculations were also made with a square pitch because the fuel can be modeled with more tightly reflecting material.

2.5.5.3 Criticality Results

These calculations show that the subcritical $k_{eff} + 2\sigma$ upper safety limit of 0.9130 will be reached with 45 TRIGA fuel elements in a tightly packed dry hexagonal array reflected by one inch of water that is in a corner of the FPA. It will take 53 elements to reach the limit with the fuel packed in a square pitched array. Therefore, the hexagonal limit is controlling. Table 2.5-1 and Figure 2.5-1 summarize these results.

2.5.6 References

Characterization of TRIGA Fuel, N Tomsio, ORNL/Sub/86-22047/3, GA-C18542, October 1986.

2.6 BASKETS WITH TRIGA ELEMENTS IN THE FUEL PACKAGING AREA

2.6.1 Criticality Evaluation

This evaluation was made with MCNP (MCNP4B2) to determine whether two ISF Baskets, each containing 54 TRIGA fuel elements, will remain safely subcritical if they are passed side-by-side in the ISF Fuel Packaging Area (FPA). This case differs from the case discussed in Section 2.2 in that it uses a more general model of the fuel and basket and multiple cases are analyzed to evaluate the potential effect of neutron scatter from the inside of the FPA walls and basket flooding.

2.6.2 Discussion and Results

These calculations show that 2 dry ISF storage baskets loaded with 54 TRIGA fuel elements each, and passed side-by-side in the FPA, remain safely subcritical, with a $k_{eff} + 2\sigma$ equal to 0.6273. The use of nominal reflection (equivalent to one inch of water) to allow for minor reflection from the building surfaces and equipment is standard practice. The $k_{eff} + 2\sigma$ value drops to 0.5332 with no water reflector.

If the ISF baskets are assumed to be flooded, the $k_{eff} + 2\sigma$ value increases to 0.8543 with a 12-inch water reflector, which is still subcritical. The possibility of these conditions existing is considered very unlikely because as described in the Accident Analysis subsection of SAR Section 8.2.5.3 Flood, the FPA is designed to prevent the ingress of floodwater. Additional design features that ensure the FPA is free of water include no water systems are located within the FPA and the work bench (operating deck) elevation (4938.5 feet) is above the maximum probable flood elevation (4920.71 feet). Also, the basket does not contain an external shell to hold the water.

The results of these calculations are summarized in Table 2.6-1.

2.6.3 Spent Fuel Loading

Each TRIGA ISF basket contained 54 TRIGA fuel elements for a total of 2.37 kilograms of ^{235}U per basket. The nominal TRIGA fuel element fissile material content specified in the ISF Contract (39g ^{235}U) was adjusted to account for variations in post-1964 fuel elements to provide the most reactive and bounding source term for criticality analysis. Manufacturing variations resulted in a higher uranium content and a greater H:Zr atom ratio. The two baskets contained a total of 4.74 kilograms of ^{235}U.

2.6.4 Model Specification

2.6.4.1 Description of Calculational Model

The MCNP model for the dry TRIGA ISF baskets with a 1-inch water reflector is shown in Figures 2.6-1 and 2.6-2. Note that a reflective surface was used on one side of the basket to simulate 2 baskets side-by-side. Table 2.6-2 summarizes the modeled configurations.

2.6.4.2 Regional Densities

Table 2.6-3 summarizes the material atom density compositions used in this calculation.

2.6.5 Criticality Calculations

2.6.5.1 Calculational Methodology

The MCNP4B2 code was used to calculate the k_{eff} value to demonstrate that two baskets of TRIGA fuel passed side-by-side in the FPA would be safely subcritical.

2.6.5.2 Fuel Loading and Other Contents Optimization

Each TRIGA fuel assembly used in these calculations contained 43.875 grams of ^{235}U. There are 108 fuel assemblies per canister. The nominal TRIGA fuel element fissile material content specified in the ISF Contract (39g ^{235}U) was adjusted to account for variations in post-1964 fuel elements to provide the most reactive and bounding source term for criticality analysis. Manufacturing variations resulted in a higher uranium content and a greater H:Zr atom ratio.

There is a potential for two ISF baskets containing TRIGA fuel to be passed side-by-side during operations in the FPA. No water would normally be present during normal or accident conditions, so the model assumes dry conditions within the baskets and between the baskets. A 1-inch water reflector was used to account for minor reflection from building surfaces and equipment. The use of nominal reflection (equivalent to one inch of water) to allow for minor reflection from the building surfaces and equipment is standard practice. A second case was run with no water reflection to assess the impact of far field reflection on the calculated k_{eff} value. A third case was run with the baskets flooded and with a 12-inch reflector.

2.6.5.3 Criticality Results

Table 2.6-1 summarizes the results of these calculations. These calculations show that two dry ISF storage baskets loaded with 54 TRIGA fuel elements each, and passed side-by-side in the FPA, remain safely subcritical, with a $k_{eff} + 2\sigma$ equal to 0.6273 (Case 15-1). A 1-inch water reflector was included to account for reflection from the floor, walls, etc. The $k_{eff} + 2\sigma$ value drops to 0.5332 (Case 15-2) with no water reflector.

If the baskets are assumed to be flooded, the $k_{eff} + 2\sigma$ value increases to 0.8543 (Case 15-3) with a 12-inch water reflector, which is still safely subcritical. The possibility of these conditions existing in the FPA is considered very unlikely because there is no water available in the facility and it is located above the maximum 100 year floodplain. Also, the basket does not contain an external shell to hold the water.

2.6.6 References

Characterization of TRIGA Fuel, N Tomsio, ORNL/Sub/86-22047/3, GA-C18542, October 1986

2.7 TRIGA BASKET OF STAINLESS STEEL CLAD ELEMENTS VERSUS ALUMINUM CLAD ELEMENTS

2.7.1 Criticality Evaluation

The k_{eff} value of stainless steel clad TRIGA fuel was computed and compared against a similar configuration of aluminum clad TRIGA fuel to determine the more reactive of the two fuel systems.

MCNP4C was used to determine k_{eff} of the two systems. The more reactive fuel type was subsequently used in the other criticality safety evaluations.

2.7.2 Discussion and Results

TRIGA fuel was modeled in a fully loaded ISF TRIGA fuel basket configuration. This arrangement consists of 54 fuel elements per basket. Each fuel configuration (stainless steel clad and aluminum clad) was analyzed in both a dry state and fully flooded environment. Full density water was used as the moderator and reflector in the fully flooded cases.

TRIGA fuel baskets in a dry environment served as the baseline for this analysis. Stainless steel clad fuel elements in the dry environment configuration resulted in a computed $k_{eff} + 2\sigma$ of 0.4871. A similar configuration of aluminum clad fuel elements had a calculated $k_{eff} + 2\sigma$ of 0.2804, just over 50% of the computed value for the stainless steel clad fuel element system.

Although the k_{eff} values for the flooded scenarios were notably higher, the difference between the two systems was not as large. The highest k_{eff} was recorded for the fully flooded stainless steel clad TRIGA fuel basket. In this case, $k_{eff} + 2\sigma$ was calculated to be 0.8030. A flooded basket of aluminum clad TRIGA fuel had a calculated $k_{eff} + 2\sigma$ of 0.7488.

The analysis demonstrated that stainless steel clad fuel is the more reactive of the two fuel types and was the more conservative selection used for other calculations supporting the criticality safety evaluation. Results are summarized in Table 2.7-1.

2.7.3 Spent Fuel Loading

Stainless steel clad TRIGA fuel contained a ^{235}U loading of 43.875 grams. Aluminum clad TRIGA fuel, on the other hand, had a nominal ^{235}U loading of 36 grams. A basket of stainless steel clad fuel elements thus contained 2.37 kg of ^{235}U, while a full basket of aluminum clad TRIGA fuel elements contained 1.94 kg of ^{235}U.

2.7.4 Model

2.7.4.1 Description of Calculation Model

The MCNP model of the TRIGA fuel basket is shown in Figures 2.7-1 and 2.7-2. Table 2.7-2 summarizes the modeled properties of each fuel element. As previously mentioned, the basket configuration was the same for both the stainless steel TRIGA fuel system and the aluminum clad fuel system. Variations in the fuel loading, enrichment, and slight changes in geometry were the only differences between the two models.

For this evaluation the gadolinium phosphate neutron poison was not removed from the center of the basket. Removal of the poison was not necessary because the calculations were merely a comparative analysis of the reactivity of a stainless steel clad fuel element configuration against the reactivity of an aluminum clad fuel element configuration. Most important was that the two configurations were identical allowing for direct comparison of the end result. This criterion was met by setting up the model to be a fully loaded ISF TRIGA basket including the gadolinium phosphate.

2.7.4.2 Regional Densities

Both the stainless steel and aluminum clad fuel types have an $UZrH_x$ fuel matrix, where the subscript x represents the H:Zr (hydride) ratio. Table 2.7-3 summarizes the material atom density compositions for materials used in these calculations.

2.7.5 Criticality Calculations

2.7.5.1 Calculation Methodology

The MCNP4C code was used to determine the effective multiplication factor for a basket full of TRIGA fuel with stainless steel cladding and a basket containing aluminum clad fuel. The resulting values were used to determine which fuel type, either the stainless steel clad fuel or the aluminum clad fuel, was the more reactive of the two fuel types. Each basket configuration was evaluated in a dry configuration and then fully flooded and reflected.

2.7.5.2 Fuel Loading and Other Contents Optimization

Stainless steel clad TRIGA fuel elements evaluated contained a 43.875-gram ^{235}U fuel loading. Each element had approximately 9-weight % total uranium enriched to 20% in ^{235}U. Aluminum clad elements contained a nominal 36-gram ^{235}U fuel. Each aluminum-clad element had 8.0 weight % total uranium enriched to 20% in ^{235}U. Hydrogen-zirconium ratios were 1.7 and 1.0 for stainless steel clad and aluminum clad fuel elements, respectively.

A water moderator and reflector was added to the baseline dry model to ensure the presence of a moderator would also demonstrate that stainless steel clad fuel was the more reactive fuel type.

2.7.5.3 Criticality Results

These calculations show that the stainless steel clad fuel elements are the more reactive fuel system. The highest $k_{eff} + 2\sigma$ value of 0.8030 was obtained for stainless steel clad fuel elements in a fully moderated and reflected ISF basket configuration. In contrast the fully flooded ISF basket configuration containing aluminum clad fuel produced a $k_{eff} + 2\sigma$ value of 0.7488. Dry configurations produced an even wider variation in k_{eff} values.

2.7.6 References

Characterization of TRIGA Fuel, N. Tomsio, ORNL/Sub/86-22047/3, GA-C18542, October 1986.

3.0 PEACH BOTTOM FUEL

3.1 PEACH BOTTOM SIDE-BY-SIDE ARRAYS OF 18 ELEMENTS EACH

3.1.1 Criticality Evaluation

Peach Bottom Core 1 fuel will be shipped to the ISF facility in groups of 18 fuel elements that are referred to as fuel-handling units (FHUs). The fuel elements will be delivered in individual cans; however, for this calculation the cans were not included in the calculation model. This allowed a tighter geometric configuration and removed the metal cans that would have reduced the reactivity of the array of Peach Bottom fuel elements.

The calculation was performed to assure that two FHUs passing in close proximity would remain subcritical. This calculation is necessary since the ISF facility may receive more than one FHU during handling of Peach Bottom fuel. It is unlikely that two full arrays of 18 elements would be handled in ISF facility simultaneously because the first FHU would have had some elements removed and packaged into an ISF basket and canister and subsequently removed from the FPA. Two full FHUs were considered in this calculation as a conservative calculation methodology.

3.1.2 Discussion and Results

The MCNP code was used to determine the k_{eff} for an 18 element unmoderated, unreflected array of Peach Bottom fuel. The k_{eff} for the same 18-element array was then computed in a moderated and reflected configuration. Selection of 18 elements was based on the maximum number of Peach Bottom fuel elements delivered to the ISF facility in the Peach Bottom cask. Computed values of k_{eff} were used to demonstrate that two of the 18 element arrays in closed proximity would be subcritical. Results are summarized in Table 3.1-1.

3.1.3 Spent Fuel Loading

Peach Bottom fuel compacts consisted of carbides of uranium (enriched to 93.15% ^{235}U at beginning of life) and thorium, uniformly dispersed as coated particles in a graphite matrix. Each compact, which was approximately 7.62 cm long, contained an initial ^{235}U loading of 9.70 grams. Thirty of these compacts formed the fuel assembly for a total ^{235}U loading of 291.0 grams.

3.1.4 Model Specifications

3.1.4.1 Description of Calculation Model

The MCNP model of the side-by-side Peach Bottom arrays is shown in Figures 3.1-1 and 3.1-2. Table 3.1-2 summarizes the modeled properties of each fuel element.

3.1.4.2 Regional Densities

MCNP is capable of accepting material specifications in a number of forms. The most fundamental of the available forms is in terms of the atom densities of each isotope, expressed in units of atoms per barn centimeter. MCNP internally converts material specifications in the other forms to atom densities in atoms per barn centimeter, using program specific values of Avogadro's constant, isotopic mass, and

isotopic abundance. Material atom densities used in the Peach Bottom array analysis are summarized in Table 3.1-3. Graphite is the exception because this material was entered using its density as opposed to developing an atom density.

3.1.5 Criticality Calculations

3.1.5.1 Calculation Methodology

The MCNP4C code (Monte Carlo N-Particle Transport Code System) was used to perform the criticality calculations. Calculations were performed on two 18-element arrays of Peach Bottom fuel, each array having a pitch of 9 cm. Approximately 9 cm separated the two arrays from one another remaining consistent with the pitch of the arrays themselves.

3.1.5.2 Fuel Loading and Other Contents Optimization

The Peach Bottom fuel element consisted of 30 fuel compacts, each approximately 7.62 cm long, comprising an active fuel length of 228.6 cm. A stack of Type A fuel compacts was located above a stack of Type C fuel compacts, which is located above another stack of Type A fuel compacts. As mentioned previously, Peach Bottom fuel compacts consisted of carbides of uranium (enriched to 93.15% ^{235}U at beginning of life) and thorium, uniformly dispersed as coated particles in a graphite matrix. Each compact contained an initial ^{235}U loading of 9.70 grams. Thirty of these compacts formed the active fuel section for a total ^{235}U loading of 291.0 grams.

A water moderator and reflector was added to the baseline dry model as a very conservative analysis to demonstrate that a moderated and reflected pair of arrays would be subcritical.

3.1.5.3 Criticality Results

Two arrays of Peach Bottom fuel consisting of 18 elements each will remain subcritical in close proximity to one another. This analysis demonstrated this to be true for a dry environment evaluation and an evaluation of a moderated, reflected set of arrays. As expected the higher $k_{eff} + 2\sigma$ value of 0.8594 was obtained for moderated and reflected case.

3.1.6 References

Characterization of Peach Bottom Unit 1 Fuel, R.P. Morisette, N. Tomsio, J. Razvi, ORNL/Sub/86-22047/2, GA-C18525, October 1986.

3.2 CRITICALITY OF CRUSHED PEACH BOTTOM FUEL ASSEMBLIES MODERATED WITH GRAPHITE

3.2.1 Criticality Evaluation

As DOE's contractor, FWENC performed bounding calculations to determine the k_{eff} of graphite moderated Peach Bottom fuel, assuming that all the fuel and graphite in multiple fuel elements was crushed. The analyses assumed that the fragmented fuel assemblies formed a graphite reflected sphere. These calculations determined the number of crushed/shattered fuel assemblies that are needed to reach the criticality safety limit of $k_{eff} + 2\sigma \leq 0.95$.

The DOE also performed criticality analyses for the Peach Bottom fuel. Although DOE assumed that the Peach Bottom fuel was rubblized, they did not consider the non-mechanistic separation of graphite from the fuel and subsequent redistribution as a sphere surrounding the fuel material.

3.2.2 Discussion and Results

The results of these calculations show that in the crushed condition, assumed geometry, and a mix density of 2.14 g/cm^3, significantly more than 21 assemblies can be crushed before the limit set by the validation study of $k_{eff} + 2\sigma \leq 0.9304$ is approached. A density of 2.14 g/cm^3 corresponds to UC_2 and ThC_2 fuel compacts and could only be produced if all the broken fuel pieces were highly compressed into a solid spherical fuel/graphite mass. Such compression would require an external force, but no such force is present. Therefore, this scenario is only hypothetical in nature.

The DOE analyses, which assumed that the fuel is rubblized into a homogenous mixture, required greater than 18 Peach Bottom fuel elements to achieve a k_{eff} of greater than 0.95. Since no more than 18 Peach Bottom fuel elements will be transferred to the ISF Facility in a single fuel container, no criticality concern has been identified.

3.2.3 Spent Fuel Loading

Spent fuel loading is the same as described in Section 3.1.3.

3.2.4 Model Specification

3.2.4.1 Description of Calculational Model

The Peach Bottom Core 1 fuel compacts consisted of carbides of uranium enriched to 93.15% ^{235}U at the beginning of life and thorium, uniformly dispersed as coated particles in a graphite matrix. The total carbon within the carbide substrates was between 11% and 16%, by weight. The pyrolytic carbon-coated particles were between 210 and 595 μm in diameter, with a coating thickness of 55 μm.

The fuel region of a Peach Bottom fuel element is composed of 30 fuel compacts (disks). For this model the graphite in the fuel compacts was evenly homogenized with the fuel. The homogenized mixture was modeled as a sphere with a volume equivalent to that of the fuel compact cylinders. The remaining graphite mass in the fuel elements was assumed to form a reflecting shell surrounding the homogenized fuel/graphite sphere. The sphere size was varied from a volume equal to that from 3 assemblies to that from 21 assemblies. Figure 3.2-1 illustrates a Peach Bottom fuel element. Figure 3.2-2 shows the MCNP model that was used to support the analysis.

As described in SAR Appendix A, Section 4.7.1.2.2 Peach Bottom Core 2 Packaging, the Peach Bottom Unit 1 Core 2 fuel elements have been in dry storage at INTEC. They are transferred in a dry Peach Bottom Transfer Cask. In addition, as further described in SAR Appendix A, the Peach Bottom 1 Core 2 packaging involves the use of three steel liners (the outer Cask Liner, the middle Canister Overpack, and the inner IFSF Fuel Storage Can) that each has a welded bottom plate to the cylindrical portion of the liner. Each of these liners prevents water from entering from the bottom portion of the respective liner. Thus, during normal and off-normal conditions the fuel is in a dry condition. In the case of the accident

condition involving a flood, the maximum probable flood elevation is 4920.71 feet and the Transfer Cask bottom is at elevation 4920.5 feet (refer to SAR Section 3.2.2.4 Flood Protection).

However, in order to assess the sensitivity of the modeled system to additional moderation, calculations were run assuming a 30.5 cm (12-inch) layer of water surrounding the outer graphite reflector. Each base configuration was run both with and without the presence of this additional water reflector.

Table 3.2-1 summarizes the modeled configuration.

3.2.4.2 Regional Densities

The input data for the size and composition of the microspheres and fuel /graphite mixtures was taken from DOE/SNF/REP-041 and Contract Attachment C-A-A. In addition GA-C18525, ORNL/Sub/86-22047/2 shows that there are 33 kg of carbon per element. This additional carbon was assumed to form a reflecting shell surrounding the homogenized fuel/graphite sphere.

Table 3.2-2 summarizes the MCNP material atom densities used in these calculations. The fuel/graphite density was calculated to be 2.14 g/cm^3 based on the mass of fuel and carbon present in the compacts. The 2.14 g/cm^3 could only be produced if all the broken pieces were highly compressed into a solid mass, and there is no mechanism for that to happen. This represents a limiting case.

3.2.5 Criticality Calculations

3.2.5.1 Calculational Methodology

The MCNP4C code (Monte Carlo N-Particle Transport Code System, CCC-700, Radiation Safety Information Computational Center, Oak Ridge National Laboratory) was used for the criticality calculations. The k_{eff} was determined for graphite moderated Peach Bottom fuel in a spherical configuration (see Figure 3.2-2) with the MCNP code.

3.2.5.2 Fuel Loading and Other Contents Optimization

Spent fuel loading is the same as described in Section 3.1.3.

3.2.5.3 Criticality Results

The results of these calculations, both with and without additional reflection by water, are shown in Table 3.2-3 and Figure 3.2-3. The results show a moderate sensitivity to the addition of reflecting material (i.e., water) surrounding the outer graphite shell. However, the calculated values of k_{eff} did not approach the upper safety limit, even when 21 fuel elements were assumed to be crushed and reconfigured into a spherical configuration and additional moderation provided by an outer layer of water.

3.2.6 References

Section C, Attachment C-A-A, “Fuel and Fuel Package Description”, to DOE Contract DE-AC07-00ID13729.

GA-C18525, ORNL/Sub/86-22047/2, Characteristics of Peach Bottom Unit 1 Fuel, R. P. Morissette et al., October 1986.

3.3 PEACH BOTTOM ELEMENTS IN STORAGE CANISTER

3.3.1 Criticality Evaluation

The purpose of this calculation is to determine the reactivity of the Peach Bottom spent fuel elements in the ISF storage canister configuration as a function of spacing between the elements and as a function of moderation and reflection. The results of these calculations will be used in a nuclear criticality safety assessment for handling the Peach Bottom spent fuel elements in ISF Facility.

3.3.2 Discussion and Results

The criticality analyses for moderated conditions with the 18 elements in a hexagonal array and 0.1 cm separation distance edge to edge shows that 18 Peach Bottom fuel elements will have a maximum $k_{eff} + 2\sigma = 0.913$ for full density water between the fuel elements. Hexagonal arrays of Peach Bottom fuel elements ranging from 6 to 37 fuel elements were analyzed.

3.3.3 Spent Fuel Loading

Spent fuel loading is the same as described in Section 3.1.3.

3.3.3.1 Description of Calculational Model

The number of Peach Bottom fuel elements was varied from 6 to 37 and the analyses were done with and without moderation and reflection for these criticality analyses. The number of fuel elements was varied by removing the fuel elements from an outer surface of the hexagonal model. As an example, four elements along one surface were removed to change the MCNP model for 37 elements (Case 26C-1), to the model for 33 elements (Case 26C-2). Figure 3.2-1 illustrates a Peach Bottom fuel element. Typical Peach Bottom arrays used in these analyses are shown in Figures 3.3-1, 3.3-2, 3.3-3 and 3.3-4. The fuel elements and the graphite reflector and spine were modeled both dry and containing entrained water (saturated). Table 3.3-1 summarizes the modeled configuration.

Fuel compact composition types A and C in Table 3.3-2 were used for the criticality analyses to make the Type II fuel elements which are the majority of the fuel elements, as shown in Table 3.3-3. As shown in Table 3.3-2 and 3.3-3, Type II fuel is the combination with the maximum amount of U235 and the minimum amount of thorium, rhodium, or poison in the spines. It is therefore the most reactive element.

3.3.3.2 Regional Densities

Peach bottom fuel material atom density compositions are shown on Table 3.3-4.

3.3.4 Criticality Calculations

3.3.4.1 Calculational Methodology

The MCNP Monte Carlo radiation transport program, MCNP4B2, Monte Carlo N-Particle Transport Code System, CCC-660, Radiation Safety Information Computational Center, Oak Ridge National Laboratory, Oct 1997 (MCNP1997) was used for the criticality calculations.

3.3.4.2 Fuel Loading and Other Contents Optimization

Hexagonal arrays of Peach Bottom fuel elements ranging from 6 to 37 fuel elements were analyzed.

3.3.4.3 Criticality Results

The criticality analyses for moderated conditions with the 18 elements in a hexagonal array and 0.1 cm separation distance edge to edge shows that 18 Peach Bottom fuel elements will have a maximum value of $k_{eff} + 2\sigma = 0.913$ for full density water between the fuel elements. Hexagonal arrays of Peach Bottom fuel elements ranging from 7 to 37 fuel elements were analyzed. Results of the calculation are shown in Tables 3.3-5 and 3.3-6 and Figures 3.3-5 through 3.3-10.

3.3.5 References

Section C, Attachment C-A-A, DOE Contract No. DE-AC07-00ID13729, 'Fuel and Fuel Package Descriptions.

3.4 PEACH BOTTOM CANISTERS IN STORAGE TUBES

3.4.1 Criticality Evaluation

The purpose of this calculation is to calculate the reactivity of Peach Bottom ISF canisters filled with 10 elements and placed in a storage tube. The reactivity of a single tube up to an infinite array of tubes was evaluated as a function of moderation and reflection. The results of these calculations are used in the nuclear criticality safety assessment for handling the Peach Bottom spent fuel canisters in the ISF Facility. This calculation was used as the basis for estimating the reactivity associated with the movement of a filled canisters past another filled canister.

3.4.2 Discussion and Results

The maximum calculated value of reactivity was $k_{eff} + 2\sigma = 0.496$ for an infinite array of storage tubes at optimum spacing, 1.1 cm edge to edge. This is more reactive than will be encountered with the actual storage tube spacing. The criticality analyses for the stored fuel show that the reactivity does not change significantly if the storage vault is flooded or if the storage tube steel walls were replaced with water. The movement of one filled canister past another filled canister is not a possibility but it does bound the reactivity associated with any type of charging accident. Reactivity of double stacking in a tube is less because the neutron interaction between side-by-side canisters is greater than the interaction between canisters end-to-end.

3.4.3 Spent Fuel Loading

A Peach Bottom fuel element contains 291 grams of ^{235}U, which results in a total of 2.91 kilograms of ^{235}U for a Peach Bottom ISF basket containing 10 Peach Bottom fuel elements.

3.4.4 Model Specification

3.4.4.1 Description of Calculational Model

The Peach Bottom fuel elements were modeled using the dimensions in Figure 1-1 which is included in this document as Figure 3.2-1. Table 1-4 describes the fuel elements and is included here as Table 3.4-1, the fuel compositions in Table 1-1 are included in Table 3.3-2. Table 1-2 is included as Table 3.3-3 and shows the four different types of fuel elements that were fabricated and used in the Peach Bottom reactor. Tables 3.3-2 and 3.3-3 indicate that fuel compacts were types A,B,C, and D and fuel elements are types I,II,III, and IV. The majority of elements were type II, which were also the most reactive, and the majority of fuel compacts were type C. Therefore the Type C fuel compact composition was used for these criticality calculations. The fuel elements and the graphite reflector and spine were analyzed both dry and containing entrained water (saturated). Table 3.4-2 summarizes the model configurations.

The Peach Bottom fuel storage basket loaded with 10 fuel elements was analyzed for a number of wet and dry conditions. The basket was modeled in the canister in a storage tube. These analyses used reflecting planes to model arrays of 2 storage tubes, 4 storage tubes, and an infinite array of storage tubes. The infinite array was also analyzed with the storage tube metal replaced with water. Views of the model are included as Figures 3.4-1, 3.4-2, and 3.4-3. The fuel elements are loaded into the ISF fuel baskets and the fuel basket is then placed in the ISF canister which is then inserted into the storage tubes.

3.4.4.2 Regional Densities

Peach Bottom fuel material atom density compositions are the same as used in the calculation described in Section 3.3 and are provided in Table 3.3-4.

3.4.5 Criticality Calculations

3.4.5.1 Calculational Methodology

The MCNP Monte Carlo radiation transport program, MCNP4B2, Monte Carlo N-Particle Transport Code System, CCC-660, Radiation Safety Information Computational Center, Oak Ridge National Laboratory, Oct 1997 (MCNP1997) was used for the criticality calculations.

3.4.5.2 Fuel Loading and Other Contents Optimization

A Peach Bottom fuel element contains 291 grams of ^{235}U, which results in a total of 2.91 kilograms of ^{235}U for a Peach Bottom basket containing 10 Peach Bottom fuel elements.

3.4.5.3 Criticality Results

Table 3.4-3 summarizes the results of the criticality calculations. The maximum calculated value of reactivity was $k_{eff} + 2\sigma = 0.496$ for an infinite array of storage tubes at optimum spacing of 1.1 cm edge to edge. This is more reactive than will be encountered with the actual storage tube spacing. The criticality analyses for the stored fuel show that the reactivity does not change significantly if the storage vault is flooded or if the storage tube steel walls were replaced with water. The fuel is expected to be dry rather than the saturated condition used in the most reactive configuration.

3.4.6 References

Section C, Attachment C-A-A, DOE Contract No. DE-AC07-00ID13729, 'Fuel and Fuel Package Descriptions'.

3.5 PEACH BOTTOM AND TRIGA CANISTERS IN STORAGE TUBES

3.5.1 Criticality Evaluation

The purpose of this calculation is to calculate the reactivity of the Peach Bottom and TRIGA spent fuel element storage canisters in storage tubes in the storage facility array configuration. The results of these calculations will be used in a nuclear criticality safety assessment for handling the Peach Bottom spent fuel canisters in ISF Facility.

3.5.2 Discussion and Results

The maximum calculated value of reactivity was $k_{eff} + 2\sigma = 0.838$ for a single Peach Bottom fuel canister in a storage tube combined with a single TRIGA fuel canister in a storage tube for a storage tube spacing of 34 inches on centers. There is no criticality concern for the spent fuel storage facility as long as the fuel elements are retained within the basket and canister.

The neutron interactions between the Peach Bottom fuel and the TRIGA fuel for the side-by-side configuration are greater than the interactions for an end-to-end configuration. Thus, the results serve as an upper limit for the end-to-end configuration.

3.5.3 Spent Fuel Loading

A Peach Bottom fuel element contains 291 grams of ^{235}U, which results in a total of 2.91 kilograms of ^{235}U for a Peach Bottom basket containing 10 Peach Bottom fuel elements. A TRIGA fuel element contains 43.875 grams of ^{235}U, which results in a total of 2.37 kilograms of ^{235}U for a full TRIGA basket containing 54 TRIGA fuel elements. The nominal TRIGA fuel element fissile material content specified in the ISF Contract (39g ^{235}U) was adjusted to account for variations in post-1964 fuel elements to provide the most reactive and bounding source term for criticality analysis. Manufacturing variations resulted in a higher uranium content and a greater H:Zr atom ratio.

3.5.4 Model Specification

3.5.4.1 Description of Calculational Model

The Peach Bottom fuel element dimensions are included as Figure 3.2-1. Fuel element descriptions are included in Table 3.4-1. The fuel compositions are included as Table 3.3-2. Table 3.3-3 shows the four different types of fuel elements that were fabricated and used in the Peach Bottom reactor. Fuel compacts of Type C are the most reactive and the majority of fuel elements from Table 3.3-3. Therefore, the Type C fuel composition was used for these criticality calculations. The Peach Bottom fuel elements and graphite reflector and spine are modeled containing entrained water (saturated) for these analyses. The saturated fuel elements include a 20% void fraction that is assumed to be filled with water. Table 3.4-2 summarizes the modeled configuration for Peach Bottom fuel.

The spent fuel ISF storage basket in each ISF canister in the ISF storage tube were modeled as shown in Figure 3.4-1. The Peach Bottom fuel storage basket contains 10 fuel elements and is stored in fuel storage tubes in the basket in the locations as shown in Figure 3.4-3.

The TRIGA fuel elements were modeled using the dimensions in Figure 3-1 and the material descriptions in Table 3-1, of the DOE Contract. Figure 3-1 is included as Figure 3.5-1 and Table 3-1 is included as Table 3.5-1. The fuel rod ISF basket model was based on the basket drawing, shown in Figure 3.5-2. The TRIGA ISF canister containing two baskets is shown in Figure 3.5-3. The TRIGA impact plate and canister head details are included in Figure 3.5-3. Each basket contains 54 fuel elements as shown in the cross-section view through the MCNP model in Figure 3.5-4. The fuel elements are stored in the ISF basket in storage pipes in the locations as shown in Figure 3.5-4. Figure 3.5-5 is a plan view for the MCNP model of the TRIGA and Peach Bottom fuel canisters and storage tubes. A poison rod is placed in the TRIGA basket center position and it is not possible to load fuel elements in that position. No credit was taken for the neutron poison rod in the calculation. Tables 3.4-2 and 3.5-2 summarize the Peach Bottom and TRIGA modeled configurations.

The water density between the storage tubes was varied from dry (0 g/cm^3) to 1 g/cm^3 to evaluate the sensitivity of the reactivity as a function of interspersed moderation. Results from varying the density are shown in Table 3.5-3.

3.5.4.2 Regional Densities

Peach Bottom fuel material atom density compositions are the same as used in previous calculations and are provided in Table 3.3-4. Table 3.5-4 summarizes the material atom density compositions for TRIGA fuel materials.

3.5.5 Criticality Calculations

3.5.5.1 Calculational Methodology

The MCNP Monte Carlo radiation transport program, MCNP4B2, MCNP1997 was used for the criticality calculations. All calculations associated with this report were performed using the MCNP4B2 Monte Carlo Code, and the ENDF/B-VI cross section library.

3.5.5.2 Fuel Loading and Other Contents Optimization

A Peach Bottom fuel element contains 291 grams of ^{235}U, which results in a total of 2.91 kilograms of ^{235}U for a Peach Bottom basket containing 10 Peach Bottom fuel elements. A TRIGA fuel element contains 43.875 grams of ^{235}U, which results in a total of 2.37 kilograms of ^{235}U for a full TRIGA basket containing 54 TRIGA fuel elements. Note that the TRIGA fuel element was conservatively modeled without the 0.25-inch diameter hole through the center of the fuel. Because the density was not adjusted the resulting fissile mass loading is approximately 3% higher than it would be if the hole were included in the model.

3.5.5.3 Criticality Results

The maximum calculated value of reactivity was $k_{eff} + 2\sigma = 0.838$ for a single Peach Bottom fuel canister and a single TRIGA fuel canister in separate storage tubes spaced 34 inches on centers. The criticality

analyses for the stored Peach Bottom fuel in an infinite array of fuel canisters in storage tubes showed that the reactivity does not change significantly for a flooded storage vault or if the storage tube steel walls are replaced with water. This is documented in Section 3.4. The maximum calculated value of reactivity for an infinite array of Peach Bottom fuel canisters in storage tubes was $k_{eff} + 2\sigma = 0.496$.

The maximum calculated value of reactivity for storage vault fully loaded with TRIGA fuel canisters in storage tubes was $k_{eff} + 2\sigma = 0.815$. This is documented in Section 2.3. Thus there is no criticality concern as long as the fuel elements are intact and retained within the basket and canister.

The neutron interactions between the Peach Bottom fuel and the TRIGA fuel for the side-by-side configuration are greater than the interactions for an end-to-end configuration. Thus, the results serve as an upper limit for the end-to-end configuration.

3.5.6 References

Section C, Attachment C-A-A, Contract No. DE-AC07-00ID13729, ‘Fuel and Fuel Package Descriptions.

4.0 SHIPPINGPORT FUEL

4.1 REFLECTOR RODS IN AN INFINITE ARRAY

4.1.1 Criticality Evaluation

Criticality analyses are required for all fuel that will be brought into the ISF storage facility. The only Shippingport components that are currently planned to be stored in the ISF storage vault are the reflector assemblies. Therefore, bounding criticality analyses were performed for the reflector rods. The active region of the fuel rods is composed of reflector pellets (about 140 pellets/rod). This is considered a non-credible event, since it is not possible to create an infinite array of fuel pellets or rods. This case was performed to determine if the Shippingport reflector fuel (Type IV and V assemblies, and loose rods) represents any criticality hazard.

4.1.2 Discussion and Results

These MCNP (MCNP4B2) calculations show that an infinite array of dry reflector pellets will have a k_{eff} of 0.185 (k_{eff} of 0.184 + 2σ=0.001). The array of pellets was considered to be dry because water flooding of the pellets after an accident involving the release of the pellets from the rods is considered incredible.

The calculations show that an infinite array of water moderated reflector rods with an optimum triangular pitch spacing of one inch will have a k_{eff} of 0.652 (k_{eff} of 0.649 +2σ of 0.003). Therefore, reflector assemblies will be critically safe in all credible condition in the ISF Facility.

4.1.3 Spent Fuel Loading

The maximum post irradiation fissile content measured for any rod was 39.7 grams (WAPD-TM-1614). The entire 39.7 grams was assumed to be U-233 for all rods in these calculations.

4.1.4 Model Specification

4.1.4.1 Description of Calculational Model

Calculations were performed for an infinite array of unmoderated reflector pellets, and for an infinite array of moderated rods with varying pitch. The pellet and rod dimensions were taken from WAPD-TM-1208.

The MCNP geometry for the rod calculations is shown in Figures 4.1-1 and 4.1-2. The model is a single rod with a triangular pitch. The infinite array is generated by putting reflecting surfaces on all sides of the model. An inch of water was placed above and below the rod prior to the reflecting surfaces on the top and bottom. Table 4.1-1 summarizes the modeled configuration.

4.1.5 Criticality Calculations

4.1.5.1 Calculational Methodology

MCNP4B2 was used to determine the reactivity of this fuel. At the beginning of life the reflector assembly rods were composed of Zr clad ThO_2 pellets only, but reactor operation bred U-233 (and significantly less other fissile materials) into the assemblies. Therefore, criticality calculations were

performed for post irradiation reflector components. The U-233 content for these calculations was taken from the maximum post-irradiation measurement of reflector rods (WAPD-TM-1614). The remainder of the post irradiation composition was taken from Attachment C-A-A. Calculations were performed for an infinite array of unmoderated reflector pellets, and for an infinite array of moderated rods with varying pitch.

4.1.5.2 Fuel Loading and Other Contents Optimization

The maximum post irradiation fissile content measured for any rod was 39.7 grams (WAPD-TM-1614). The entire 39.7 grams was assumed to be U-233 for all rods in these calculations. The maximum post irradiation rod loadings were taken from WAPD-TM-1614 and the resulting MCNP input data are given in Table 4.1-2.

4.1.5.3 Criticality Results

These MCNP (MCNP4B2) calculations show that an infinite array of dry reflector pellets will have a k_{eff} of 0.184 and 1 σ of 0.0005.

The calculations show that an infinite array of water moderated reflector rods with an optimum triangular pitch spacing of one inch will have a k_{eff} of 0.649 and σ of 0.0015. Table 4.1-3 and Figure 4.1-3 show the results of the calculations as a function of rod spacing.

Since the reflector rods will be critically safe in any configuration the reflector assemblies will also be safe in any configuration.

4.1.6 References

Section C, Attachment C-A-A, Fuel and Fuel Package Descriptions, DOE Contract No. DE-AC07-00ID13729

WAPD-TM-1614, Nondestructive Assay of Spent Fuel Rods from a Light Water Breeder Reactor, G Tessler et al, September 1987.

WAPD-TM-1208, Design of the Shippingport Light Water Breeder Reactor, D. R. Connors et al., January 1979.

5.0 CRITICAL BENCHMARK EXPERIMENTS

The validation process was used to determine biases for calculating the k_{eff} of fuel element systems. Therefore, the experiments selected as benchmark cases included $U(17)O_2$ annular rods and TRIGA Mark II Reactor fuel in water (IEU experiments), Rover fuel which had HEU in thorium in a graphite matrix, HEU and ZrH rods in water, Oralloy cubes in water, and SPERT-D plate fuel elements in water. These cases were selected because they represent the range of fuel to be repackaged and stored at the ISF Facility.

Described in more detail below, these configurations were varied enough in fuel, material, and moderation that they were considered adequate validation for calculating a number of fuel handling and accident conditions.

5.1 BENCHMARK EXPERIMENTS AND APPLICABILITY

Water-Moderated U(17)O2 Annular Fuel Rods without Absorber and with Gadolinium or Calcium Absorbers in 6.8-cm-Pitch Hexagonal Lattices at Different Temperatures [IEU-COMP-THERM-002]

These experiments were critical approach experiments using stainless-steel-clad UO_2 fuel rods (17 weight percent ^{235}U) in a water-filled tank. Lattice arrangements were comprised of one of three forms of the fuel rod, which created either a configuration with an absorber element (Gd or Cd) or with no absorber element. Evaluated experiments contained no absorber element. Fuel elements were constructed of two sets of concentric stainless steel tubes. The first set consisted of concentric cylinders with outside diameters of 2.40 cm and 2.92 cm with a wall thickness of 0.03 cm and an overall length of 60.6 cm. Uranium dioxide filled the interstitial space between the two cylinders. The second set of tubes was similar to the first with the exception of having 3.66 cm and 4.18 cm. Fuel rod parts were placed into a stainless-steel tube with an outer diameter of 4.58 cm. Lattice arrangements were investigated at room and raised temperatures. These experiments allowed evaluation of temperature effects on the reactivity of latticed fuel element systems.

TRIGA Mark II Reactor: U(20) – Zirconium Hydride Fuel Rods in Water with Graphite Reflector [IEU-COMP-THERM-003]

Selection of these critical experiments for the validation allowed for the evaluation of an arrayed system of TRIGA fuel elements in the presence of a water moderator. At 28 inches in length (15 inches of fuel meat), 1.478 inches in diameter, and clad by stainless-steel (SS-304), the fuel elements are nearly identical to those modeled in ISF Facility analyses. Fuel elements in the experiment are slightly higher in total uranium loading (12 weight percent U vs. 8.5 weight percent U) than the ISF Facility fuel; however, each is enriched to 20% in ^{235}U. The fuel is a homogenous mixture of uranium and zirconium hydride (ZrH) with a H:Zr ratio of 1.60 according to manufacturer documentation. Overall, the physical characteristics, geometry of the problem, and moderator material make this an excellent validation problem set for the TRIGA fuel type.

Graphite and Water Moderated NRX-A3 and NRX-A4 Assemblies [HEU-COMP-THERM-002]

Consisting of a fuel type commonly referred to as Rover fuel, these experiments are critical experiments of hexagonal graphite rods containing highly enriched uranium moderated and reflected by water. Each

NRX-A fuel element was a nominally 52-inch-long hexagonal graphite cylinder with a 0.870-inch diagonal, containing 19 uniformly spaced longitudinal holes. Distributed uniformly within the graphite matrix were pyrolytic-graphite-coated uranium dicarbide beads. With an enrichment of 93.15 weight percent ^{235}U, the Rover fuel possesses fuel characteristics very similar to those of Peach Bottom fuel. The experiments consist of various arrays of the NRX-A4 and NRX-A3 fuel intermixed in predefined geometric patterns. As in the case of Peach Bottom fuel, the hexagonal Rover is an unclad fuel element. Overall, these experiments were judged excellent as a representative group of critical experiments satisfactory to validate determination of k_{eff} for Peach Bottom fuel.

Water-Moderated Hexagonally Pitched Double Lattices of U(80%)O_2 + Cu Fuel Rods and Zirconium Hydride Rods [HEU-COMP-THERM-007]

Selected as a benchmark experiment for validation of parameters similar to TRIGA fuel, these critical experiments contain water-moderated hexagonally pitched lattices with highly enriched (approximately 80% ^{235}U) fuels rods of cross-shaped cross-section. Included in the lattice along with the fuel rods were several zirconium hydride rods. Although higher in enrichment than TRIGA fuel, the double lattices allowed for evaluation of the reactivity effects of varying zirconium hydride parameters.

Intermediate Heterogeneous Assembly with Highly Enriched Uranium Dioxide (96% ^{235}U) and Zirconium Hydride Moderator [HEU-COMP-MIXED-003; Formerly HEU-COMP-INTER-001]

These experiments were performed to investigate the criticality safety of a highly enriched fuel system (approximately 96% in ^{235}U) in the presence of a zirconium hydride moderator and beryllium reflector. Safety drums in the configuration contained a natural boron carbide poison. The experiment was selected for analysis based on the presence of ZrH as moderator and a chance to evaluate the effects of an absorber poison.

Lattices of Oralloy Cubes in Water [HEU-MET-THERM-003]

These experiments were conducted using cubic or nearly cubic lattices of oralloy cubes immersed in a tank of water. Oralloy denotes uranium enriched to approximately 93%, very similar to the enrichment of the Peach Bottom fuel. Water moderation and reflection were also strong contributors for selection of this fuel system as a benchmark experiment.

SPERT-D Aluminum-Clad Plate Type Fuel in Water, Dilute Uranyl Nitrate, or Borated Uranyl Nitrate

Several critical configurations involving SPERT-D fuel elements were used in experiments performed to determine specifications for storage, transport, and chemical processing of SPERT-D fuel. Twenty-two plates containing on average 304.46 g ^{235}U made up the fuel system configuration. The core was enriched to 93.17%, with the uranium-alloy being 23.8 weight percent uranium. Each individual plate contained on average 13.93 grams, with individual plate loadings varying between 13.2 grams and 14.7 grams. Selected benchmark experiments were moderated and reflected with demineralized water.

5.2 RESULTS OF BENCHMARK CALCULATIONS USING MCNP4B2

5.2.1 Experiment Descriptions

A combination of 55 IEU and HEU critical experiments were selected for use in determining the calculation bias for the MCNP4B2 computer code system. The bias value was subsequently used in the computation of the upper safety limit (USL) for any calculation performed with MCNP4B2. Table 5.2-1 gives a brief summary and number of the critical experiments selected.

5.2.2 Validation Approach

The data from the criticality experiments do not meet the necessary test results for a statistically normal data distribution. Therefore, a non-parametric approach based on NUREG/CR-6698 guidance was used to develop the final USL for calculations using MCNP4B2. Determination of the confidence level is based on the number of experiments available in the dataset population. The confidence level, β, is calculated using the following equation:

$$\beta = 1 - q^n$$

where, q = the desired population fraction (normally 0.95) and n = the number of data in one data sample.

The confidence level computed is to be applied to 95% of the dataset population. Substitution of 0.95 into the equation and replacing n with 55 (the number of critical experiments in the dataset), results in a confidence level calculated to be 0.9405 or 94.05%.

A 95% confidence level is required by guidance documents (NUREG-1567, Section 4.5.3.5, Criticality). Therefore, an additional margin of safety will be added in the computation to ensure that the selected USL provides the necessary confidence level.

For non-parametric data analysis the combination of bias and bias uncertainty, K_L, is calculated by subtracting the uncertainty and a non-parametric margin (NPM) from the lowest observed k_{eff} value of the dataset. The NPM is added to account for small sample sizes. For confidence levels greater than 90%, the NPM is "0" as provided in Table 2.2 of NUREG/CR-6698. Removal of NPM reduces the equation for K_L to the lowest value of k_{eff} minus the uncertainty.

The USL is then calculated by subtracting a subcriticality margin from K_L. An additional term may be added in the safety evaluation if it is intended to operate outside the area of applicability. Before actually computing the confidence level and the USL, certain parameters were plotted to assess the presence of trends in the data. Figures 5.2-1 and 5.2-2 illustrate k_{eff} plotted against the independent variables ^{235}U enrichment and average neutron lethargy causing fission, respectively. No clear trends exist in the data population as shown in these figures. An attempt to fit trend lines to the data produced very low R^2 values, symptomatic of a poorly fitting trend line. Therefore, the conclusion was drawn that the area of applicability term in the USL calculation could be set to 0 based on the fact that the calculations to be performed with MCNP4B2 would not be evaluating systems with parameters outside the area of applicability. A minimum subcritical margin (Δ_{SM}) is used in the calculation of the USL to ensure subcriticality of the system being analyzed. The value of this subcritical margin may vary under different circumstances; however, standard practice assumes a value of 0.05.

For systems that will be evaluated using the MCNP4B2 computer code, the definition of the USL will be modified as follows:

$$USL = K_L - \Delta_{SM} - \Delta_{SF}$$

where the Δ_{SF} term is an additional safety factor that will be applied to compensate for the fact that the confidence level was calculated to be 94%. This safety factor will be assigned the very conservative value of 0.02.

5.2.3 Summary of Results

Calculated k_{eff} results are listed in Table 5.2-2 along with the benchmark k_{eff} results, and a normalized k_{eff} value. At times it is necessary to make an adjustment to the calculated k_{eff} if the critical experiment was at other than a critical state (i.e., slightly supercritical or subcritical). Taking a ratio of the calculated k_{eff} value to the benchmark k_{eff} value accomplishes this normalization process. Normalized values were subsequently used in determination of the USL. Individual standard deviation values are included as well for the calculated k_{ef}f results.

Using the equation above and substituting in the appropriate values produces the following result for the USL:

$$USL = K_L - \Delta_{SM} - \Delta_{SF}$$

$$USL = (0.9840 - 0.0010) - 0.05 - 0.02$$

$$USL = 0.9130$$

5.3 RESULTS OF BENCHMARK CALCULATIONS USING MCNP4C

5.3.1 TRIGA Fuel

Criticality experiments were selected from the International Handbook of Evaluated Criticality Safety Benchmark Experiments [Handbook] as the basis of the validation for TRIGA fuel. The Handbook data is used preferentially because these benchmarks are well described for criticality safety purposes and because descriptions are subject to an extensive peer review. In all cases, these experiments were either remodeled based on their description, or models developed by others were checked to ensure that modeling techniques and input are comparable to this evaluation's methodology.

The validation of MCNP4C resulted in distinct upper safety limits for TRIGA and Peach Bottom fuel types. Both evaluations employed a statistical approach to derivation of the upper safety limit to be used in criticality calculations. The validation methodology for TRIGA fuel is described in this section and for Peach Bottom is described in the section that follows.

5.3.1.1 Experiment Descriptions

The 72 critical experiments selected for use in this evaluation were comprised of three main categories: lattice experiments, reactor configuration experiments, and square pitched array experiments. Table 5.3-1 gives a brief summary and number of the critical experiments selected. The experiments covered a wide range of parameters representative of storage configurations.

5.3.1.2 Validation Approach

Validation of the MCNP computer code is required by the criticality safety standard ANSI/ANS-8.1. The criterion to establish subcriticality safety margins is prescribed in ANSI/ANS-8.17, as follows:

$$k_s \leq k_c - \Delta k_s - \Delta k_c - \Delta k_m$$

where:

k_s = calculated allowable maximum multiplication factor, k_{eff}, of system being evaluated for all normal or credible abnormal conditions or events

k_c = mean k_{eff} that results from calculation of benchmark criticality experiments using particular calculation method. If calculated k_{eff} values for criticality experiments exhibit trend with parameter, then k_c shall be determined by extrapolation based on best fit to calculated values. Criticality experiments used as benchmarks in computing k_c should have physical compositions, configurations, and nuclear characteristics (including reflectors) similar to those of system being evaluated

Δk_s = allowance for: (a) statistical or convergence uncertainties, or both, in computation of k_s, (b) material and fabrication tolerances, and (c) geometric or material representations used in computation method [uncertainty in the value of k_s]

Δk_c = margin of uncertainty in k_c which includes allowance for: (a) uncertainties in critical experiments, (b) statistical or convergence uncertainties, or both, in computation of k_c, (c) uncertainties resulting from extrapolation of k_c outside range of experimental data, and (d) uncertainties resulting from limitations in geometrical or material representations used in computation method [uncertainty in the value of k_c]

Δk_m = arbitrary margin to ensure subcriticality of k_s

Prior to calculating the subcriticality safety margin, certain parameters were plotted to assess the presence of trends in the benchmark criticality data. Figures 5.3-1 through 5.3-4 illustrate k_{eff} plotted against the independent variables ^{235}U enrichment, average neutron lethargy causing fission, average fission group energy, and moderator/fuel volume ratio, respectively. No clear trends exist in the data population as shown in these figures. An attempt to fit trend lines to the data produced very low R^2 values, symptomatic of a poorly fitting trend line. Therefore, the mean value of k_{eff} results of benchmark criticality experiments can be used for k_c in this calculation.

Setting Δk_m to 0.05 and substituting $\Delta\beta$ for Δk_c, the above equation can be rewritten as:

$$k_s \leq k_c - \Delta k_s - \Delta\beta - 0.05$$

k_c can be rewritten as $1-(1-k_c)$ which allows the substitution of β for $(1-k_c)$, which is the bias. Substitution of terms results in further reduction of the equation to:

$$k_s \leq 1-(1-k_c) - \Delta k_s - \Delta\beta - 0.05$$

Or

$$k_s \leq 1 - \beta - \Delta k_s - \Delta\beta - 0.05$$

Finally, the equation can be reduced to a final form that applies the bias and uncertainties to the k_{eff} of the system being analyzed. The modified equation appears as:

$$k_{eff} + \Delta k_s + \beta + \Delta\beta \leq 0.95$$

5.3.1.3 Summary of Results

The k_{eff} results for the experiments along with their associated uncertainty are shown in Table 5.3-2. The overall average and standard deviation of these 72 cases is 0.9894±0.0062. The average Monte Carlo error (statistical convergence) is ±0.0015 for the 72 cases. Uncertainty resulting from limitations of geometrical modeling is taken to be 0.0 based on the fact that the MCNP models are three-dimensional, fully explicit representations (no homogenization) of the experiment geometry. Experiment error is conservatively taken to be ±0.0001 so that the criticality can then be represented as 1.0000±0.0010.

Average difference between code calculated and the critical condition is $\beta = 1 - 0.9894 = 0.0106$. The uncertainty in the bias, accounting for the statistical convergence and the uncertainty in criticality is $(0.0062^2 - 0.0015^2 + 0.0010^2)^{1/2} = 0.0061$. For 72 samples of criticality, the 95/95 one-sided tolerance factor can be taken as 2.065 [Table 2.1, NUREG/CR-6698]. The result is a 95/95 one-sided uncertainty in the bias, $\Delta\beta$, of 2.065 x 0.0061 = 0.0126. The equation from above may now be written as:

$$k_{eff} + \Delta k_s + 0.0106 + 0.0126 \leq 0.95$$

If the worst-case mechanical and material tolerances are used to calculate k_s, the value of Δk_s can be taken as 0 and an upper safety limit (USL) can be extracted as:

$$USL = 0.95 - 0.0106 - 0.0126$$

Or

$$USL = 0.9268$$

5.3.2 Peach Bottom Fuel

5.3.2.1 Experiment Descriptions

The 58 critical experiments selected for use in this evaluation were comprised of three main categories: lattice experiments, reactor configuration experiments, and square pitched array experiments. Table 5.3-3 gives a brief summary and number of the critical experiments selected for Peach Bottom fuel. The experiments covered a wide range of parameters representative of storage configurations.

5.3.2.2 Validation Approach

Validation of MCNP4C for use in calculating k_{eff} for Peach Bottom fuel systems was performed using a non-parametric analysis as described in NUREG/CR-6698. This analysis results in determination of the degree of confidence that a fraction of the true population of data lays above the smallest observed value.

An equation for the percent confidence that a fraction of the population is above the lowest observed value reduces to:

$$\beta = 1 - q^n$$

where:

q = the desired population fraction (normally 0.95)

n = the number of data in one sample

Information extracted from this equation and evaluation is then used to determine K_L, which represents the combination of bias and bias uncertainty:

K_L = lowest k_{eff} - σ (uncertainty of lowest k_{eff}) – NPM (non-parametric margin)

The non-parametric margin is a value that is added to account for variability in results that may result from the use of small sample sizes. A table of recommended values is provided in NUREG/CR-6698, Section 2.4.4.

An additional term may be added in the safety evaluation if it is intended to operate outside the area of applicability. Before actually computing the confidence level and the USL, certain parameters were plotted to assess the presence of trends in the data. Figures 5.3-5 through 5.3-8 illustrate k_{eff} plotted against the independent variables ^{235}U enrichment, average neutron lethargy causing fission, average fission group energy, and moderator/fuel volume ratio, respectively. No clear trends exist in the data population as shown in these figures. An attempt to fit trend lines to the data produced very low R^2 values, symptomatic of a poorly fitting trend line. Therefore, the conclusion was drawn that the area of applicability term in the USL calculation could be set to 0 based on the fact that the calculations to be performed with MCNP4C would not be evaluating systems with parameters outside the area of applicability.

As discussed in the previous validation sections, calculation of the upper safety limit includes a conservative safety margin, or margin of subcriticality (- Δ_{sm}) as it is called in NUREG/CR-6698. With this in mind the upper safety limit (USL) may be computed as follows:

$$USL = K_L - \Delta_{sm}$$

5.3.2.3 Summary of Results

Table 5.3-3 shows that 58 critical experiments were included in the validation of k_{eff} for Peach Bottom fuel systems. The k_{eff} results for the experiments along with their associated uncertainty are shown in Table 5.3-4. Thus, the number of data points in this sample set, n, is equal to 58. Setting q equal to 0.95 and plugging in n = 58 resulted in the following calculated value for β:

$$\beta = 1 - (0.95)^{58}$$

$$\beta = 0.9490$$

$$\beta = 94.9\%$$

The above calculation indicated that there was a 94.9% confidence that 95% of the population lies above the smallest value in the dataset. A 94.9% computed value for β was used as the entering argument to Table 2.2, Non-Parametric Margins, found in Section 2.4.4 of NUREG/CR-6698. For a degree of

confidence of >90% the correlating non-parametric margin is 0. Thus, the final term in the calculation of K_L would be taken as 0 and the calculation of K_L was reduced to the lowest value of k_{eff} in the sample set minus its associated uncertainty.

Dividing the calculated k_{eff} value by the experimental k_{eff} value normalized experiment results that exhibited slightly supercritical or subcritical behavior. A Δk term was then computed that measured the deviation of the normalized k_{eff} value from 1.0000.

Evaluation of the dataset indicated that the lowest normalized k_{eff} value of the 58 experiments was 0.9908 with an associated uncertainty of 0.0012.

In the determination of an upper safety limit a standard practice is to assign a value of 0.05 for the margin of subcriticality. As an additional conservative measure the Δk term associated with a k_{eff} of 0.9908 was summed with 0.05 to produce a margin of subcriticality equal to 0.0592. Analysis of Peach Bottom fuel systems was then assigned the following upper safety limit:

$$USL = (0.9908 - 0.0012) - 0.0592$$

Or

$$USL = 0.9304$$

5.4 REFERENCES

J. Blair Briggs, Ed., (1999), International Handbook of Evaluated Criticality Benchmark Experiments, NEA/NSC/Doc/(95) 03, September.

MCNP-Monte Carlo Neutron and Photon Transport Code System, MCNP4B2, CCC-660, Oak Ridge National Laboratory, RISC Computer Code Collection.

MCNP-Monte Carlo Neutron and Photon Transport Code System, MCNP4C, CCC-700, Oak Ridge National Laboratory, RISC Computer Code Collection.

ENDF/B-VI Library Evaluated Nuclear Data File/B Library, National Nuclear Data Center, Brookhaven National Laboratory, Upton, New York.

Chapter 4 Appendix 4A Tables

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Table 2.2-1
Analysis Results for TRIGA Baskets Side-by-Side

Description	k_{eff}	σ	$k_{eff} + 2\sigma$
TRIGA fuel baskets side-by-side; dry; no gadolinium phosphate	0.5669	0.0006	0.5681

Table 2.2-2
Modeled Configuration for TRIGA Baskets Side-by-Side

Parameter	Dimension, cm
Fuel Element Configuration	
Fuel Element Length	73.406
Fuel Meat Length	38.100
Fuel Meat Outer Radius	1.822
Cladding Inner Radius	1.822
Cladding Outer Radius	1.877
Reflector Length	8.687
Reflector Outer Radius	1.822
ISF Basket Configuration	
Basket Length	118.186
Basket Outer Radius	21.400
Basket Tube Outer Radius	2.223
Basket Tube Inner Radius	2.060
Lifting Plate Thickness	4.445
Bottom Plate Thickness	3.175

Table 2.2-3
TRIGA Material Compositions

Isotope	Atom Density (atoms/b-cm)
$UZrH_{1.7}$ Fuel	
H	0.06261
Zr	0.03683
U-235	0.0002828
U-238	0.001117
Graphite [2.62 g/cc]	
C	0.1313615
304 Stainless Steel [7.9 g/cc]	
C	0.000316872
Mn-55	0.001731948
P-31	0.000061439
S	0.000044512
Si	0.001693931
Ni-58	0.005242194
Ni-60	0.002019273
Ni-61	0.000087784
Ni-62	0.000279832
Ni-64	0.000071306
Cr-50	0.000755354
Cr-52	0.014566245
Cr-53	0.001651695
Cr-54	0.000411142
Fe-54	0.003403421
Fe-56	0.053426429
Fe-57	0.001233849
Fe-58	0.000164203

Isotope	Atom Density (atoms/b-cm)
316L Stainless Steel [8.027 g/cc]	
Mn-55	0.00175386
Si	0.00171536
Ni-58	0.00672489
Ni-60	0.00257096
Ni-61	0.0011131
Ni-62	0.0035363
Ni-64	0.00008964
Cr-50	0.00068439
Cr-52	0.01319803
Cr-53	0.00149638
Cr-54	0.00011131
Mo	0.00125539
Fe-54	0.00333374
Fe-56	0.0518255
Fe-57	0.00118658
Fe-58	0.00015821
630 Stainless Steel [7.75 g/cc]	
C	0.000271999
Mn-55	0.000849531
P-31	0.000060272
S	0.000043667
Si	0.001661768
Ni-58	0.002165330
Ni-60	0.000834077
Ni-61	0.000036260
Ni-62	0.000115587
Ni-64	0.000029453
Cr-50	0.000614260
Cr-52	0.011845385
Cr-53	0.001343172
Cr-54	0.000334344
Cu-63	0.002032098
Cu-65	0.000905733
Fe-54	0.003620167
Fe-56	0.056828874
Fe-57	0.001312427
Fe-58	0.000174660

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Table 2.3-1
Analysis Results for a Fully Loaded Storage Vault

Description	Density (g/cc)	k_{eff}	σ	$k_{eff} + 2\sigma$
Baseline Case, Dry	--	0.7124	0.0009	0.7142
Flooded	1.0	0.8135	0.0009	0.8153
	0.8	0.7942	0.0009	0.7960
	0.6	0.7676	0.0007	0.7690
	0.4	0.7294	0.0008	0.7310
	0.2	0.6797	0.0009	0.6815

Table 2.3-2
Modeled Configuration for Fully Loaded Storage Vault

Parameter	Dimension, cm
TRIGA Fuel Element Configuration	
Fuel Element Length	73.406
Fuel Meat Length	38.100
Fuel Meat Outer Radius	1.822
Cladding Inner Radius	1.822
Cladding Outer Radius	1.877
Reflector Length	8.687
Reflector Outer Radius	1.822
ISF Basket Configuration	
Basket Length	118.186
Basket Outer Radius	21.400
Basket Tube Outer Radius	2.223
Basket Tube Inner Radius	2.060
Lifting Plate Thickness	4.445
Bottom Plate Thickness	3.175
ISF Canister Configuration	
Canister (Short) Length	300.626
Canister Outer Radius	22.86
Canister Inner Radius	21.908
ISF Storage Tube Configuration	
Storage Tube Length	624.84
Storage Tube Outer Radius	25.400
Storage Tube Inner Radius	24.448

Table 2.4-1
Analysis Results for TRIGA Canister

MCNP Case	Configuration	Canister Flooded	Water Reflector	$k_{eff} \pm \sigma$	$k_{eff} + 2\sigma$
9-1	Single Canister	No	1-inch	0.5725 ± 0.0008	0.5741
9-2	Single Canister	No	12-inches	0.6047 ± 0.0008	0.6063
9-3	2 Side-by-Side	No	1-inch	0.6040 ± 0.0008	0.6056
9-4	2 Side-by-Side	Yes	12-inches	0.8389 ± 0.0008	0.8405
9-5	2 End-to-End	No	1-inch	0.5739 ± 0.0008	0.5755
9-6	2 End-to-End	No	12-inches	0.6044 ± 0.0008	0.6060

Table 2.4-2 **Sheet 1 of 2**
Modeled Configuration for TRIGA Canister

Region	Documented Configuration		Modeled Configuration	
	Material (g/cc)	**Dimensions, cm**	**Material (g/cc)**	**Dimensions, cm**
Fuel Description				
Fuel (Zr rod)	Zr (6.49)	OR=0.28575 Length=38.1	Zr (6.49)	OR=0.28575 Length=38.1
Fuel (meat)	U-$ZrH_{1.7}$ (6.0875)	IR=0.3175 OR=1.82245	U-$ZrH_{1.7}$ (6.0875)	IR=0.3175 OR=1.82245
		Length=38.1		Length=38.1
Fuel Clad	SS-304 (7.93)	IR=1.82626 OR=1.87706	SS-304 (7.93)	IR=1.82626 OR=1.87706
		Length=55.4736		Length=55.4736
Graphite Cylinders				
Graphite Reflector	Graphite	OR=1.82245	Graphite (1.7)	OR=1.82245
		Length=2 @ 8.6868		Length=2 @ 8.6868
End Fittings				
End Fittings	SS	OR=irregular	SS-316 (8.0)	OR=1.82245
		Length=2 @ 9.0932		Length=2 @ 9.0932

Table 2.4-2 **Sheet 2 of 2**
Modeled Configuration for TRIGA Canister

Region	Documented Configuration		Modeled Configuration	
	Material (g/cc)	**Dimensions, cm**	**Material (g/cc)**	**Dimensions, cm**
Basket Description				
Basket		OR=21.3995		OR=21.3995
		Length=83.185		Length=83.185
Tubes (54)	SS-316 (8.0)	OR=2.2225 IR=2.05994	SS-316 (8.0)	OR=2.2225 IR=2.05994
	Pitch=5.08	L=74.295	Pitch=5.08	L=74.295
Lifting Plate		Thickness=6.985		Thickness=6.985
Bottom Plate		Thickness=3.175		Thickness=1.905
Canister				
Canister Shell	SS-316 (8.0)	IR=21.9075 OR=22.86	SS-316 (8.0)	IR=22.027 OR=22.86
		$Top_{Thickness}$=1.27 $Bottom_{Thickness}$=1.27		$Top_{Thickness}$ =1.271 $Bottom_{Thicknes}$=1.27
Steel Plug				
Cylinder	SS-316 (8.0)	OR=21.75 Thickness=25.4	SS-316 (8.0)	OR=22.02656 Thickness=25.4
Reflector				
Reflector	None		Water (1.0)	Thickness=2.54 (or) Thickness=30.48

Table 2.4-3 **Sheet 1 of 2**
TRIGA Material Compositions

NAME	ISOTOPE	Atom/b-cm	ELEM SUM	MAT SUM	ITEM
92U	U235	0.000292			Fuel (6.0875 g/cc)
	U238	0.001152	0.00144336		
40Zr		0.035758	0.03575764		
1H		0.060788	0.06078798	0.09798898	
40Zr		0.042843	0.04284336	0.04284336	Zr rod (6.49 g/cc)
6C		0.085235	0.08523495	0.08523495	Graphite (1.7 g/cc)
1H		0.066872	0.066872	0.100309	Water (1.0 g/cc)
8O		0.033436	0.033436		
26Fe	Fe54	0.003506			304 ss (7.93 g/cc)
26Fe	Fe56	0.054509			
26Fe	Fe57	0.001248			
26Fe	Fe58	0.000166	0.05943004		
24Cr	Cr50	0.000758			
24Cr	Cr52	0.014622			
24Cr	Cr53	0.001658			
24Cr	Cr54	0.000413	0.01745038		
28Ni	Ni58	0.005277			
28Ni	Ni60	0.002018			
28Ni	Ni61	8.74E-05			
28Ni	Ni62	0.000278			
28Ni	Ni64	7.03E-05	0.00773002		
25Mn	Mn55	0.001739	0.00173851	0.08634895	
26Fe	Fe54	0.003334			316 ss (8.0 g/cc)
26Fe	Fe56	0.051826			
26Fe	Fe57	0.001187			
26Fe	Fe58	0.000158	0.05650403		
24Cr	Cr50	0.000684			

Table 2.4-3 **Sheet 2 of 2**
TRIGA Material Compositions

NAME	ISOTOPE	Atom/b-cm	ELEM SUM	MAT SUM	ITEM
24Cr	Cr52	0.013198			
24Cr	Cr53	0.001496			
24Cr	Cr54	0.000373	0.01575132		
28Ni	Ni58	0.006725			
28Ni	Ni60	0.002571			
28Ni	Ni61	0.000111			
28Ni	Ni62	0.000354			
28Ni	Ni64	8.96E-05	0.00985043		
42Mo		0.001255	0.00125539		
25Mn	Mn55	0.001754	0.00175386		
14 Si		0.001715	0.00171536	0.08683039	

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Table 2.5-1
Analysis Results for TRIGA Fuel in Concrete Corner

Fuel Elements in the Corner of a 36 inch Thick Concrete Cell with a One Inch of Water Reflector on the other Three Sides, Both Hexagonal and Square Pitch Arrays Analyzed, Fuel Pitch 3.7542 cm (touching) in all Runs, No Moderation Present between Elements

MCNP Case	Type of Array	Number of Fuel Elements	keff ± σ	keff + 2σ
12-1	Hexagonal	39	0.8721 ± 0.0010	0.8741
12-2	Hexagonal	46	0.9179 ± 0.0010	0.9199
12-3	Square	36	0.8135 ± 0.0009	0.8153
12-4	Square	49	0.8905 ± 0.0010	0.8925
12-5	Square	64	0.9549 ± 0.0009	0.9567

Table 2.5-2
Modeled Configuration for TRIGA Fuel in Concrete Corner

Region	Documented Configuration		Modeled Configuration	
	Material (g/cc)	**Dimensions, cm**	**Material (g/cc)**	**Dimensions, cm**
Fuel Description				
Fuel (Zr rod)	Zr (6.49)	OR=0.28575 Length=38.1	Zr (6.49)	OR=0.28575 Length=38.1
Fuel (meat)	U-$ZrH_{1.7}$ (6.0875)	IR=0.3175 OR=1.82245	U-$ZrH_{1.7}$ (6.0875)	IR=0.3175 OR=1.82245
		Length=38.1		Length=38.1
Fuel Clad	SS-304 (7.93)	IR=1.82626 OR=1.87706	SS-304 (7.93)	IR=1.82626 OR=1.87706
		Length=55.4736		Length=55.4736
Graphite Cylinders				
Graphite Reflector	Graphite	OR=1.82245	Graphite (1.7)	OR=1.82245
		Length=2 @ 8.6868		Length=2 @ 8.6868
End Fittings				
End Fittings	SS	OR=irregular	SS-316 (8.0)	OR=1.82245
		Length=2 @ 9.0932		Length=2 @ 9.0932
Reflector				
Reflector	Concrete (2.3)	$Conc_{Thickness}$=121.92	Concrete (2.3) Water (1.0)	$Conc_{Thicknes}$=91.44 $Water_{Thickness}$=2.54

Table 2.5-3 **Sheet 1 of 2**
TRIGA Material Compositions

NAME	ISOTOPE	atom/b-cm	ELEM SUM	MAT SUM	ITEM
92U	U235	0.000290			Fuel (6.0875 g/cc)
	U238	0.001196	0.00144336		
40Zr		0.035758	0.03575764		
1H		0.060788	0.06078798	0.09798898	
40Zr		0.042843	0.04284336	0.04284336	zr rod (6.49 g/cc)
6C		0.085235	0.08523495	0.08523495	graphite (1.7 g/cc)
26Fe	Fe54	0.003506			304 ss (7.93 g/cc)
26Fe	Fe56	0.054509			
26Fe	Fe57	0.001248			
26Fe	Fe58	0.000166	0.05943004		
24Cr	Cr50	0.000758			
24Cr	Cr52	0.014622			
24Cr	Cr53	0.001658			
24Cr	Cr54	0.000413	0.01745038		
28Ni	Ni58	0.005277			
28Ni	Ni60	0.002018			
28Ni	Ni61	8.74E-05			
28Ni	Ni62	0.000278			
28Ni	Ni64	7.03E-05	0.00773002		
25Mn	Mn55	0.001739	0.00173851	0.08634895	
26Fe	Fe54	0.003334			316 ss (8.0 g/cc)
26Fe	Fe56	0.051826			
26Fe	Fe57	0.001187			
26Fe	Fe58	0.000158	0.05650403		
24Cr	Cr50	0.000684			

Table 2.5-3 **Sheet 2 of 2**
TRIGA Material Compositions

NAME	ISOTOPE	atom/b-cm	ELEM SUM	MAT SUM	ITEM
24Cr	Cr52	0.013198			
24Cr	Cr53	0.001496			
24Cr	Cr54	0.000373	0.01575132		
28Ni	Ni58	0.006725			
28Ni	Ni60	0.002571			
28Ni	Ni61	0.000111			
28Ni	Ni62	0.000354			
28Ni	Ni64	8.96E-05	0.00985043		
42Mo		0.001255	0.00125539		
25Mn	Mn55	0.001754	0.00175386		
14 Si		0.001715	0.00171536	0.08683039	
8O		0.045796	0.04579602		Port conc (2.3 g/cc)
14Si		0.01662	0.01661971		
1H		0.013742	0.01374227		
13 Al		0.001745	0.00174537		
20 Ca		0.001521	0.00152063		
11 Na		0.000964	0.00096396		
19 K		0.000461	0.00046053		
26 Fe	Fe54	2.05E-05			
27 Fe	Fe56	0.000318			
28 Fe	Fe57	7.29E-06			
29 Fe	Fe58	9.72E-07	0.00034722		
12 Mg		0.000114	0.00011398		
6 C		0.000115	0.00011532	0.08142501	
1 H		0.066856	0.06685577		water
8 O		0.033428	0.03342788	0.10028365	

Table 2.6-1
Analysis Results for TRIGA Fuel in Two ISF Baskets

MCNP Case	Canister Flooded	Water Reflector	keff ± σ	keff + 2σ
15-1	No	1-inch	0.6257 ± 0.0008	0.6273
15-2	No	None	0.5316 ± 0.0008	0.5332
15-3	Yes	12-inch	0.8527 ± 0.0008	0.8543

Table 2.6-2
Modeled Configuration of TRIGA Fuel in Two ISF Baskets

Region	Documented Configuration		Modeled Configuration	
	Material (g/cc)	**Dimensions, cm**	**Material (g/cc)**	**Dimensions, cm**
Fuel Description				
Fuel (Zr rod)	Zr (6.49)	OR=0.28575 Length=38.1	Zr (6.49)	OR=0.28575 Length=38.1
Fuel (meat)	U-$ZrH_{1.7}$ (6.0875)	IR=0.3175 OR=1.82245	U-$ZrH_{1.7}$ (6.0875)	IR=0.3175 OR=1.82245
		Length=38.1		Length=38.1
Fuel Clad	SS-304 (7.93)	IR=1.82626 OR=1.87706	SS-304 (7.93)	IR=1.82626 OR=1.87706
		Length=55.4736		Length=55.4736
Graphite Cylinders				
Graphite Reflector	Graphite	OR=1.82245	Graphite (1.7)	OR=1.82245
		Length=2 @ 8.6868		Length=2 @ 8.6868
End Fittings				
End Fittings	SS	OR=irregular	SS-316 (8.0)	OR=1.82245
		Length=2 @ 9.0932		Length=2 @ 9.0932
Basket Description				
Basket		OR=21.3995		OR=21.3995
		Length=83.185		Length=83.185
Tubes (54)	SS-316 (8.0)	OR=2.2225 IR=2.05994	SS-316 (8.0)	OR=2.2225 IR=2.05994
	Pitch=5.08	L=74.295	Pitch=5.08	L=74.295
Lifting Plate		Thickness=6.985		Thickness=6.985
Bottom Plate		Thickness=3.175		Thickness=1.905
Reflector				
Reflector	None		Water (1.0)	Th_{water}=2.54 (or) Th_{water}=30.48

Table 2.6-3 **Sheet 1 of 2**
TRIGA Material Compositions

NAME	ISOTOPE	atom/b-cm	ELEM SUM	MAT SUM	ITEM
92U	U235	0.000292			Fuel (6.0875 g/cc)
	U238	0.001152	0.00144336		
40Zr		0.035758	0.03575764		
1H		0.060788	0.06078798	0.09798898	
40Zr		0.042843	0.04284336	0.04284336	Zr rod (6.49 g/cc)
6C		0.085235	0.08523495	0.08523495	Graphite (1.7 g/cc)
1H		0.066872	0.066872	0.100309	Water (1.0 g/cc)
8O		0.033436	0.033436		
26Fe	Fe54	0.003506			304 ss (7.93 g/cc)
26Fe	Fe56	0.054509			
26Fe	Fe57	0.001248			
26Fe	Fe58	0.000166	0.05943004		
24Cr	Cr50	0.000758			
24Cr	Cr52	0.014622			
24Cr	Cr53	0.001658			
24Cr	Cr54	0.000413	0.01745038		
28Ni	Ni58	0.005277			
28Ni	Ni60	0.002018			
28Ni	Ni61	8.74E-05			
28Ni	Ni62	0.000278			
28Ni	Ni64	7.03E-05	0.00773002		
25Mn	Mn55	0.001739	0.00173851	0.08634895	
26Fe	Fe54	0.003334			316 ss (8.0 g/cc)
26Fe	Fe56	0.051826			
26Fe	Fe57	0.001187			
26Fe	Fe58	0.000158	0.05650403		
24Cr	Cr50	0.000684			
24Cr	Cr52	0.013198			

Table 2.6-3 **Sheet 2 of 2**
TRIGA Material Compositions

NAME	ISOTOPE	atom/b-cm	ELEM SUM	MAT SUM	ITEM
24Cr	Cr53	0.001496			
24Cr	Cr54	0.000373	0.01575132		
28Ni	Ni58	0.006725			
28Ni	Ni60	0.002571			
28Ni	Ni61	0.000111			
28Ni	Ni62	0.000354			
28Ni	Ni64	8.96E-05	0.00985043		
42Mo		0.001255	0.00125539		
25Mn	Mn55	0.001754	0.00175386		
14 Si		0.001715	0.00171536	0.08683039	

Table 2.7-1
Analysis Results for Single TRIGA Basket (SS and Aluminum Clad)

Description	k_{eff}	σ	$k_{eff} + 2\sigma$
Stainless-steel-clad TRIGA elements in dry basket.	0.4851	0.0010	0.4871
Stainless-steel-clad TRIGA elements in flooded basket.	0.7990	0.0020	0.8030
Aluminum-clad TRIGA elements in dry basket.	0.2790	0.0007	0.2804
Aluminum-clad TRIGA elements in flooded basket.	0.7470	0.0009	0.7488

Table 2.7-2
Modeled Configuration for Single TRIGA Basket (SS and Aluminum Clad)

Parameter	Aluminum Clad	Stainless Steel Clad
Fuel Element Length (cm)	70.51	73.406
Fuel Meat Length (cm)	35.560	38.100
Fuel Meat Outer Radius (cm)	1.791	1.822
Cladding Inner Radius (cm)	1.791	1.822
Cladding Outer Radius (cm)	1.867	1.877
Reflector Length	10.033	8.687
Reflector Outer Radius (cm)	1.791	1.822

Table 2.7-3
TRIGA Material Compositions

Isotope	Atom Density (atoms/b-cm)
$UZrH_{1.0}$ Fuel	
H	0.0381337
Zr	0.0381337
U-235	0.0010166
U-238	0.0002574
$UZrH_{1.7}$ Fuel	
H	0.06261
Zr	0.03683
U-235	0.0002828
U-238	0.001117
Graphite [2.62 g/cc]	
C	0.1313615
Gadolinium Phosphate [5.0 g/cc]	
Gd-52	2.38779E-05
Gd-54	0.000260269
Gd-55	0.001766966
Gd-56	0.002443904
Gd-57	0.001868447
Gd-58	0.002965637
Gd-60	0.002609856
P-31	0.011938957
O-16	0.047755827
304 Stainless Steel [7.9 g/cc]	
C	0.000316872
Mn-55	0.001731948
P-31	0.000061439
S	0.000044512
Si	0.001693931
Ni-58	0.005242194
Ni-60	0.002019273
Ni-61	0.000087784
Ni-62	0.000279832
Ni-64	0.000071306
Cr-50	0.000755354
Cr-52	0.014566245
Cr-53	0.001651695
Cr-54	0.000411142
Fe-54	0.003403421
Fe-56	0.053426429
Fe-57	0.001233849
Fe-58	0.000164203

Isotope	Atom Density (atoms/b-cm)
316L Stainless Steel [8.027 g/cc]	
Mn-55	0.00175386
Si	0.00171536
Ni-58	0.00672489
Ni-60	0.00257096
Ni-61	0.0011131
Ni-62	0.0035363
Ni-64	0.00008964
Cr-50	0.00068439
Cr-52	0.01319803
Cr-53	0.00149638
Cr-54	0.00011131
Mo	0.00125539
Fe-54	0.00333374
Fe-56	0.0518255
Fe-57	0.00118658
Fe-58	0.00015821
630 Stainless Steel [7.75 g/cc]	
C	0.000271999
Mn-55	0.000849531
P-31	0.000060272
S	0.000043667
Si	0.001661768
Ni-58	0.002165330
Ni-60	0.000834077
Ni-61	0.000036260
Ni-62	0.000115587
Ni-64	0.000029453
Cr-50	0.000614260
Cr-52	0.011845385
Cr-53	0.001343172
Cr-54	0.000334344
Cu-63	0.002032098
Cu-65	0.000905733
Fe-54	0.003620167
Fe-56	0.056828874
Fe-57	0.001312427
Fe-58	0.000174660

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Table 3.1-1
Analysis Results for Side-by-Side Peach Bottom Fuel Arrays

Description	k_{eff}	σ	$k_{eff} + 2\sigma$
Peach Bottom fuel, two 18-element arrays side-by-side, unmoderated and unreflected.	0.3874	0.0007	0.3888
Peach Bottom fuel, two 18 element arrays side-by-side, moderated and reflected	0.8578	0.0008	0.8594

Table 3.1-2
Modeled Configuration for Peach Bottom Fuel Element

Parameter	Dimension
Fuel Element Length	365.151 cm
Active Fuel Length	227.076 cm
Fuel Meat Outer Radius	3.484 cm
Sleeve Outer Radius	4.445 cm
Spine Outer Radius	2.223 cm

(1) The spine runs the entire active fuel length.

Table 3.1-3
Peach Bottom Material Compositions

Isotope	Atom Density (atoms/b-cm)
Type A Fuel Compacts	
H	0.0138000
C	0.0875400
O	0.0875400
Th-232	0.0008284
U-234	2.459E-06
U-235	0.0001523
U-236	8.128E-07
U-238	7.827E-06
Type C Fuel Compacts	
H	0.0138000
C	0.0875400
O	0.0077690
Th-232	0.0008284
U-234	2.459E-06
U-235	0.0001523
U-236	8.128E-07
U-238	7.827E-06
Graphite [2.25 g/cc]	
C	--
Water [0.4 g/cc]	
H	0.02674249
O	0.01337125

Note: graphite in this calculation was modeled as pure carbon.

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Table 3.2-1
Modeled Configuration for Peach Bottom Fuel/Graphite Sphere with Graphite Reflector

(Uses fuel and graphite material available from 3, 6, 9, 12, 15, 18, and 21 elements)

Region	Material (g/cc)	Dimensions (cm)
Homogenized Fuel and Graphite Description		
Solid Sphere (Fuel and Graphite)	UC_2 and ThC_2 and Graphite (2.14)	OR = 15.2 (for 3 element model) OR = 29.1 (for 21 element model) Sphere size was varied from a volume equal to that from 3 assemblies to that of 21 assemblies
Graphite Reflector Sphere Description		
Graphite Reflector surrounding Solid Sphere	Graphite (1.85)	IR = 15.2 (for 3 element model) OR = 25.4 (for 3 element model) IR = 29.1 (for 21 element model), OR = 48.5 (for 21 element model) Sphere size was varied to account for change in size of solid sphere and volume of additional graphite available from fuel element components
Additional Water Reflector		
Outer Sphere	Water (1.00)	30.5 (layer surrounding outer graphite reflector shell)

Table 3.2-2
Peach Bottom Material Compositions

Fuel (UC2/ThC2/C) **Density = 2.14 g/cc**		
Material	**Weight Percent**	**Atom Density** (atoms/b-cm)
Th-232	15.00	8.332E-04
U-235	2.79	1.531E-04
U-238	0.15	7.872E-06
Carbon	82.06	8.805E-02
Carbon **Density = 1.85 g/cc**		
Material	**Weight Percent**	**Atom Density** (atoms/b-cm)
C	100.00	1.314E-01

Table 3.2-3
Analysis Results for Peach Bottom Fuel/Graphite Sphere with Graphite Reflector

No Water Reflection			
Assemblies per Sphere	**k_{eff}**	**σ**	**$k_{eff} + 2\sigma$**
3	0.1151	0.0003	0.1157
6	0.2399	0.0004	0.2407
9	0.3368	0.0005	0.3378
12	0.4142	0.0006	0.4154
15	0.4757	0.0006	0.4769
18	0.5273	0.0007	0.5287
21	0.5702	0.0006	0.5714

With Additional Water Reflector (12 inch)			
Assemblies per Sphere	**k_{eff}**	**σ**	**$k_{eff} + 2\sigma$**
3	0.3266	0.0005	0.3276
6	0.4326	0.0005	0.4336
9	0.5092	0.0006	0.5104
12	0.5708	0.0006	0.5720
15	0.6193	0.0006	0.6205
18	0.6597	0.0007	0.6611
21	0.6959	0.0007	0.6973

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Table 3.3-1
Modeled Configuration for Peach Bottom Fuel in Storage Canister

Region	Documented Configuration		Modeled Configuration	
	Material (g/cc)	**Dimensions, cm**	**Material (g/cc)**	**Dimensions, cm**
Spine Description				
Spine	Graphite (2.107)	OR=2.225 Length=228.6	Graphite (2.107)	OR=2.225 Length=228.6
Fuel Description				
Fuel	UC_2 & ThC_2 (2.143)	IR=2.2225 OR=3.429	UC_2 & ThC_2 (2.143)	IR=2.225 OR=3.429
		Length=228.6		Length=228.6
Reflector Description				
Reflector	Graphite (2.107)	IR=3.429 OR=4.445	Graphite (2.107)	IR=3.429 OR=4.445
		Length=228.6		Length=228.6
Basket Tube				
Tube	SS-304 (7.92)	IR=4.917 OR=5.08	SS-304 (7.92)	IR=4.917 OR=5.08
		Length=228.6		Length=228.6
Canister				
Canister	SS-304 (7.92)	IR=21.755 OR=22.86	SS-304 (7.92)	IR=21.755 OR=22.86
		Length=397.29		Length=397.29

Table 3.3-2
Peach Bottom Fuel Compact Loading (in grams)

Compact Type	**A**	**B**	**C**	**D**
Description	**Standard**	**Heavy Rhodium**	**Light Rhodium**	**Heavy Thorium**
Th^{232}	52.10	52.10	52.10	115.36
U^{234} (1)	0.156	0.156	0.156	0.082
U^{235}	9.70	9.70	9.70	5.14
U^{236} (1)	0.052	0.052	0.052	0.028
U^{238}	0.505	0.505	0.505	0.268
Rh^{103}	0	1.028	0.342	0
Carbon	285.00	285.00	285.00	273.00

Note:

(1) U^{234} and U^{236} loading were not required. These are the maximum amounts expected in the fully enriched fuel material.

Table 3.3-3
Peach Bottom Types of Fuel Elements Based on Nuclear Properties

Fuel Element Type				
Description	**I** **Heavy Rhodium**	**II** **Light Rhodium**	**III** **Light Rhodium with burnable poison**	**IV** **Heavy Thorium: Light Uranium**
Spine	Solid Graphite	Solid Graphite	Hollow with poison compacts	Solid Graphite
Compact Type				
In upper 9 inches	A	A	A	D
In middle 54 inches	B	C	C	D
In lower 27 inches	A	A	A	D
Number of types in a nominal core loading	54	588	60	102

Table 3.3-4
Peach Bottom Material Compositions

		Fuel Type A	**Fuel Type C**
		Atom	Atom
Component	Isotope	Density	Density
		(atom/b-cm)	(atom/b-cm)
Fuel ρ=2.575 g/cm^3			
	Th-232	8.284E-04	8.284E-04
	U-234	2.459E-06	2.459E-06
	U-235	1.523E-04	1.523E-04
	U-236	8.128E-07	8.128E-07
	U-238	7.827E-06	7.827E-06
	Carbon	8.754E-02	8.754E-02
	Rhodium	0.000E+00	1.226E-05
	Hydrogen	1.380E-02	1.380E-02
	Oxygen	6.898E-03	6.898E-03
	Total (Saturated)[(a)]	1.092E-01	1.092E-01
	Total (Dry)	8.853E-02	8.855E-02
Reflectors ρ=2.107 g/cm^3			
	Carbon	9.526E-02	
	Hydrogen	1.380E-02	
	Oxygen	6.898E-03	
	Total (Saturated)[(a)]	1.160E-01	
	Total (Dry)	9.526E-02	
Spine ρ=2.057 g/cm^3			
	Carbon	9.276E-02	
	Hydrogen	1.380E-02	
	Oxygen	6.898E-03	
	Total (Saturated)[(a)]	1.135E-01	
	Total (Dry)	9.276E-02	

Notes:

(a) The analyses in this document considered both the saturated and the dry fuel.

Table 3.3-5 Sheet 1 of 2
Analysis Results for Peach Bottom Fuel Arrays

A: 19 Fuel Elements Saturated and Flooded			
Case A	**Element Separation Distance (cm)**	**k_{eff}**	**Standard Deviation ± 1σ**
26A-1	0.1	0.931	± 0.00076
26A-2	0.635	0.923	± 0.00074
26A-3	0.9525	0.906	± 0.00073
26A-4	1.27	0.884	± 0.00069
26A-5	1.905	0.833	± 0.00064
26A-6	2.54	0.757	± 0.00063
B: 37 Elements Hex Array Flooded and Saturated			
Case B	**Element Separation Distance (cm)**	**k_{eff}**	**Standard Deviation ± 1σ**
26B-1	0.1	1.102	± 0.00075
26B-2	0.635	1.074	± 0.00071
26B-3	0.9525	1.042	± 0.00066
26B-4	1.27	1.027	± 0.00068
26B-5	1.905	0.927	± 0.00063

C: Fuel Elements Saturated and Flooded with 0.1 cm Separation			
Case C	**k_{eff}**	**Standard Deviation ± 1σ**	**Number Of Elements**
26C-1	1.102	± 0.00075	37
26C-2	1.07	± 0.00076	33
26C-3	1.050	± 0.00077	30
26C-4	1.023	± 0.00075	27
26C-5	0.991	± 0.00077	24
26C-6	0.955	± 0.00077	21
26C-7	0.931	± 0.00076	19
26C-8	0.912	± 0.00028	18

Table 3.3-5 Sheet 2 of 2
Analysis Results for Peach Bottom Fuel Arrays

D: Fuel Elements Dry, Reflected, with no Water Between Elements. 0.1 cm Separation Edge to Edge Between Elements.			
Case D	**k_{eff}**	**Standard Deviation ± 1σ**	**Number of Elements**
26D-1	0.545	± 0.00074	37
26D-2	0.503	± 0.00074	33
26D-3	0.474	± 0.0007	30
26D-4	0.441	± 0.00067	27
26D-5	0.407	± 0.00062	24
26D-6	0.368	± 0.00061	21
26D-7	0.343	± 0.00059	19
26D-8	0.304	± 0.00056	16
26D-9	0.262	± 0.0005	13
26D-10	0.220	± 0.00044	10
26D-11	0.171	± 0.0004	7

Table 3.3-6
Analysis Results for Peach Bottom Fuel as a Function of Moderation

19 Fully Reflected and Saturated Fuel Elements in a hexagonal array
with 0.1 cm edge to edge separation

Case	k_{eff}	Standard Deviation ± 1σ	Water Density (g/cm^3)
27-1	0.9309	± 0.00078	1
27-2	0.9293	± 0.00054	0.95
27-3	0.9272	± 0.00055	0.9
27-4	0.9262	± 0.00055	0.85
27-5	0.9227	± 0.00055	0.8
27-6	0.9160	± 0.00078	0.7
27-7	0.9069	± 0.00078	0.6
27-8	0.8995	± 0.00079	0.5
27-9	0.8866	± 0.00079	0.4
27-10	0.8745	± 0.00082	0.3
27-11	0.8597	± 0.00084	0.2
27-12	0.8422	± 0.0008	0.1
27-13	0.8318	± 0.0008	0.05
27-14	0.8284	± 0.00078	0.025

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Table 3.4-1
Physical Fuel Configuration for Peach Bottom Fuel Elements

Element Shape	Right circular cylindrical rod
Element Dim.	3.5” O. D. x 12’ long
Compact Shape	Flat annular cylinders (A doughnut shape)
Compact Dimension	2.7” O. D. X 2.98” long. Center hole 1.75” dia.
Element “Cladding” Material	Low-permeability Graphite and nuclear-grade graphite
Compact “Cladding” Material	None (Graphite matrix was not designed to be cladding)
No. of compacts/element	30 compacts
Enrichment	93.15%
Active Fuel Length	89” – 90”
Fuel Meat	UC, ThC particles
Particle Cladding	Pyrolytically deposited carbon (PyC). Monocoated
Particle Cladding thickness	55 +/- 10 um
Particle Diameter	Between 210 and 595 um
Added Material: Spines: • Solid spines, Dim. • Hollow Spines, Dim.	 1.75” O. D. x 30” long 1.75” O. D. x 30” long (hole = 0.89” dia.)
Burnable Poison Compacts • Shape • Poison Compact, Dim. • Poison material • Poison particle diameter • Stainless Steel Screen • Internal trap • Brazing ring • Thermocouple (Instrumented elements only) • Bottom Connector (Instrumented)	 Solid cylindrical pellets 0.89” O. D. x 2.0” long ZrB_2 particles pressed into a graphite matrix 100 um 18-8 SST Activated Charcoal Silicon Inconel sheath, tungsten-rhenium, chromel-alumel Nb-1% Zr sheath Graphite, stainless steel, Inconel

Criticality Model Information		
Region	Dimensions and source of information	Documented Configuration for Criticality Model Dimensions, cm (inches)
Spine	1.75“ O.D. (from above) 3 spines at 30” /spine (from above)	OR = 2.225 (.875) Length = 228.6 (90)
Fuel Compact	2.7” O.D. x 2.98” long per compact. Center hole 1.75” dia. (from above) 30 compact (from above)	IR = 2.2225 (.875) OR = 3.429 (1.35) Length = 228.6 (90)
Sleeve	3.5” Dia. (See Figure 3.1-1) and Element Dim. (from above) and sleeve length (Active Fuel Length from above)	IR = 3.429 (1.35) OD = 4.445 (1.75) Length = 228.6 (90)

Table 3.4-2
Modeled Configuration for Peach Bottom Fuel in a Storage Tube

Region	Documented Configuration		Modeled Configuration	
	Material (g/cc)	**Dimensions, cm**	**Material (g/cc)**	**Dimensions, cm**
Spine Description				
Spine	Graphite (2.107)	OR=2.225 Length=228.6	Graphite (2.107)	OR=2.225 Length=228.6
Fuel Description				
Fuel	UC_2 & ThC_2 (2.143)	IR=2.2225 OR=3.429	UC_2 & ThC_2 (2.143)	IR=2.225 OR=3.429
		Length=228.6		Length=228.6
Reflector Description				
Reflector	Graphite (2.107)	IR=3.429 OR=4.445	Graphite (2.107)	IR=3.429 OR=4.445
		Length=228.6		Length=228.6
Basket Tube				
Tube	SS-304 (7.92)	IR=4.917 OR=5.08	SS-304 (7.92)	IR=4.917 OR=5.08
		Length=228.6		Length=228.6
Canister Cylinder				
Canister Cylinder	SS-304 (7.92)	IR=21.755 OR=22.86	SS-304 (7.92)	IR=21.755 OR=22.86
		Length=397.29		Length=397.29
Storage Tube				
Storage Tube	C. Steel (7.82)	IR=24.4475 OR=25.4	C. Steel (7.82)	IR=23.495 OR=24.4475
		Length=607.06		Length=395.29

Table 3.4-3
Analysis Results for Peach Bottom Fuel in a Storage Tube

A: Steel Storage Tube Modeled Explicitly							
Case	**Storage Tube Array[(a)]**	**Fuel Condition**	**Moderated Between Elements**	**Reflected Around Elements**	**H2O bet. Between Storage Tubes**	**Calculation Results**	
						k-eff	**1 Sigma**
33A-1	1 Tube	dry	No	No	N.A.	0.0183	5E-05
33A-2	1 Tube	dry	Yes	Yes	N.A.	0.383	0.0003
33A-3	1 Tube	Sat.	Yes	Yes	N.A.	0.439	0.00032
33A-4	2 Tubes	Sat.	Yes	Yes	No	0.443	0.00032
33A-5	4 Tubes	Sat.	Yes	Yes	No	0.461	0.00032
33A-6	Inf. Array	Sat.	Yes	Yes	No	0.461	0.00032
33A-7	Inf. Array	Sat.	Yes	Yes	Yes	0.495	0.00031
B. Model As Above Except Storage Tubes Replaced With Water							
33B-1	Inf. Array	Sat.	Yes	Yes	No	0.455	0.00032
33B-2	Inf. Array	Sat.	Yes	Yes	Yes	0.477	0.00032

Note:

(a) The storage tube arrays are modeled as a square array with edge to edge separation distances of 1.1 cm for all applicable analyses.

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Table 3.5-1
Physical Characteristics of the Standard TRIGA Fuel Elements

Characteristics	Al Clad Elements	Standard SST Clad Elements
Element dim., in.	1.47 dia x 28 long	1.478 dia x 28.94 long
Geometry of fuel meat	Solid rod	Hollow rod
Effective fuel length, in.	1.41 dia x 14 long	1.435 dia x 15 long
Plenum gap length	NA	0.25 in.
Fuel meat material	$UZrH_1$	$UZrH_{1.7}$
Nominal ^{235}U	36 g	39 g
Nominal $^{Total}U$	180 g	195 g
Nominal fuel meat weight	2250 g	2283 g
Total element weight	2.9 kg	3.4 kg
U ppt size	NA	NA
Burnable poisons	Samarium trioxide	None Used
Poison dim., in.	1.42 dia x 0.05 thick	---
Rod-Cladding gap	NA	NA
Cladding	1100F Al	Type 304 SST
Clad thickness	0.03 in.	0.02 in.
Weld filler material	NA	NA
2 end fixtures	140 g	530 g
2 Graphite end reflectors	1.41 dia x 3.95 long each	1.435 dia x 3.42 long each
Material added to element	None known	0.225 in dia. Zr rod inside hollow fuel rod. Molybdenum disc,[(a)] 1.435 in. dia. X 0.031 inches thick

Note:

(a) Located between the fuel meat and the bottom graphite end reflector, only in elements produced after 4/15/71.

Table 3.5-2
Modeled Configuration for TRIGA

Region	Documented Configuration		Modeled Configuration	
	Material (g/cc)	**Dimensions, cm**	**Material (g/cc)**	**Dimensions, cm**
Fuel Description				
Fuel (Zr rod)	Zr (6.4)	OR=0.28575 Length=38.1	Zr (6.4)	OR=0.28575 Length=38.1
Fuel (meat)	U-$ZrH_{1.7}$ (6.0875)	IR=0.3175 OR=1.82245	U-$ZrH_{1.7}$ (6.0875)	IR=0.3175 OR=1.82245
		Length=38.1		Length=38.1
Fuel Clad	SS-304 (7.93)	IR=1.82626 OR=1.87706	SS-304 (7.93)	IR=1.82626 OR=1.87706
		Length=55.4736		Length=55.4736
Basket Tube				
Tube	SS-304 (7.92)	IR=2.06 OR=2.2225	SS-304 (7.92)	IR=2.06 OR=2.2225
		Length=91.44		Length=91.44
Canister				
Canister	SS-304 (7.92)	IR=21.6535 OR=22.86	SS-304 (7.92)	IR=7.3152 OR=7.467092
		Length=299.72		Length=95.25

Table 3.5-3
Analysis Results for Peach Bottom Canister and TRIGA Canister in Storage Tube

Problem ID	H2O Density Between Storage Tubes (g/cm^3)	k_{eff}	1 σ
Comc4	0	0.534	0.00041
Comc4h	0.02	0.578	0.00043
Comc4g	0.1	0.672	0.00041
Comc4f	0.2	0.691	0.00044
Comc4e	0.4	0.748	0.00042
Comc4d	0.6	0.793	0.00042
Comc4c	0.8	0.821	0.00041
Comc4b	0.9	0.830	0.00042
Comc4a	1.0	0.837	0.00040

Note: The storage tube arrays are modeled with center-to-center separation distances of 34 inches.

Table 3.5-4
TRIGA Material Compositions

Material	MCNP Isotope	Element Atom Density (atoms/b-cm)
Fuel (6.0875 g/cm^3)	1001	0.036191
	40000	0.021289
	92235	0.000157
	92238	0.000621
	26000	0.001804
	7000	2.362E-05
	8000	6.358E-06
	18000	3.028E-07
Graphite (2.3 g/cm^3)	6012	0.11532
Fe (7.86 g/cm^3)	26000	0.084758

Table 4.1-1
Modeled Configuration for Shippingport Reflector Rods

Region	Documented Configuration		Modeled Configuration	
	Material (g/cc)	**Dimensions, cm**	**Material (g/cc)**	**Dimensions, cm**
Reflector Description				
Pellet	$^{233}UO_2$-ThO_2 (9.69)	R=0.9414 Length=1.88	$^{233}UO_2$-ThO_2 (9.69)	R=0.9414 Length=1.88
Clad	Zr (6.49)	IR=0.950 OR=1.057	Zr (6.49)	IR=0.950 OR=1.057
		Length=256.39		Length=256.39

Table 4.1-2
Post Irradiation, Type V Shippingport Reflector

MCNP Case	Isotope	Activity (Ci)	Specific Activity (Ci/g)	Mass (g)	Mass per Pellet (g/pellet)	Mass per Rod (g/rod)
42-1	Th230	8.82E-04	2.02E-02	4.37E-02	1.86E-06	2.63E-04
42-2	Th232	1.15E-01	1.10E-07	1.05E+06	4.45E+01	6.30E+03
42-3	U232	5.21E+00	2.14E+01	2.43E-01	1.04E-05	1.47E-03
42-4	U233	6.38E+01	9.68E-03	6.59E+03	2.80E-01	3.97E+01
42-5	U234	1.66E-01	6.25E-03	2.66E+01	1.13E-03	1.60E-01
42-6	U235	1.20E-06	2.16E-06	5.56E-01	2.36E-05	3.35E-03
42-7	U236	2.92E-07	6.47E-05	4.51E-03	1.92E-07	2.72E-05
42-8	U238	2.54E-07	3.36E-07	7.56E-01	3.22E-05	4.55E-03
42-9	Pu236	2.08E-12	5.31E+02	3.92E-15	1.67E-19	2.36E-17
42-10	Pu238	1.39E-05	1.71E+01	8.13E-07	3.46E-11	4.90E-09
42-11	Pu239	6.65E-04	6.22E-02	1.07E-02	4.55E-07	6.44E-05
42-12	Pu240	1.58E-04	2.28E-01	6.93E-04	2.95E-08	4.17E-06
42-13	Pu241	4.88E-03	1.03E+02	4.74E-05	2.02E-09	2.85E-07
42-14	Pu242	1.45E-08	3.82E-03	3.80E-06	1.62E-10	2.29E-08
42-15	Am241	2.76E-04	3.43E+00	8.05E-05	3.42E-09	4.85E-07
42-16	O16			1.45E+05	6.15E+00	8.70E+02

Table 4.1-3
Analysis Results for Infinite Array of Shippingport Reflector Rods

Pitch (inches)	k_{eff}	Uncertainty (1 σ)	MCNP Case
0.9000	0.6210	0.0016	43-1
0.9500	0.6410	0.0015	43-2
1.0000	0.6490	0.0015	43-3
1.0500	0.6420	0.0013	43-4
1.1000	0.6370	0.0013	43-5

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Table 5.2-1
Benchmark Experiment Descriptions for Validating MCNP4B2 Code

Experiment	Number of Selected Experiments	Number of Available Experiments	Description of Criticality Experiments
IEU-COMP-THERM-002	2	6	17 wt% ^{235}U stainless-steel-clad fuel rods in 6.8-cm hexagonal-pitched lattices; gadolinium or cadmium absorber element (if present)
IEU-COMP-THERM-003	2	2	20 wt% ^{235}U TRIGA Mark II reactor; zirconium hydride fuel rods in water; graphite reflector; 12 w/o uranium concentration
HEU-COMP-THERM-002	25	25	Hexagonal graphite rods containing highly enriched uranium moderated and reflected by water, uranium enriched to 93.15 wt % ^{235}U.
HEU-COMP-THERM-007	3	3	Hexagonally pitched double lattices, $U(80)O_2$, ZrH rods, water moderated and reflected.
HEU-COMP-INTER-001	1	6	96% ^{235}U, zirconium hydride moderator, beryllium reflector, water moderated
HEU-MET-THERM-003	5	7	Nearly cubic and cubic lattices of oralloy (Oy), water moderated and reflected, various ^{235}U enrichments (~94%).
HEU-MET-THERM-006	18	23	Lattices of SPERT-D fuel elements, uranium enriched to 93.17%, cladding 0.02 in thick, water moderated and reflected.
Total	**56**	**72**	

Table 5.2-2 **Sheet 1 of 2**
Calculation Results for 56 Critical Experiments

Case ID	Calculated k_{eff}	Uncertainty (σ_{calc})	Benchmark k_{eff}	Normalized k_{eff}
ICT0201	0.9959	0.0008	1.0014	0.9945
ICT0202	1.0009	0.0008	1.0019	0.9990
ICT0301	0.9988	0.0009	1.0006	0.9982
ICT0302	1.0061	0.0009	1.0046	1.0015
HCT0201	1.0080	0.0010	1.0011	1.0069
HCT0202	1.0134	0.0010	1.0011	1.0123
HCT0203	1.0132	0.0010	1.0011	1.0121
HCT0204	1.0152	0.0010	1.0011	1.0141
HCT0205	1.0150	0.0009	1.0011	1.0139
HCT0206	1.0157	0.0009	1.0011	1.0146
HCT0207	1.0153	0.0009	1.0011	1.0142
HCT0208	1.0157	0.0008	1.0011	1.0146
HCT0209	1.0152	0.0008	1.0011	1.0141
HCT0210	1.0148	0.0008	1.0011	1.0137
HCT0211	1.0140	0.0010	1.0011	1.0129
HCT0212	1.0113	0.0010	1.0011	1.0102
HCT0213	1.0157	0.0009	1.0011	1.0146
HCT0214	1.0146	0.0009	1.0011	1.0135
HCT0215	1.0178	0.0008	1.0011	1.0167
HCT0216	1.0164	0.0008	1.0011	1.0153
HCT0217	1.0213	0.0008	1.0011	1.0202
HCT0218	1.0151	0.0011	1.0020	1.0131
HCT0219	1.0102	0.0010	1.0020	1.0082
HCT0220	1.0156	0.0009	1.0020	1.0136
HCT0221	1.0141	0.0009	1.0020	1.0121
HCT0222	1.0142	0.0009	1.0020	1.0122
HCT0223	1.0136	0.0010	1.0008	1.0128
HCT0224	1.0147	0.0010	1.0008	1.0139
HCT0225	1.0124	0.0010	1.0008	1.0116
HCT0701A	0.9969	0.0009	1.0000	0.9969

Table 5.2-2 **Sheet 2 of 2**
Calculation Results for 56 Critical Experiments

Case ID	Calculated k_{eff}	Uncertainty (σ_{calc})	Benchmark k_{eff}	Normalized k_{eff}
HCT0702A	0.9946	0.0009	1.0000	0.9946
HCT0703A	0.9943	0.0009	1.0000	0.9943
HCI0105	1.0019	0.0009	1.0000	1.0019
HMT0303	0.9812	0.0009	0.9826	0.9986
HMT0304	0.9881	0.0009	0.9876	1.0005
HMT0305	1.0028	0.0010	0.9930	1.0099
HMT0306	0.9733	0.0010	0.9889	0.9842
HMT0307	0.9867	0.0010	0.9919	0.9948
HMT0601	0.9970	0.0010	1.0000	0.9970
HMT0602	0.9987	0.0010	1.0000	0.9987
HMT0603	1.0019	0.0009	1.0000	1.0019
HMT0605	0.9987	0.0009	1.0000	0.9987
HMT0606	0.9975	0.0009	1.0000	0.9975
HMT0607	0.9975	0.0008	1.0000	0.9975
HMT0608	0.9924	0.0008	1.0000	0.9924
HMT0609	0.9946	0.0008	1.0000	0.9946
HMT0610	1.0043	0.0010	1.0000	1.0043
HMT0611	1.0047	0.0009	1.0000	1.0047
HMT0612	1.0041	0.0008	1.0000	1.0041
HMT0613[a]	1.0292[a]	0.0009	1.0000	1.0292[a]
HMT0614	0.9933	0.0008	1.0000	0.9933
HMT0615	0.9904	0.0008	1.0000	0.9904
HMT0616	1.0058	0.0009	1.0000	1.0058
HMT0617	1.0015	0.0009	1.0000	1.0015
HMT0618	1.0032	0.0010	1.0000	1.0032
HMT0619	0.9916	0.0007	1.0000	0.9916

[a] HMT0613 was reported to be high by the evaluator with no explanation. As a result, it was not used to compute the bias for this class of materials.

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Table 5.3-1
Benchmark Experiment Descriptions for Validating MCNP4C for TRIGA Fuel

Experiment	Number of Available Experiments	Number of Selected Experiments	Description of Criticality Experiments
HEU-COMP-THERM-011	5	3	~80 a/o ^{235}U UO_2 stainless-steel-clad fuel rods in an aluminum matrix in clusters of square-pitched 21x21 lattices; lattice pitch value of 14 mm; cluster distance varied from 0 to 5.6 cm
HEU-COMP-THERM-012	5	2	~80 a/o ^{235}U UO_2 stainless-steel-clad fuel rods in an aluminum matrix in clusters of square-pitched 18x18 lattices; lattice pitch value of 14 mm; cluster distance varied from 0 to 5.6 cm
HEU-COMP-THERM-013	4	2	~80 a/o ^{235}U UO_2 stainless-steel-clad fuel rods in an aluminum matrix in clusters of square-pitched 14x14 lattices; lattice pitch value of 14 mm; cluster distance varied from 1.4 to 5.6 cm
HEU-COMP-THERM-014	4	2	~80 a/o ^{235}U UO_2 stainless-steel-clad fuel rods in an aluminum matrix in clusters of square-pitched 10x10 lattices; lattice pitch value of 19.8 mm; cluster distance varied from 0 to 5.94 cm
IEU-COMP-THERM-002	6	6	17 w/o ^{235}U stainless-steel-clad fuel rods in 6.8-cm hexagonal-pitched lattices; gadolinium or cadmium absorber element (if present)
IEU-COMP-THERM-003	2	2	20 w/o ^{235}U TRIGA Mark II reactor; zirconium hydride fuel rods in water; graphite reflector; 12 w/o uranium concentration
LEU-COMP-THERM-001	8	8	2.35 w/o ^{235}U UO_2 aluminum clad fuel rods in 2.032-cm square-pitched arrays; water-moderated
LEU-COMP-THERM-002	5	5	4.31 w/o ^{235}U UO_2 aluminum clad fuel rods in 2.54-cm square-pitched arrays; water-moderated
LEU-COMP-THERM-003	23	22	2.35 w/o ^{235}U UO_2 aluminum clad fuel rods in 1.684-cm square-pitched arrays; water-moderated, gadolinium water impurity
LEU-COMP-THERM-004	20	20	4.31 w/o ^{235}U UO_2 aluminum clad fuel rods in 1.892-cm square-pitched arrays; water-moderated, gadolinium water impurity
Total	**82**	**72**	

Table 5.3-2 **Sheet 1 of 3**
K_{eff} and Uncertainty Results

Case	k_{eff}	Uncertainty (σ)	$k_{eff} + 2\sigma$
HEU-COMP-THERM-011			
hct11a	0.987	0.0009	0.9890
hct11b	0.990	0.0008	0.9920
hct11c	0.991	0.0009	0.9923
HEU-COMP-THERM-012			
hct12a	0.990	0.0011	0.9926
hct12b	0.988	0.0009	0.9902
HEU-COMP-THERM-013			
hct13a	0.991	0.0009	0.9928
hct13b	0.992	0.0010	0.9944
HEU-COMP-THERM-014			
hct14a	0.998	0.0009	0.9997
hct14b	0.997	0.0009	0.9991
IEU-COMP-THERM-002			
ict2a	0.994	0.0007	0.9957
ict2b	1.000	0.0008	1.0011
ict2c	1.000	0.0007	1.0012
ict2d	1.003	0.0007	1.0047
ict2e	0.994	0.0007	0.9958
ict2f	0.996	0.0007	0.9971
IEU-COMP-THERM-003			
ict3a	1.000	0.0003	1.0001
ict3b	1.005	0.0003	1.0053
LEU-COMP-THERM-001			
lct1a	0.995	0.0018	0.9985
lct1b	0.997	0.0015	0.9995
lct1c	0.995	0.0015	0.9976
lct1d	0.998	0.0015	1.0007
lct1e	0.993	0.0017	0.9959
lct1f	0.996	0.0016	0.9995
lct1g	1.001	0.0015	1.0035
lct1h	0.992	0.0016	0.9949

Table 5.3-2 **Sheet 2 of 3**
K_{eff} and Uncertainty Results

Case	k_{eff}	Uncertainty (σ)	k_{eff} + 2σ
LEU-COMP-THERM-002			
lct2a	0.994	0.0017	0.9970
lct2b	0.996	0.0019	1.0002
lct2c	0.993	0.0018	0.9964
lct2d	0.995	0.0020	0.9987
lct2e	0.995	0.0017	0.9988
LEU-COMP-THERM-003			
lct3a	0.986	0.0020	0.9902
lct3b	0.985	0.0017	0.9887
lct3c	0.982	0.0018	0.9857
lct3d	0.985	0.0017	0.9880
lct3e	0.987	0.0018	0.9910
lct3f	0.984	0.0015	0.9872
lct3g	0.986	0.0019	0.9898
lct3h	0.988	0.0019	0.9916
lct3i	0.980	0.0016	0.9827
lct3j	0.980	0.0017	0.9829
lct3k	0.984	0.0017	0.9870
lct3l	0.982	0.0016	0.9854
lct3m	0.982	0.0018	0.9857
lct3n	0.983	0.0016	0.9864
lct3o	0.984	0.0017	0.9878
lct3p	0.983	0.0018	0.9869
lct3q	0.982	0.0017	0.9857
lct3r	0.982	0.0017	0.9850
lct3s	0.981	0.0017	0.9845
lct3t	0.984	0.0014	0.9867
lct3u	0.982	0.0016	0.9855
lct3v	0.993	0.0017	0.9962

Table 5.3-2 **Sheet 3 of 3**
K_{eff} and Uncertainty Results

Case	k_{eff}	Uncertainty (σ)	$k_{eff} + 2\sigma$
LEU-COMP-THERM-004			
lct4a	0.990	0.0017	0.9932
lct4b	0.989	0.0019	0.9927
lct4c	0.989	0.0021	0.9932
lct4d	0.990	0.0020	0.9943
lct4e	0.989	0.0020	0.9925
lct4f	0.987	0.0020	0.9906
lct4g	0.990	0.0018	0.9933
lct4h	0.989	0.0018	0.9930
lct4i	0.988	0.0022	0.9928
lct4j	0.996	0.0019	0.9999
lct4k	0.984	0.0019	0.9875
lct4l	0.978	0.0021	0.9825
lct4m	0.986	0.0018	0.9896
lct4n	0.982	0.0021	0.9863
lct4o	0.987	0.0017	0.9900
lct4p	0.986	0.0018	0.9896
lct4q	0.985	0.0023	0.9892
lct4r	0.984	0.0019	0.9877
lct4s	0.986	0.0019	0.9900
lct4t	0.984	0.0017	0.9877

Table 5.3-3
Benchmark Experiment Descriptions for Validating MCNP4C for Peach Bottom Fuel

Experiment	Number of Available Experiments	Number of Selected Experiments	Description of Criticality Experiments
HEU-COMP-MIXED-001	26	7	Cans in variously sized arrays containing enriched uranium dioxide (UO_2), 93.15 wt% ^{235}U enrichment, cans arranged in variously sized arrays.
HEU-COMP-THERM-002	25	25	Hexagonal graphite rods containing highly enriched uranium moderated and reflected by water, uranium enriched to 93.15 wt % ^{235}U.
HEU-SOL-THERM-005	17	8	Highly enriched solutions of uranyl nitrate [$UO_2(NO_3)_2$] and uranyl fluoride [UO_2F_2], ^{235}U enrichments ranging from 87.4% to 93.2%, H/^{235}U values ranging from 99.3 to 276.
HEU-SOL-THERM-025	18	18	Highly enriched (89.0 wt% ^{235}U) uranium in uranyl nitrate solutions, solution heights varied from experiment to experiment.
Total		**58**	

Table 5.3-4 Sheet 1 of 2
K_{eff} and Uncertainty Results

Case	k_{eff}	Uncertainty (σ)	k_{eff} + 2σ
HEU-COMP-MIXED-001			
hcm1b.o	1.0089	0.0011	1.0111
hcm1d.o	0.9899	0.0010	0.9919
hcm1k.o	1.0005	0.0010	1.0025
hcm1n.o	0.9948	0.0011	0.9970
hcm1q.o	1.0151	0.0016	1.0183
hcm1x.o	1.0058	0.0015	1.0088
hcm1y.o	1.0086	0.0016	1.0118
HEU-COMP-THERM-002			
hct2a.o	1.0013	0.0017	1.0047
hct2b.o	1.0170	0.0018	1.0206
hct2c.o	1.0157	0.0016	1.0189
hct2d.o	1.0212	0.0018	1.0248
hct2e.o	1.0195	0.0015	1.0225
hct2f.o	1.0188	0.0017	1.0222
hct2g.o	1.0186	0.0015	1.0216
hct2h.o	1.0190	0.0013	1.0216
hct2i.o	1.0188	0.0016	1.0220
hct2j.o	1.0180	0.0015	1.0210
hct2k.o	1.0169	0.0017	1.0203
hct2l.o	1.0154	0.0018	1.0190
hct2m.o	1.0208	0.0016	1.0240
hct2n.o	1.0222	0.0018	1.0258
hct2o.o	1.0208	0.0017	1.0242
hct2p.o	1.0198	0.0015	1.0228
hct2q.o	1.0214	0.0014	1.0242
hct2r.o	1.0154	0.0018	1.0190
hct2s.o	1.0177	0.0018	1.0213
hct2t.o	1.0179	0.0016	1.0211
hct2u.o	1.0183	0.0016	1.0215
hct2v.o	1.0149	0.0011	1.0171
hct2w.o	1.0152	0.0020	1.0192
hct2x.o	1.0206	0.0015	1.0236
hct2y.o	1.0185	0.0015	1.0215

Table 5.3-4 Sheet 2 of 2
K_{eff} and Uncertainty Results

Case	k_{eff}	Uncertainty (σ)	k_{eff} + 2σ
HEU-SOL-THERM-005			
hst5a.o	1.0004	0.0011	1.0026
hst5c.o	1.0098	0.0011	1.0120
hst5d.o	1.0083	0.0011	1.0105
hst5f.o	1.0034	0.0013	1.0060
hst5h.o	0.9908	0.0012	0.9932
hst5i.o	1.0089	0.0012	1.0113
hst5m.o	0.9997	0.0011	1.0019
hst5p.o	1.0033	0.0010	1.0053
HEU-SOL-THERM-025			
hst25a.o	1.0007	0.0008	1.0023
hst25b.o	0.9984	0.0008	1.0000
hst25c.o	0.9952	0.0008	0.9968
hst25d.o	1.0015	0.0008	1.0031
hst25e.o	1.0031	0.0009	1.0049
hst25f.o	1.0094	0.0007	1.0108
hst25g.o	1.0146	0.0008	1.0162
hst25h.o	1.0100	0.0008	1.0116
hst25i.o	1.0056	0.0008	1.0072
hst25j.o	1.0097	0.0008	1.0113
hst25k.o	1.0104	0.0008	1.0120
hst25l.o	1.0110	0.0008	1.0126
hst5m.o	1.0167	0.0008	1.0183
hst25n.o	1.0101	0.0008	1.0117
hst25o.o	1.0028	0.0008	1.0044
hst25p.o	1.0157	0.0008	1.0173
hst25q.o	1.0084	0.0008	1.0100
hst25r.o	1.0048	0.0007	1.0062

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Chapter 4 Appendix 4A Figures

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Figure 2.2-1
MCNP Model of Two TRIGA Baskets Side-by-Side

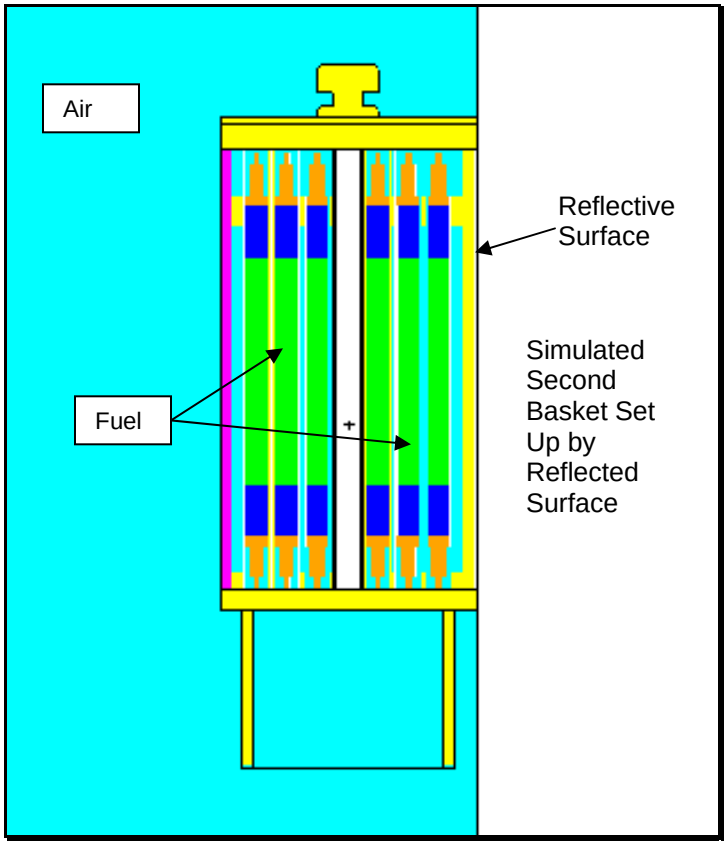


Figure 2.2-2
X-Y Plane View of TRIGA Fuel Basket

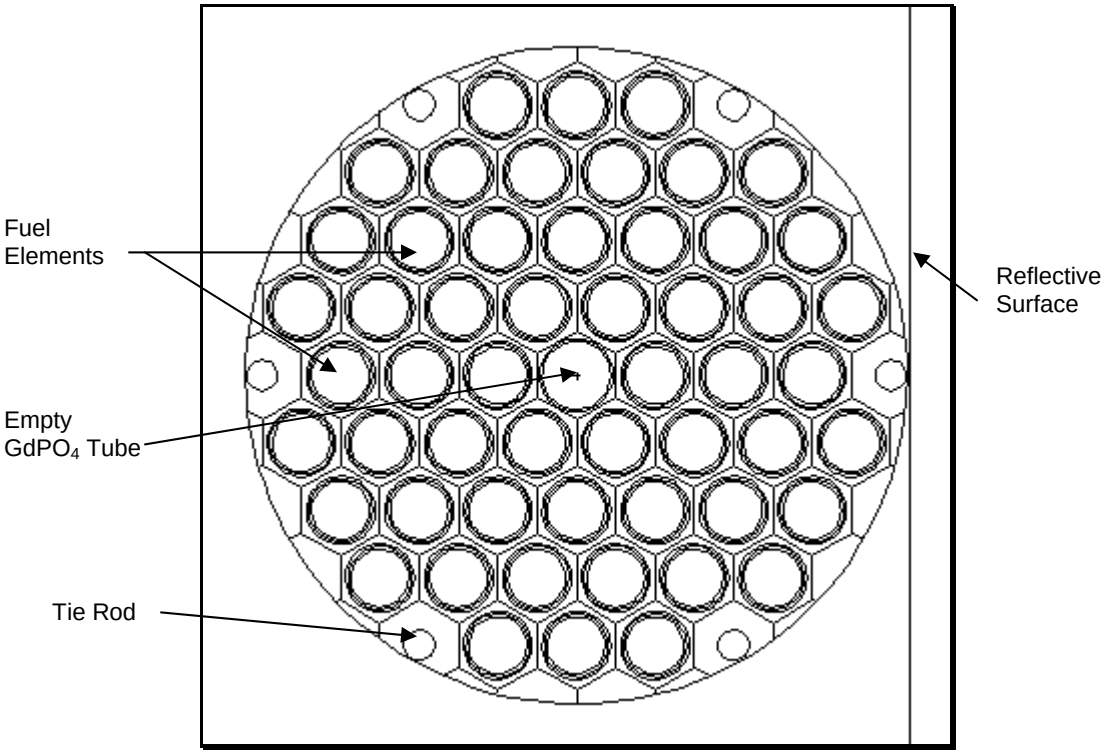


Figure 2.3-1
MCNP Model of Two Stacked TRIGA Baskets

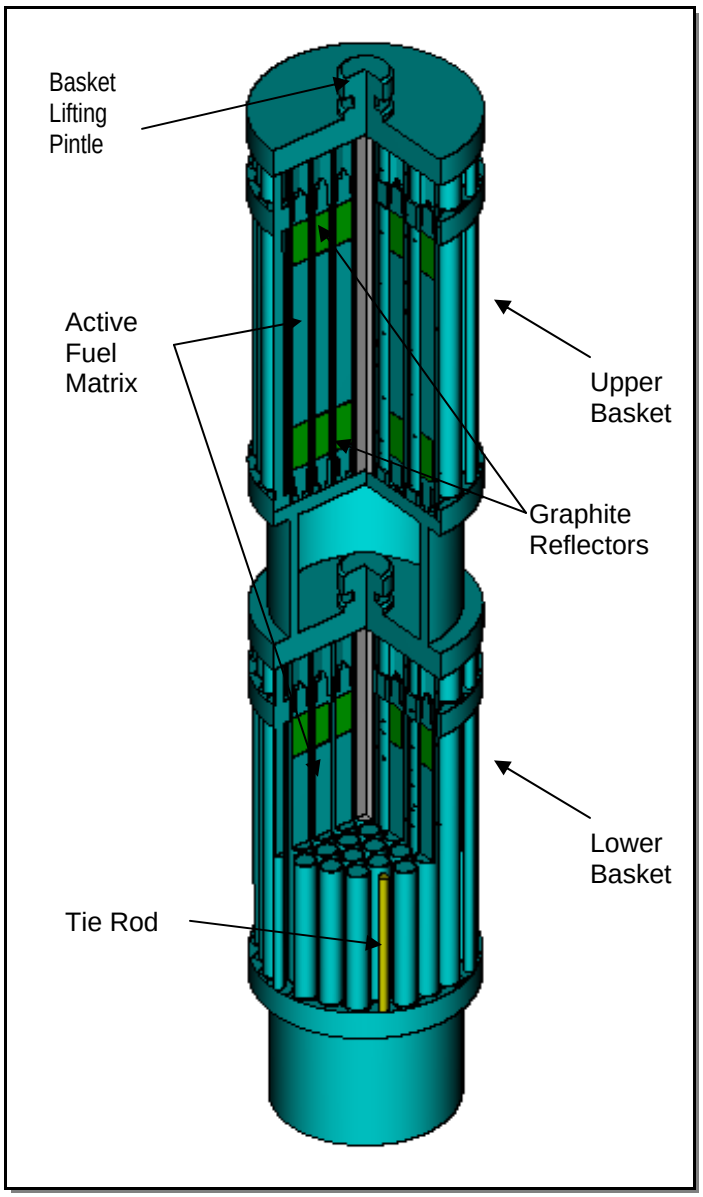


Figure 2.3-2
MCNP Model of Two Stacked TRIGA Baskets in ISF Canister

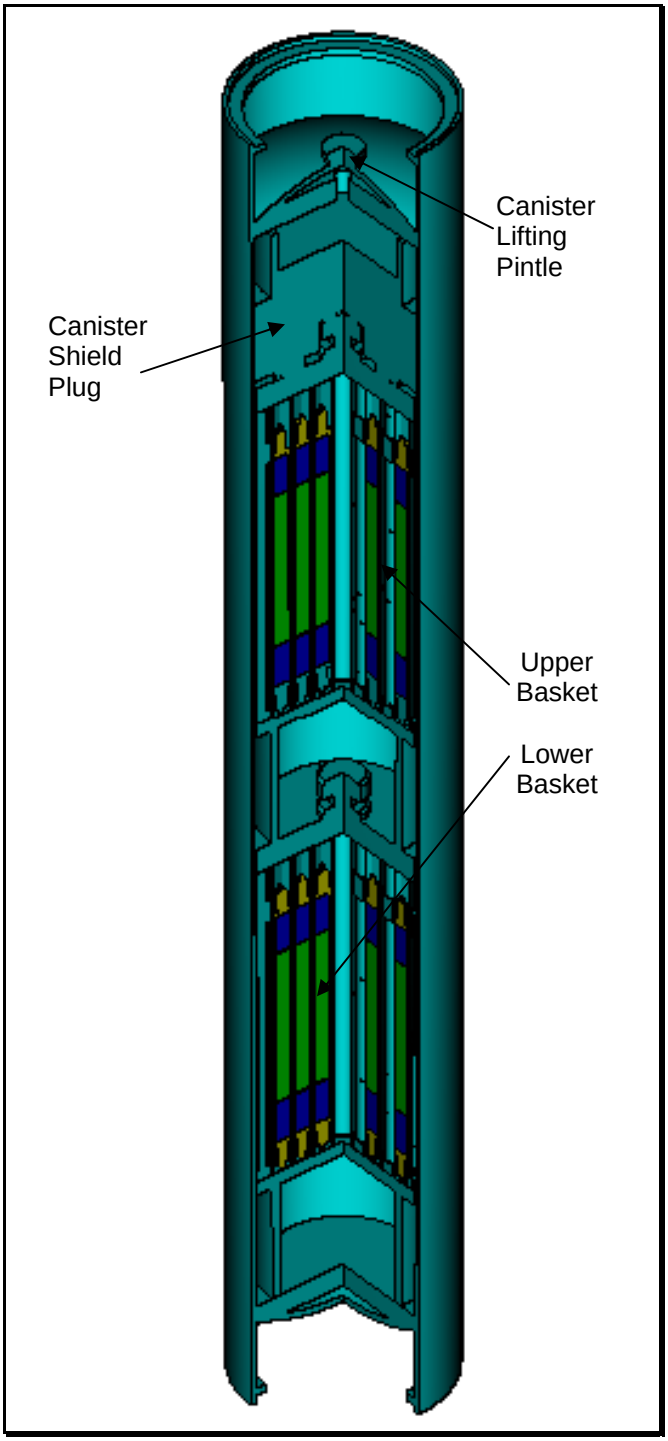


Figure 2.3-3
TRIGA Fuel Canisters in ISF Vault Storage Tubes

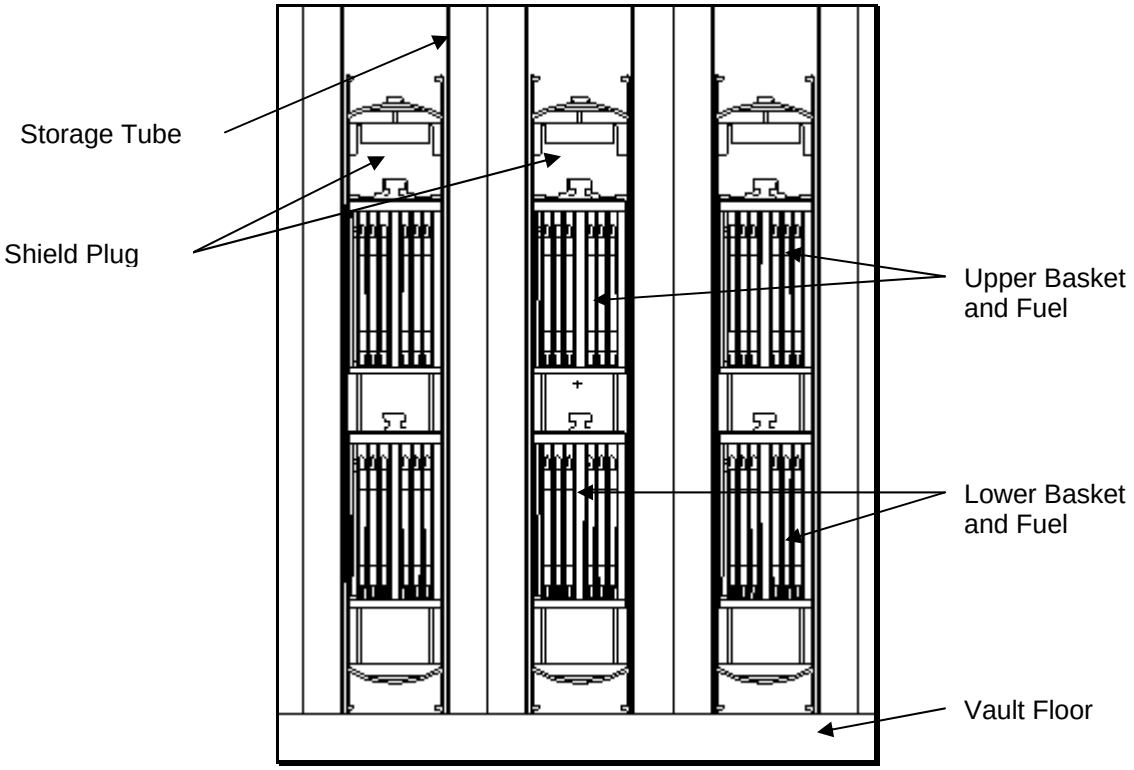


Figure 2.4-1
Radial View of MCNP Model for a Single TRIGA Canister under Dry Moderation Conditions with 1 Inch Water Reflection

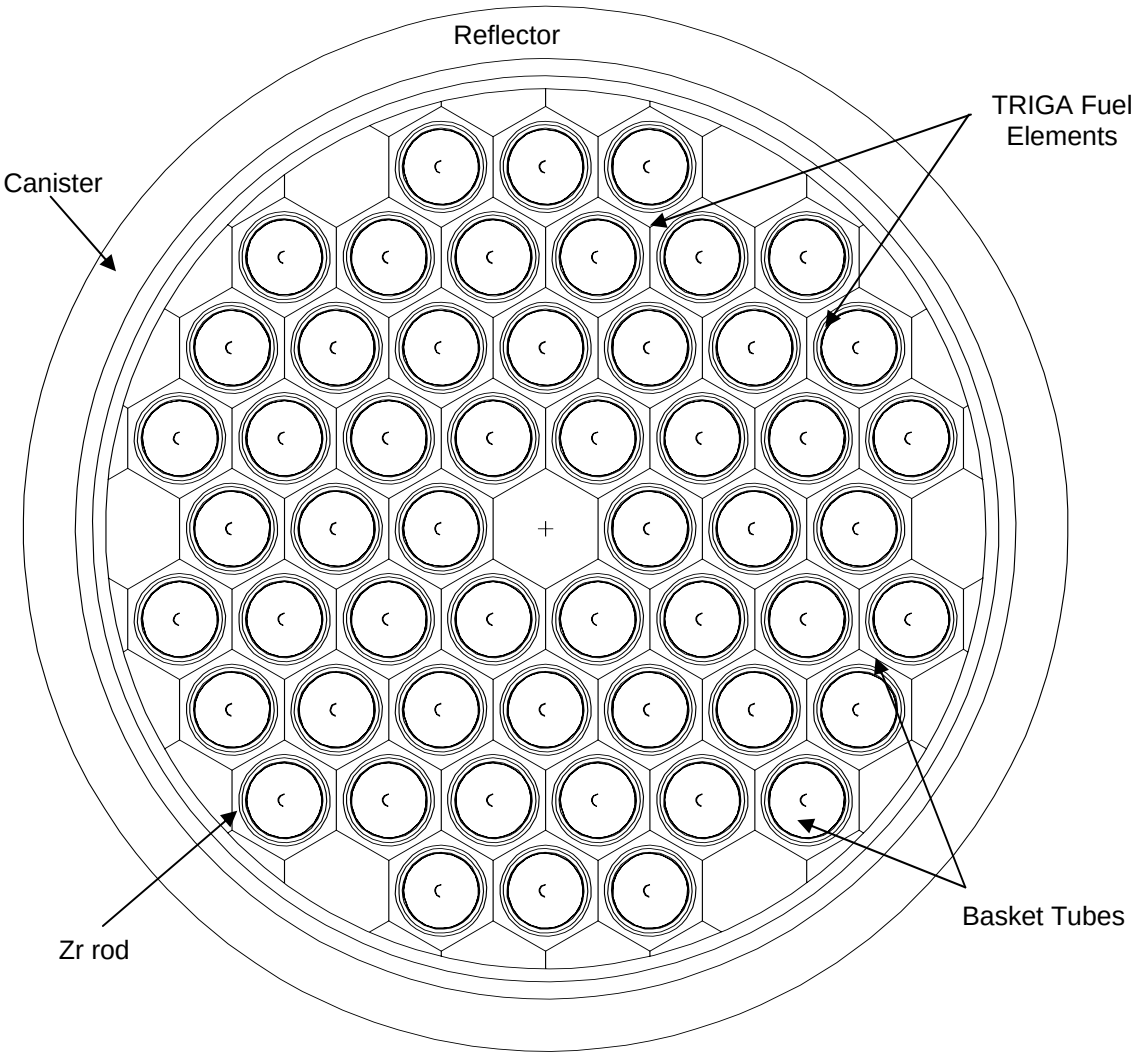


Figure 2.4-2
Axial View of MCNP Model for a Single TRIGA Canister Under Dry Moderation Conditions with 1 Inch Water Reflection

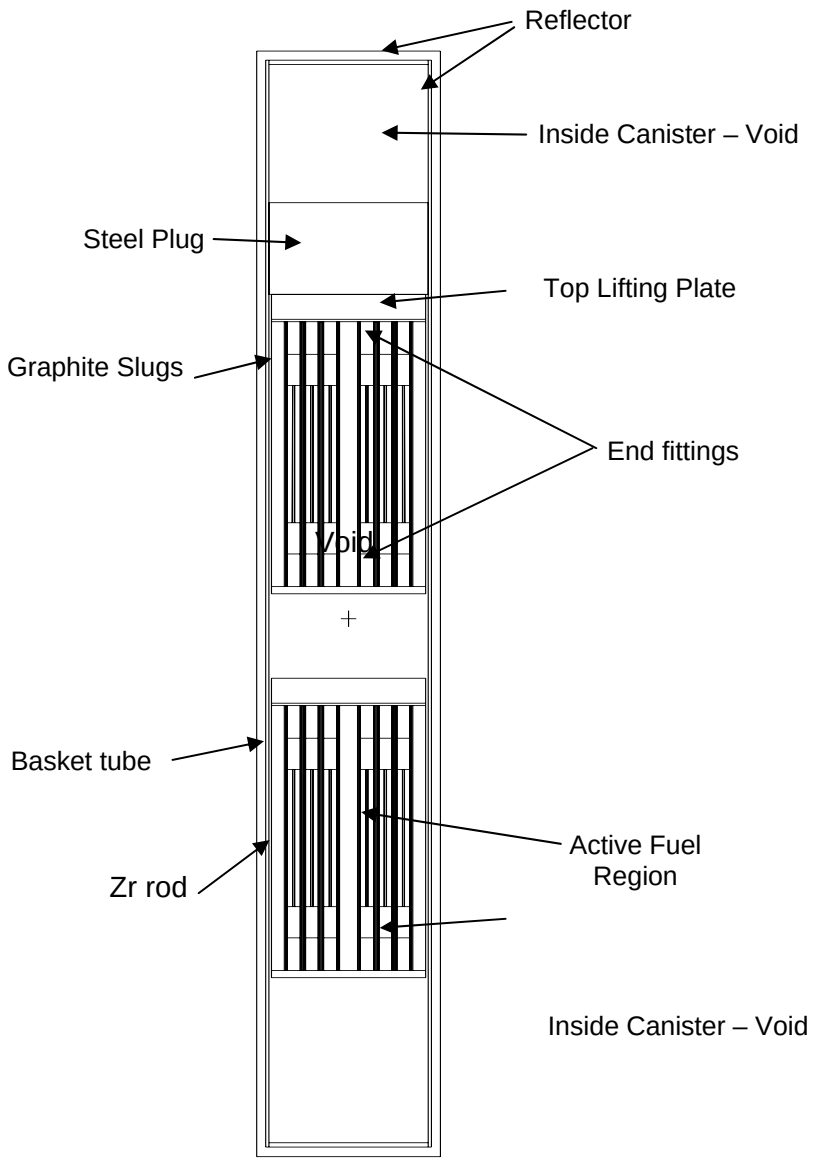


Figure 2.4-3
Radial View of MCNP Model for a Single TRIGA Canister under Dry Moderation Conditions with 12 Inches Water Reflection

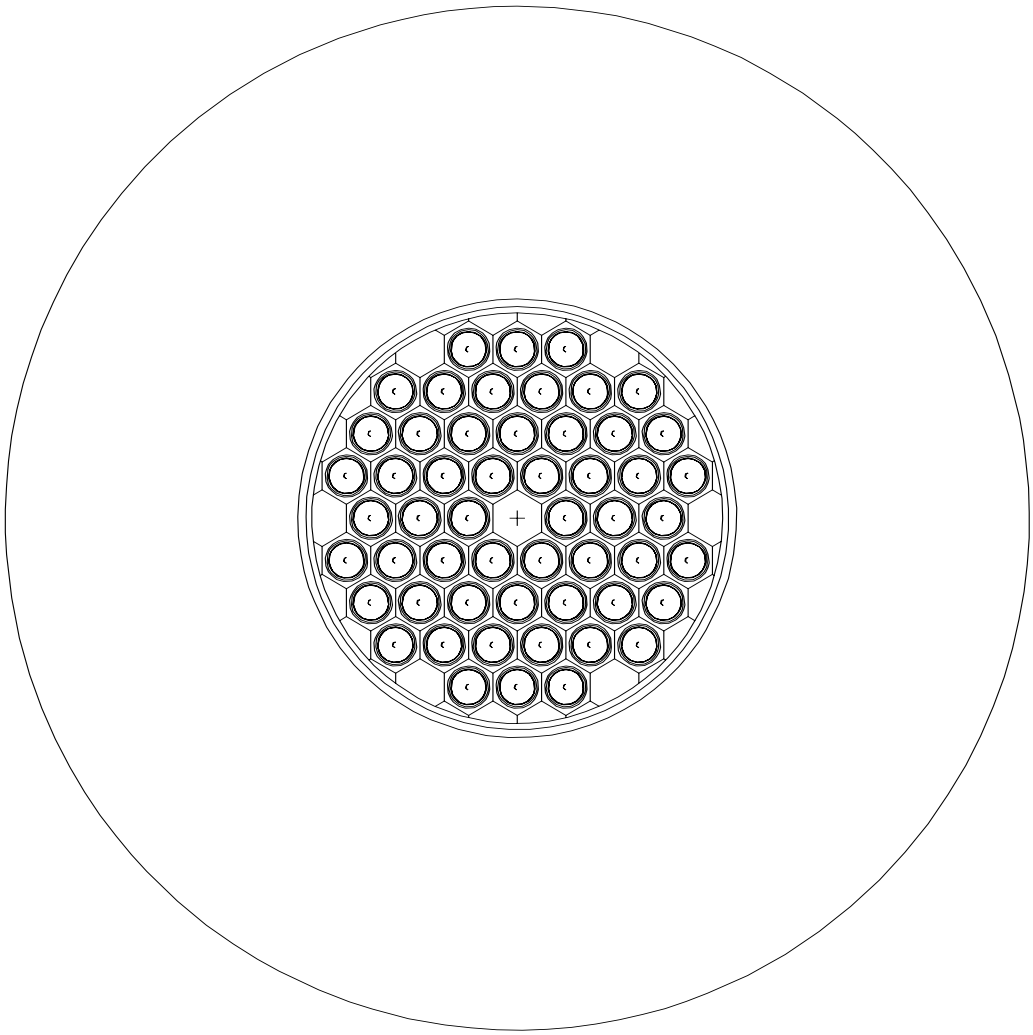


Figure 2.4-4
Axial View of MCNP Model for a Single TRIGA Canister under Dry Moderation Conditions with 12 Inches Water Reflection

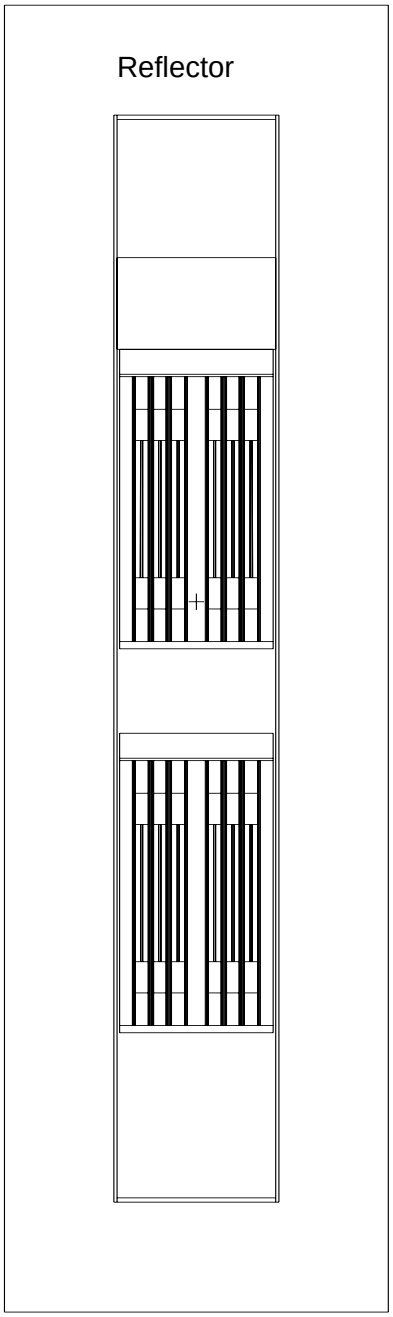


Figure 2.4-5
Radial View of MCNP Model for Two TRIGA Canisters Side-by-Side under Dry Moderation Conditions with 1 Inch Water Reflection

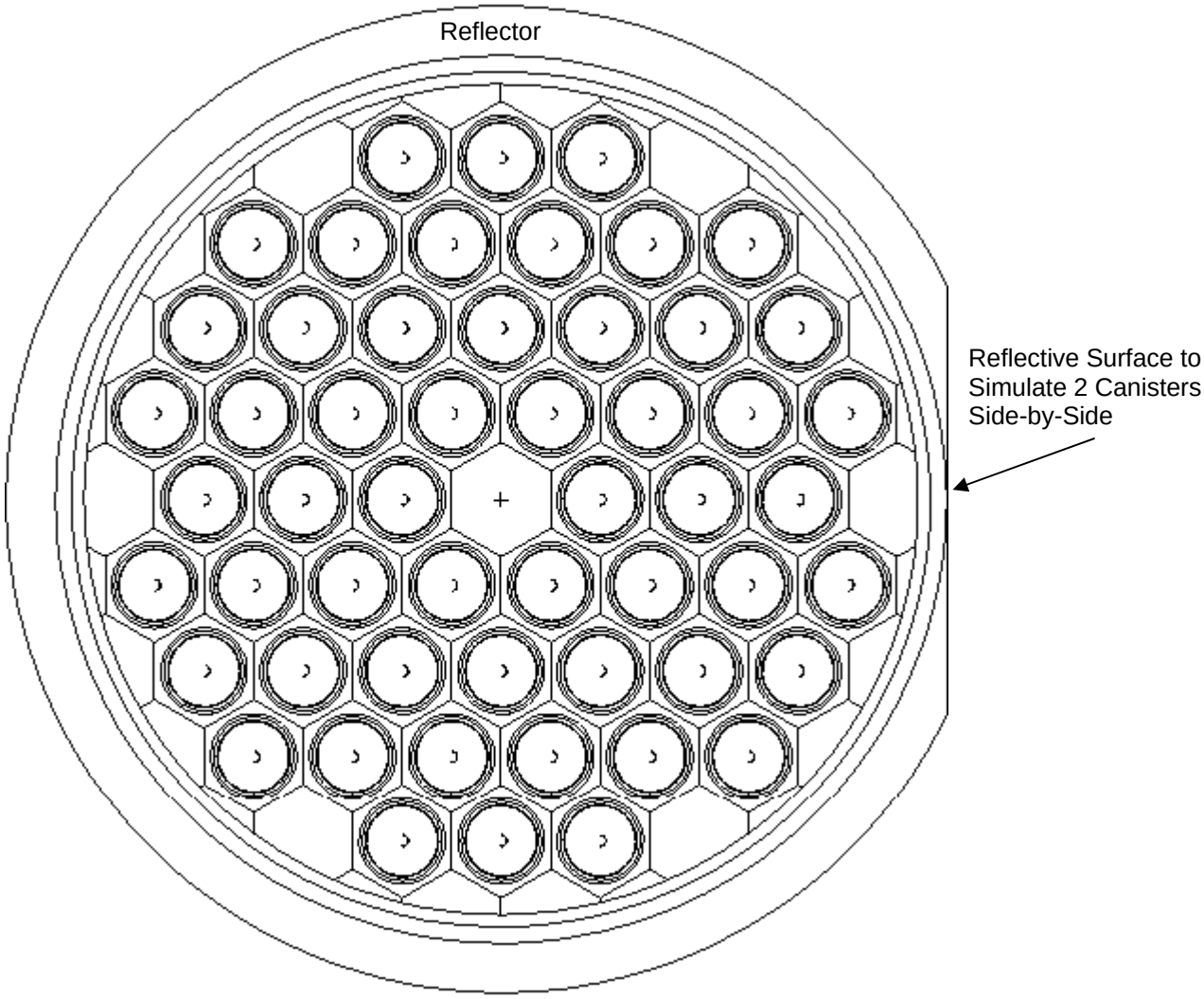


Figure 2.4-6
Axial View of MCNP Model for Two TRIGA Canisters Side-by-Side under Dry Moderation Conditions with 1 Inch Water Reflection

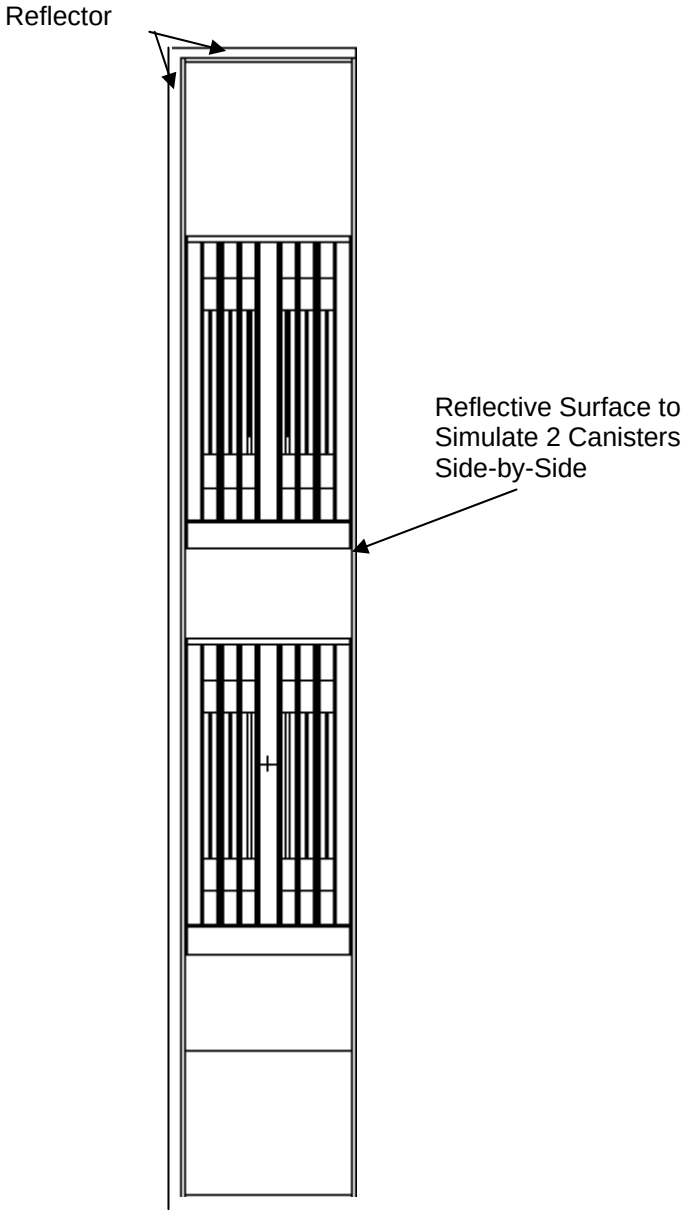


Figure 2.4-7
Radial View of MCNP Model for Two Flooded TRIGA Canisters Placed Side-by-Side with 12 Inches Water Reflection

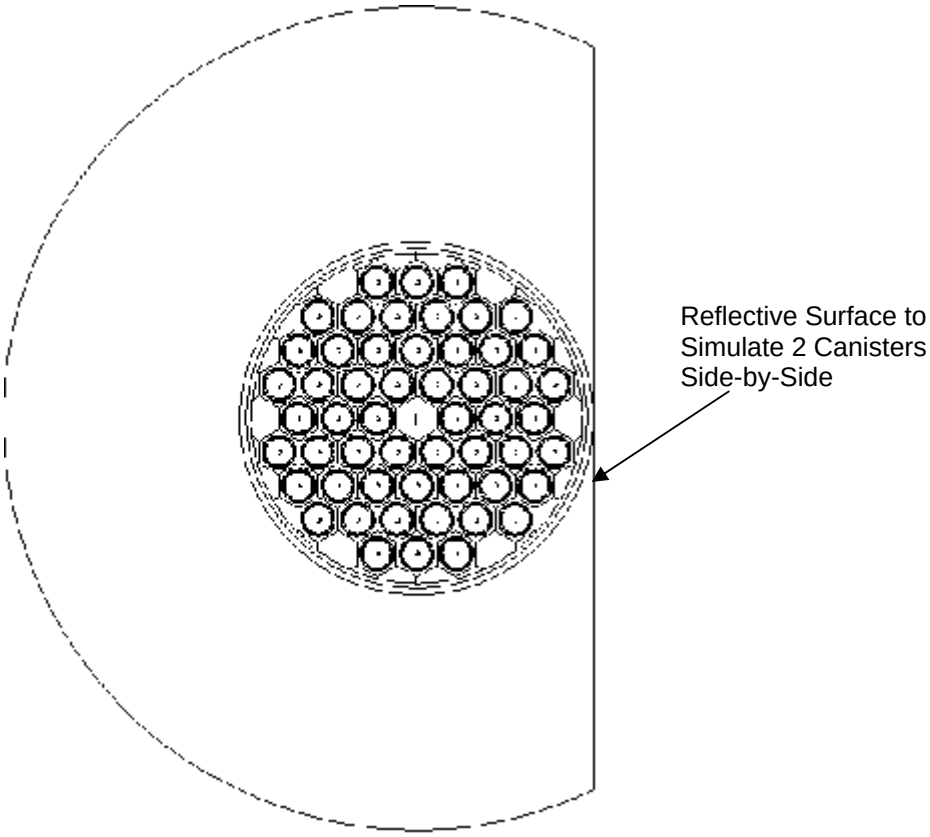


Figure 2.4-8
Axial View of MCNP Model for Two Flooded TRIGA Canisters Placed Side-by-Side with 12 Inches Water Reflection

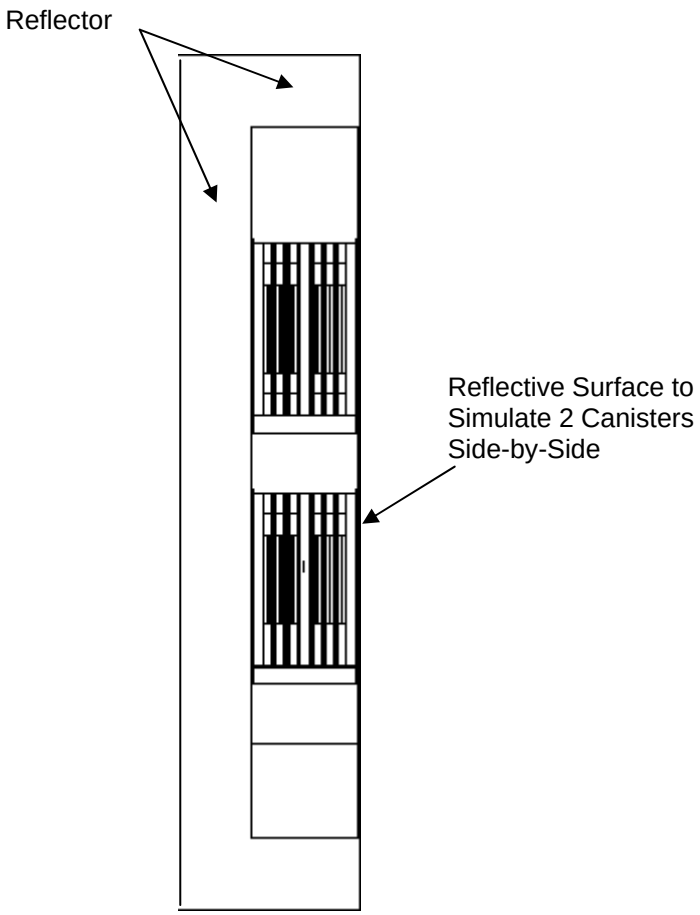


Figure 2.4-9
Axial View of MCNP Model for Two TRIGA Canisters End-to-End under Dry Moderation Conditions with 1 Inch Water Reflection

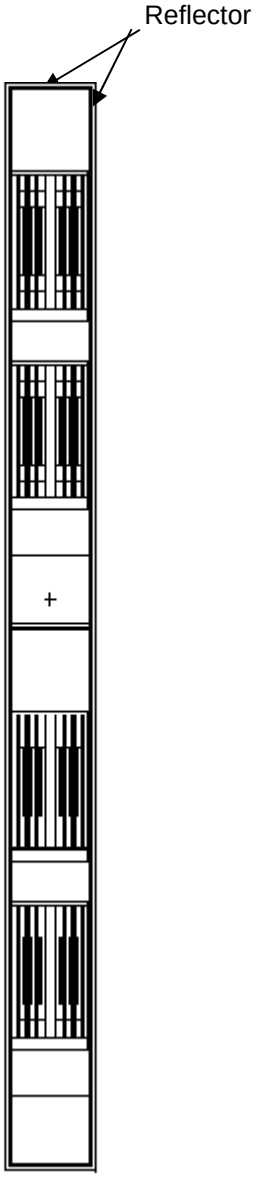


Figure 2.4-10
Axial View of MCNP Model for Two TRIGA Canisters End-to-End under Dry Moderation Conditions with 12 Inches Water Reflection

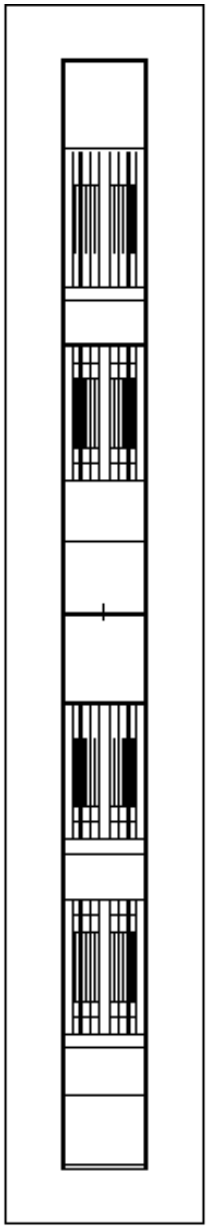
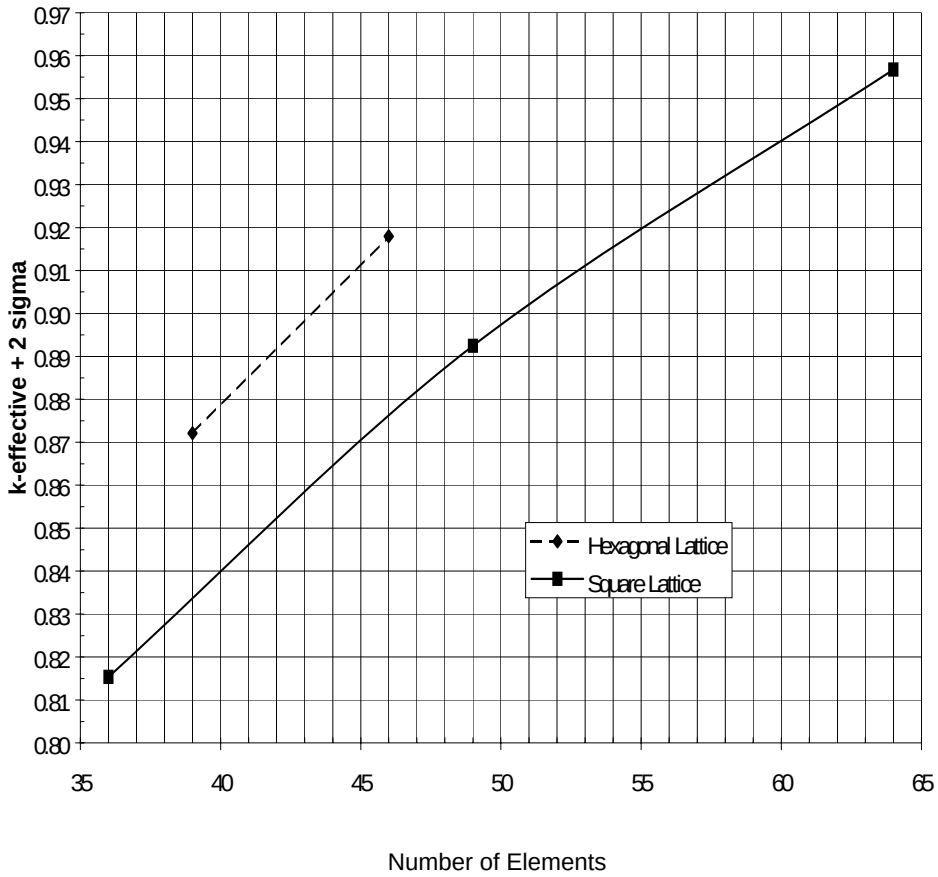


Figure 2.5-1
k_{eff} + 2σ for Arrays of TRIGA Fuel Elements



Notes:

Reactivity of SS Clad Post-1965 TRIGA Fuel Elements in an Array with No Interspersed Water
Reflector is 36 in. Concrete on 3 Sides; 1 in. Water on 3 Sides;
Pitch = Element Diameter (3.7542 cm)

Figure 2.5-2
Hexagonal Pitched MCNP Model, Transverse Cut through Fuel Stacked in Concrete Corner with Water Reflection

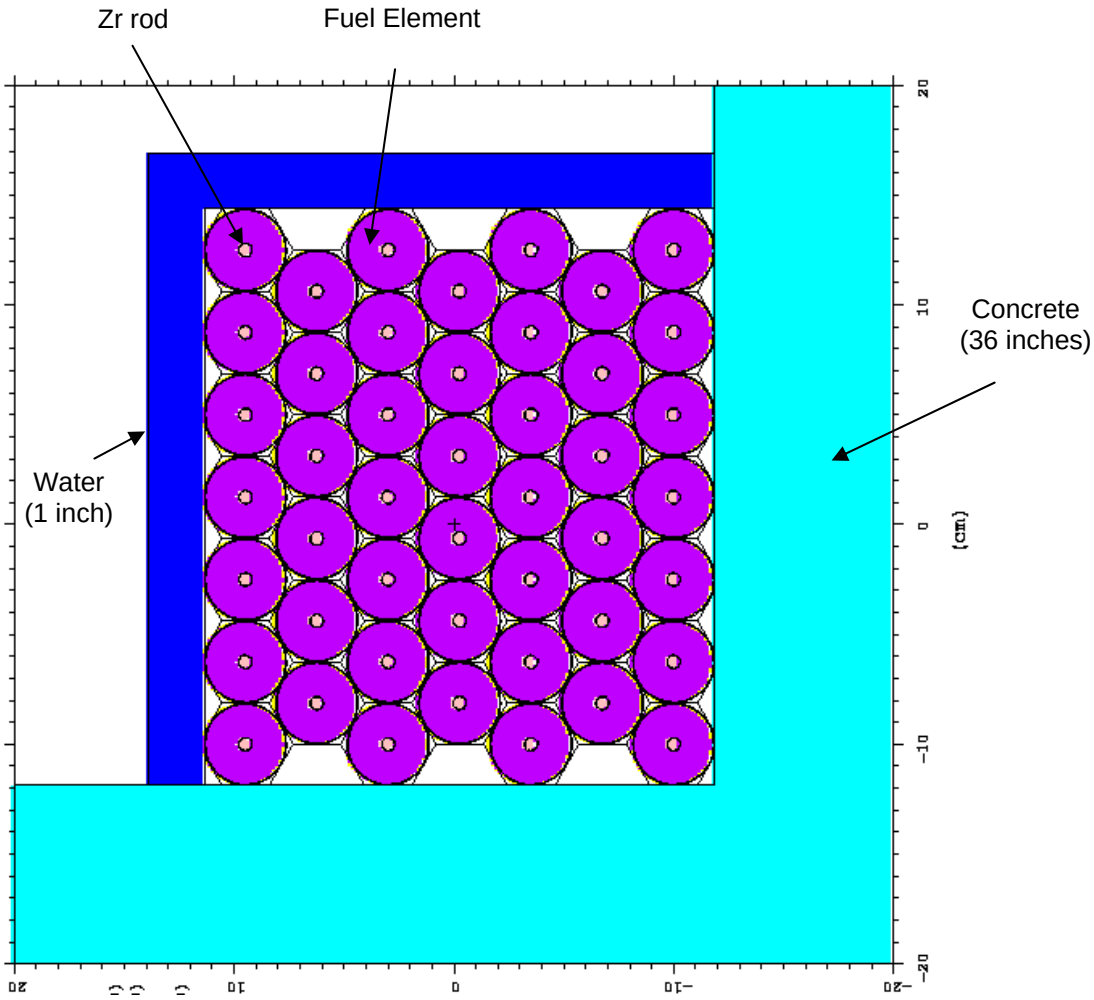


Figure 2.5-3
MCNP Model, Cut Parallel to the Longitudinal Axis of Fuel Stacked in Concrete Corner with Water Reflection

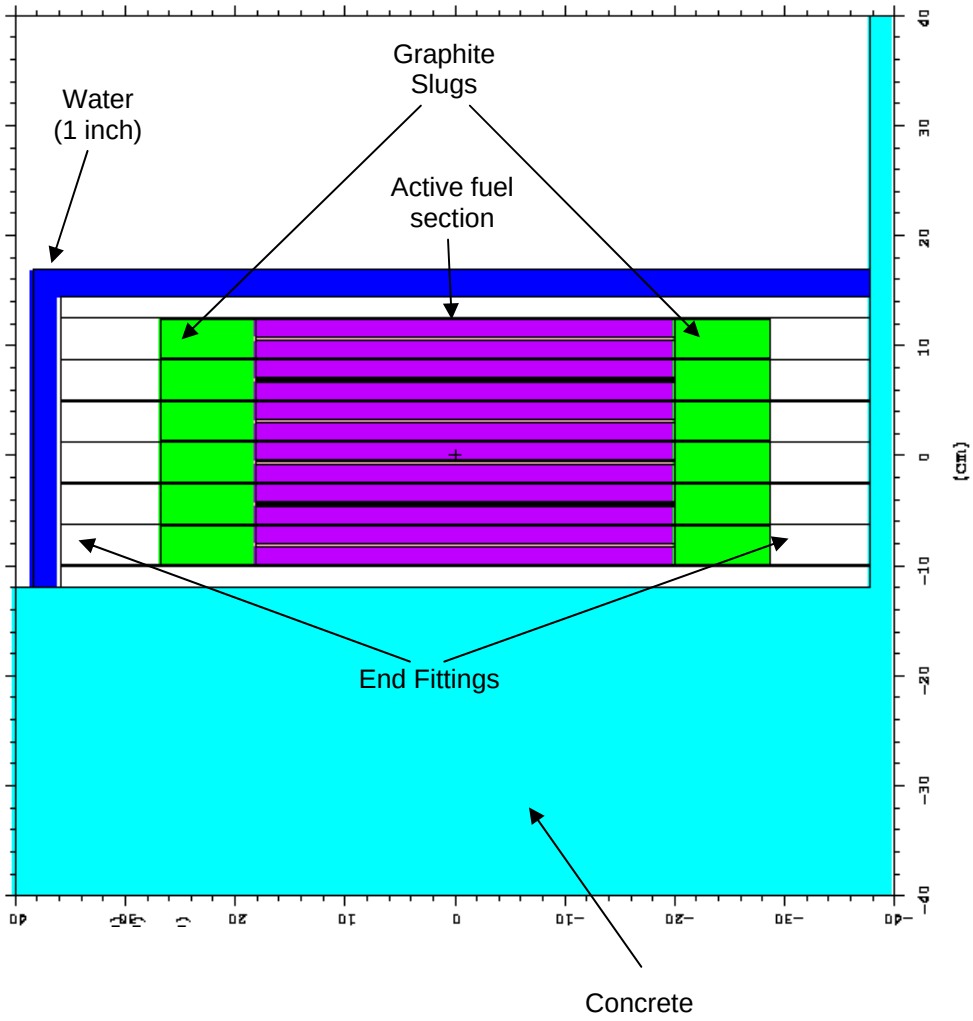


Figure 2.5-4
Square Pitched MCNP Model, Transverse Cut through Fuel Stacked in Concrete Corner with Water Reflection

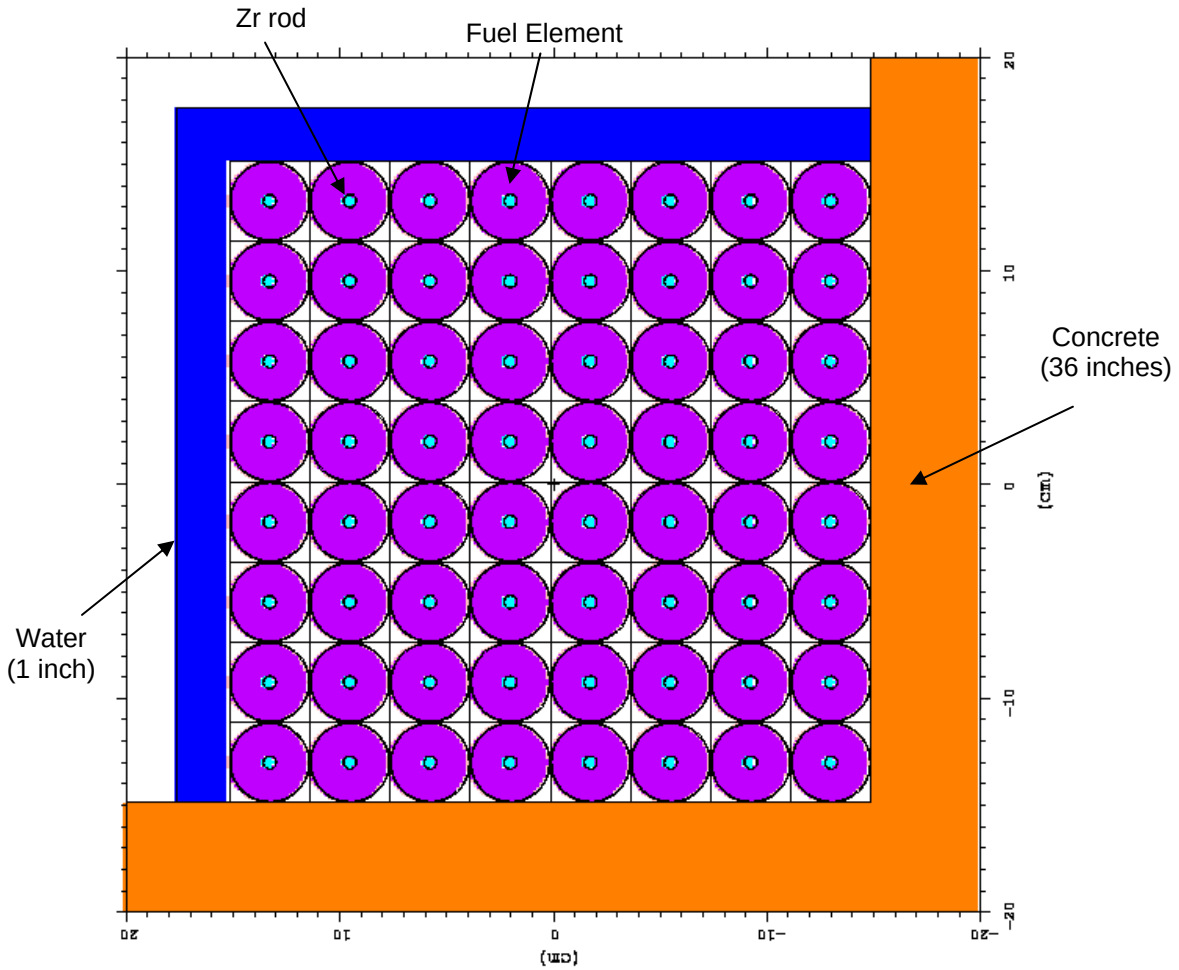


Figure 2.6-1
Radial View of MCNP Model for Two TRIGA Fuel Baskets Under Dry Moderation Conditions in the FPA with 1 Inch Water Reflection

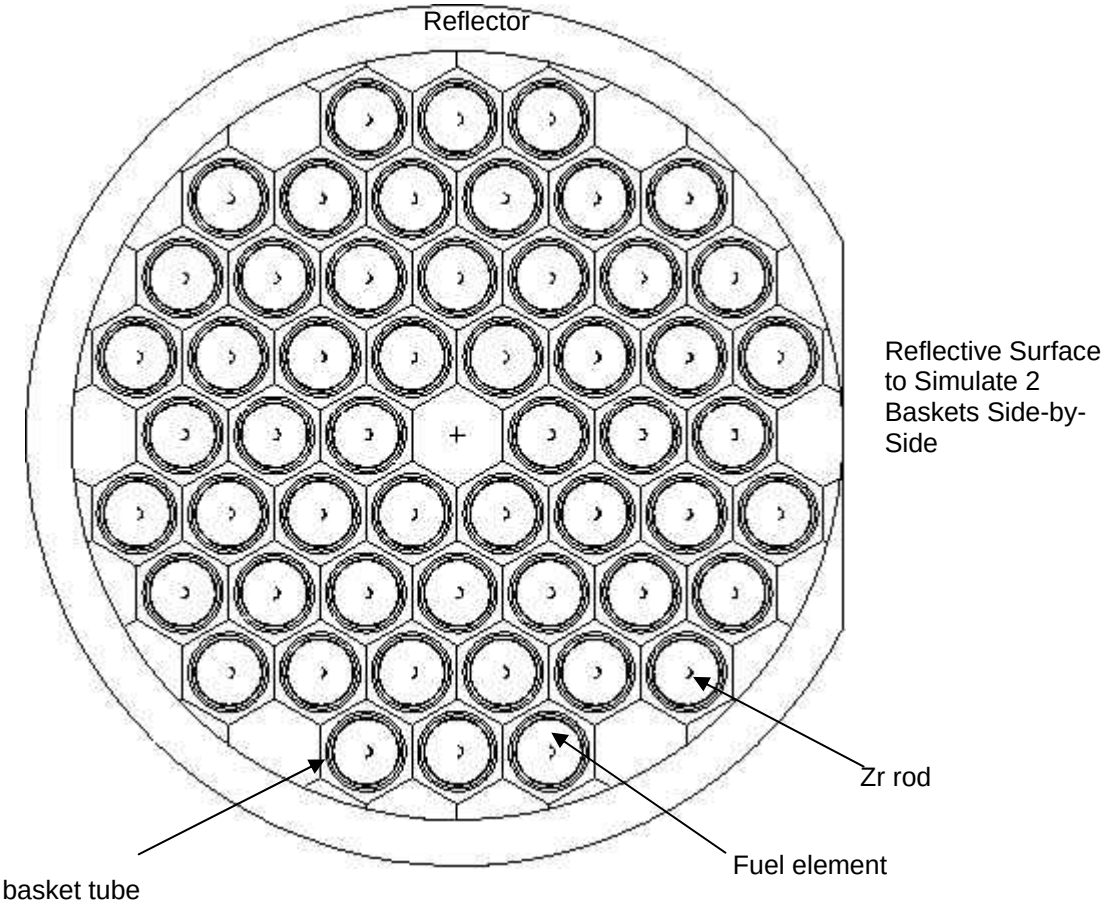


Figure 2.6-2
Axial View of MCNP Model for Two TRIGA Fuel Baskets under Dry Moderation Conditions in the FPA with 1 Inch Water Reflection

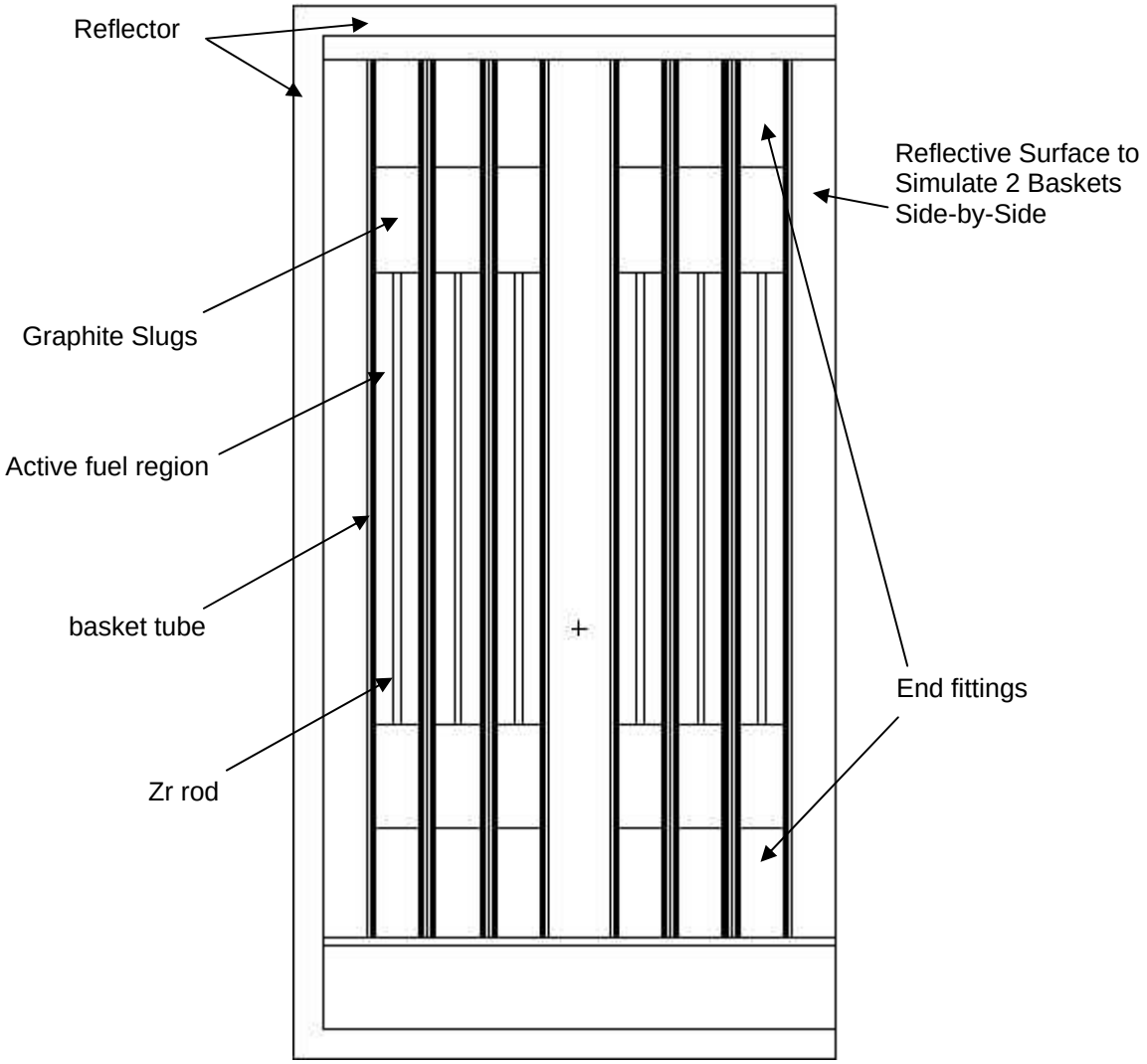


Figure 2.7-1
3D Cutaway View of MCNP Model of TRIGA Fuel Basket

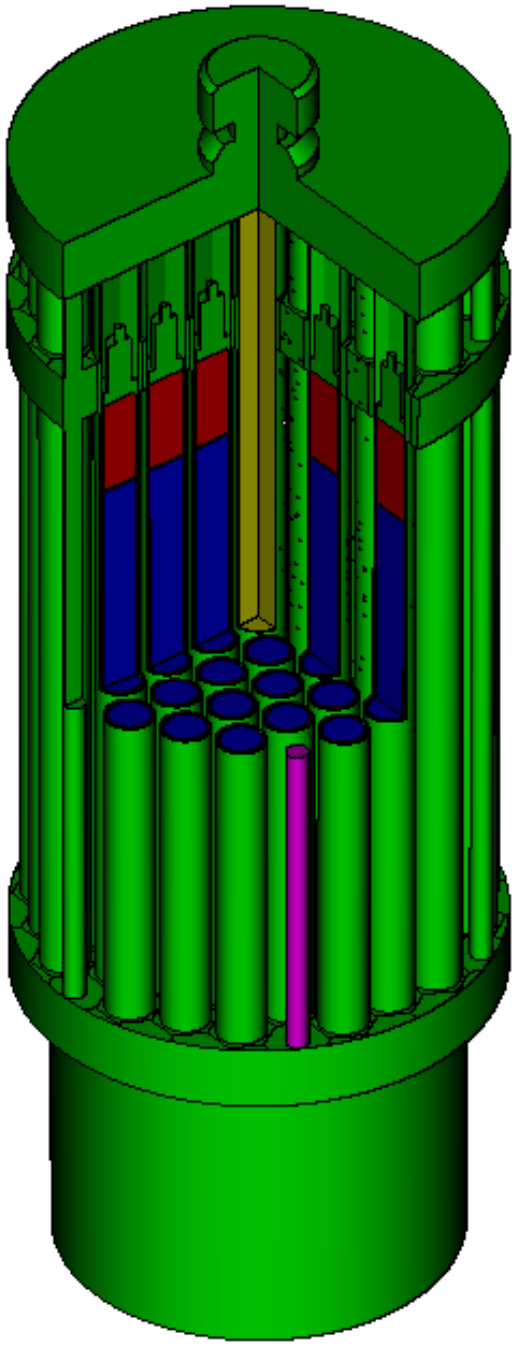


Figure 2.7-2
X-Y Plane View of TRIGA Fuel Basket

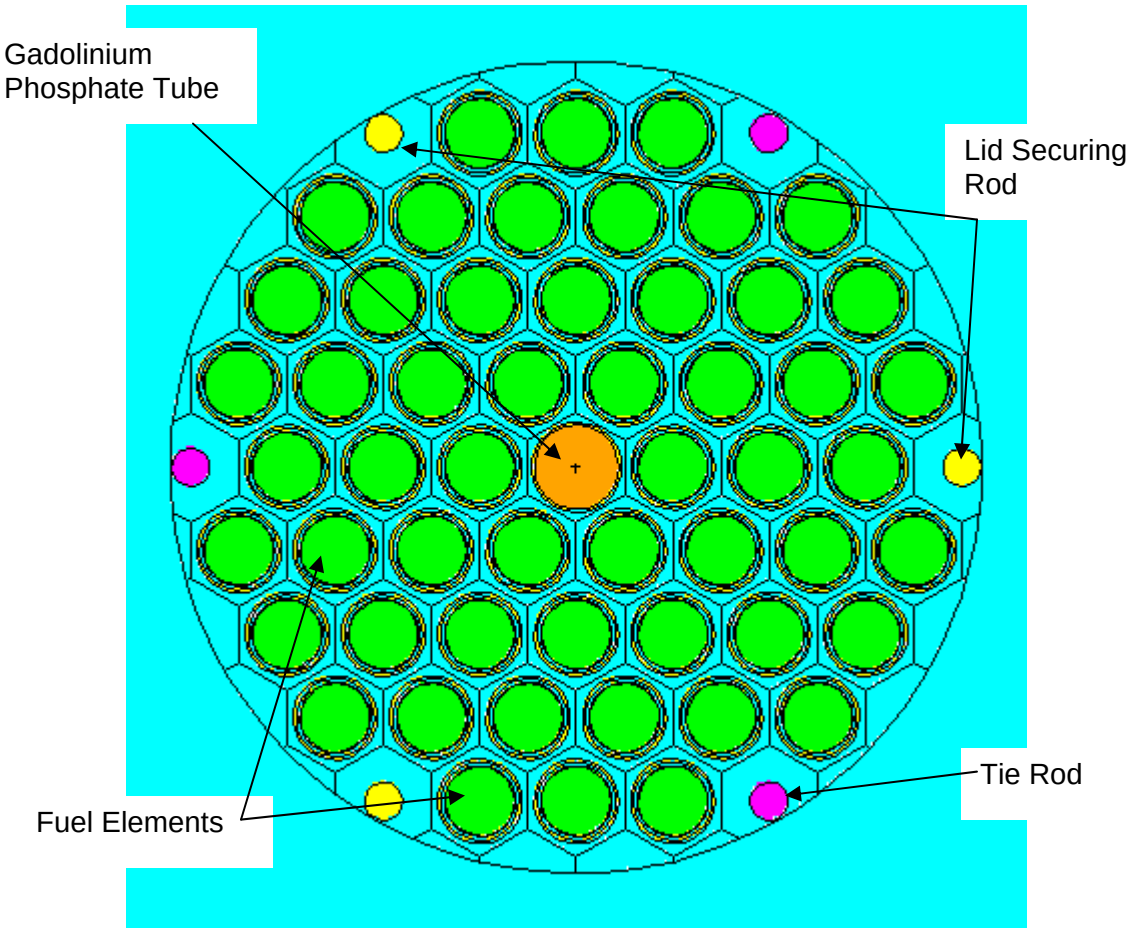


Figure 3.1-1
MCNP Model of Side-by-Side Peach Bottom Arrays

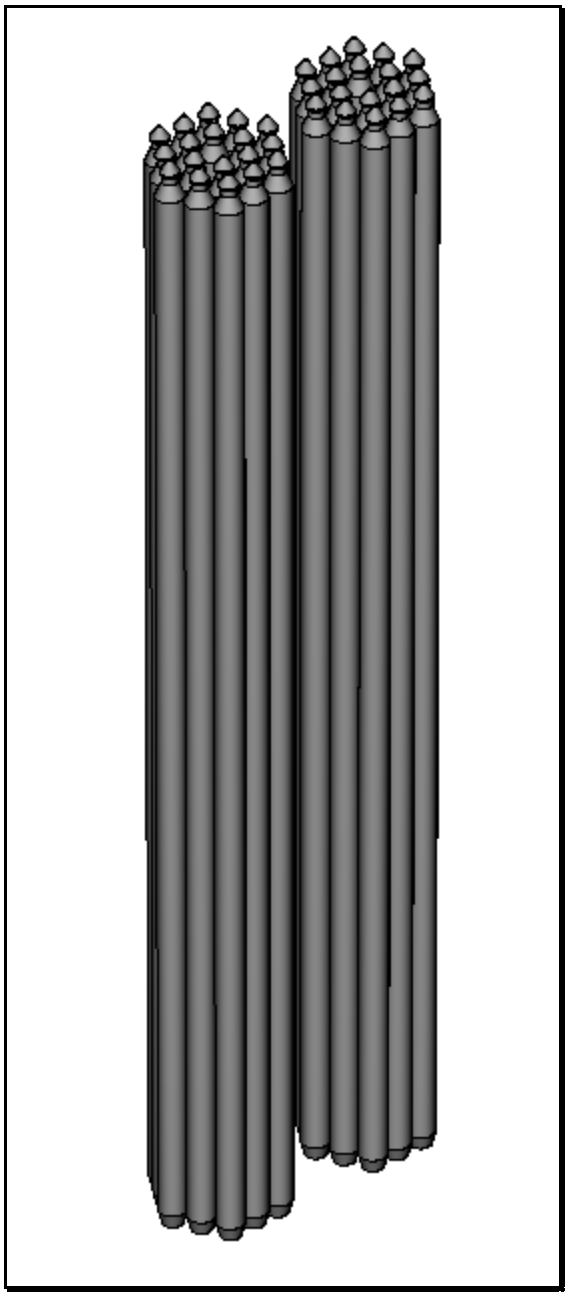


Figure 3.1-2
X-Y Plane View of Side-by-Side Peach Bottom Arrays
(18 Elements Each)

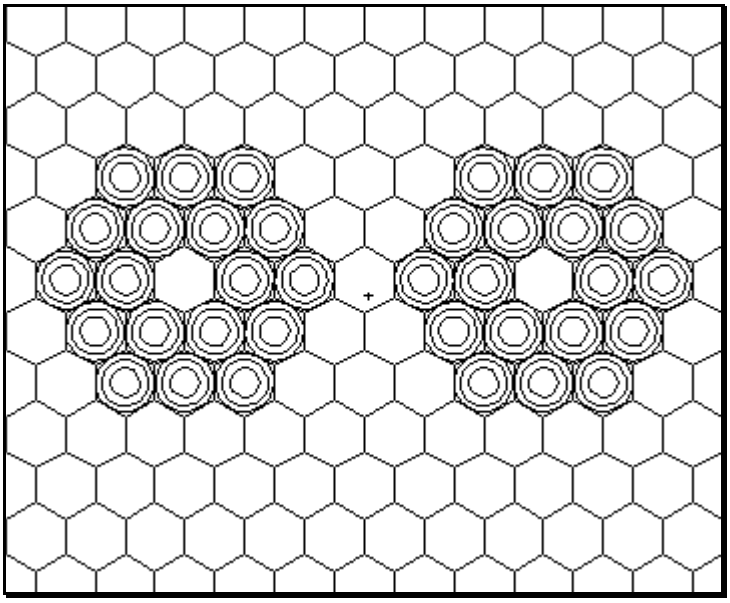


Figure 3.2-1
Peach Bottom Fuel Element

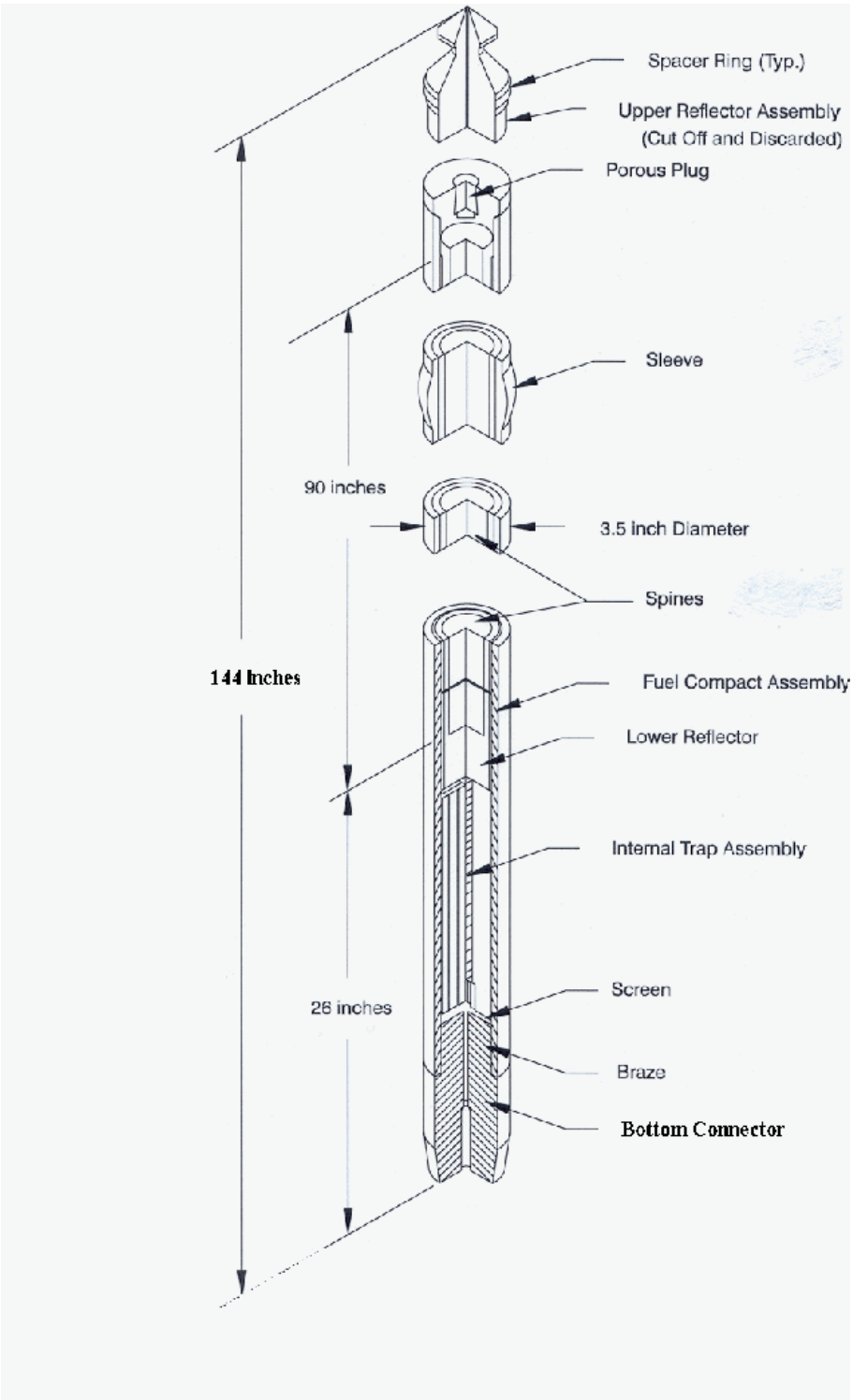


Figure 3.2-2
MCNP Geometry for Homogenized Peach Bottom Fuel Surrounded by Graphite Reflector

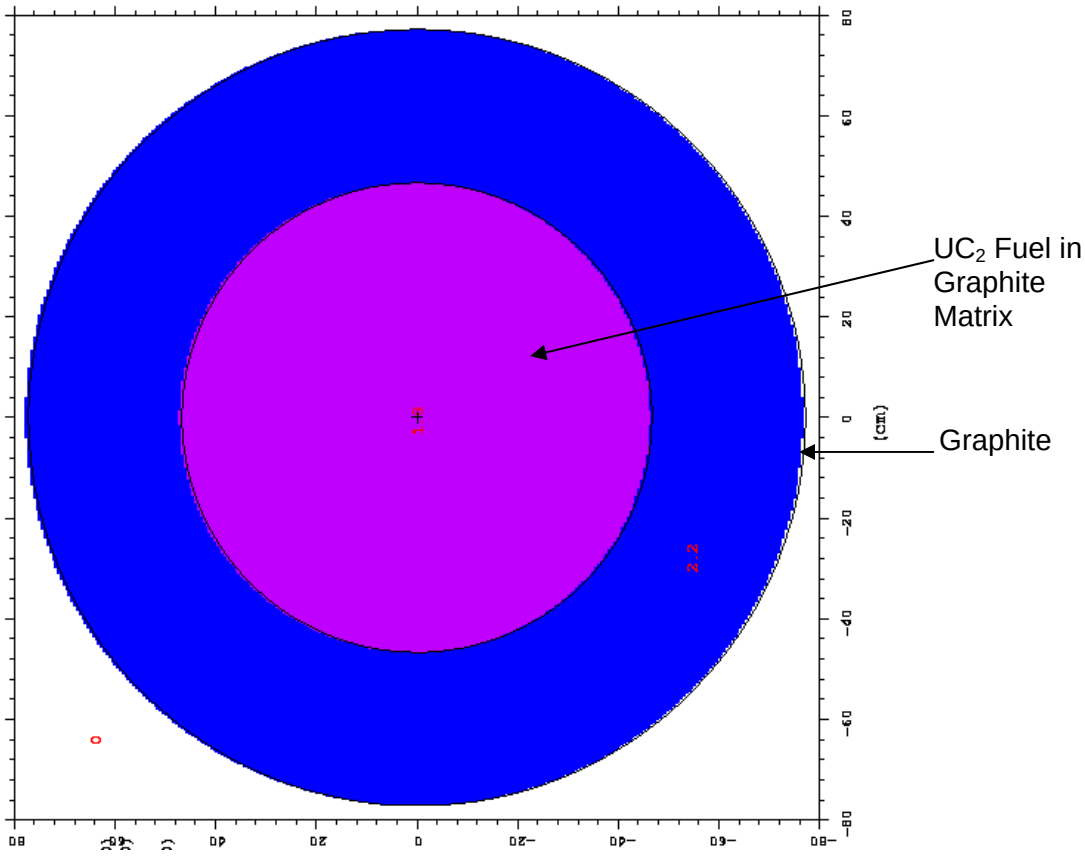


Figure 3.2-3
Peach Bottom k_{eff} (k_{eff} + 2σ shown) as a Function of Equivalent Number of Elements (Homogenized Fuel/Graphite in a Sphere)

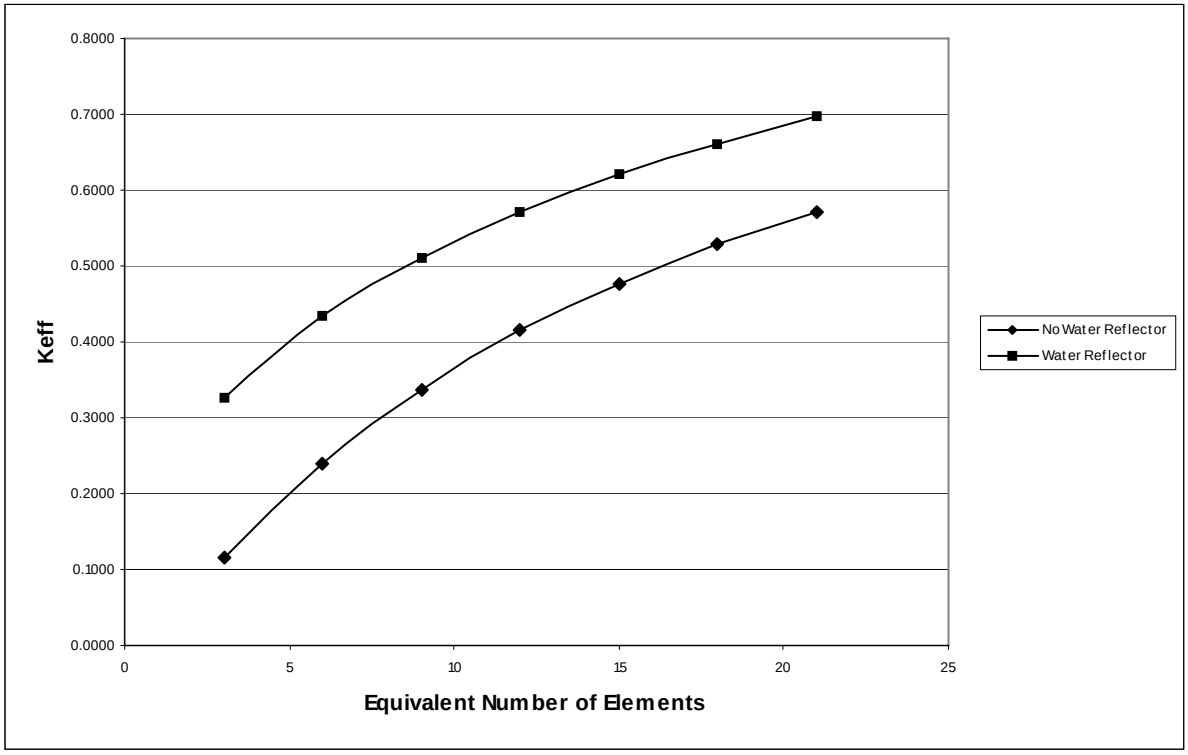


Figure 3.3-1
Cross Section of MCNP Model with 37 Peach Bottom Fuel Elements

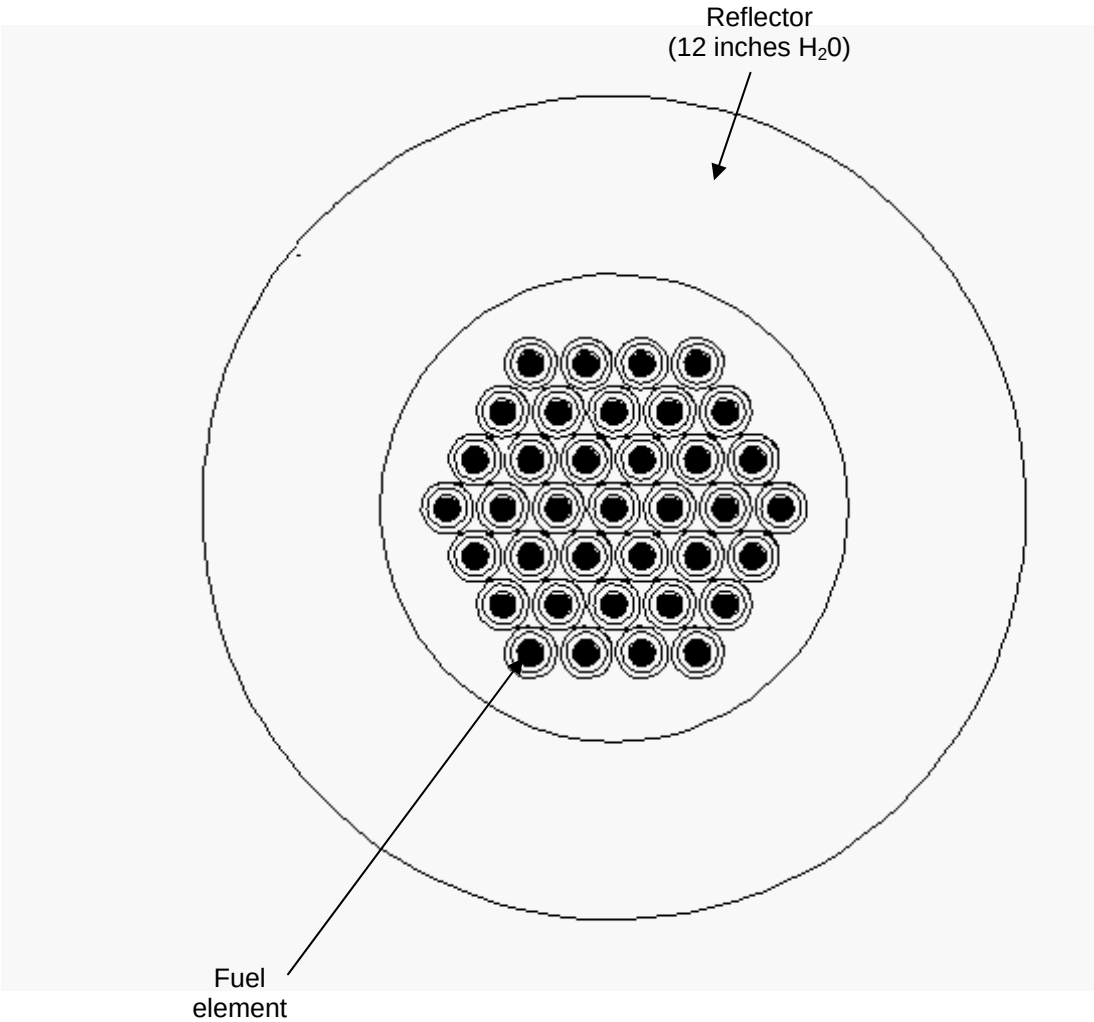


Figure 3.3-2
Cross Section View of MCNP Model with 19 Peach Bottom Fuel Elements in a Hexagonal Array within a Water Reflector

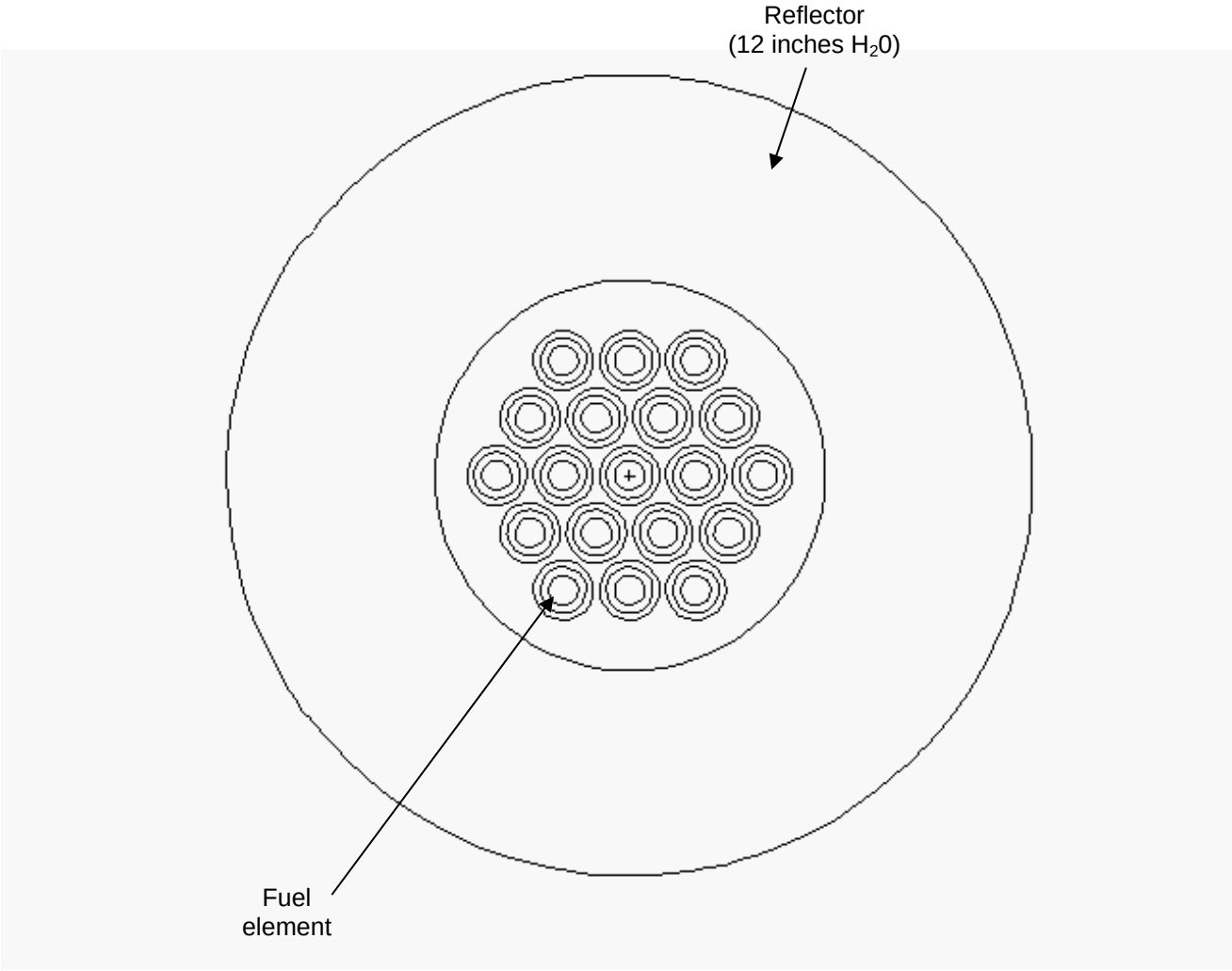


Figure 3.3-3
Cross Section View of MCNP Model with 18 Peach Bottom Fuel Elements in a Hexagonal Array within a Water Reflector

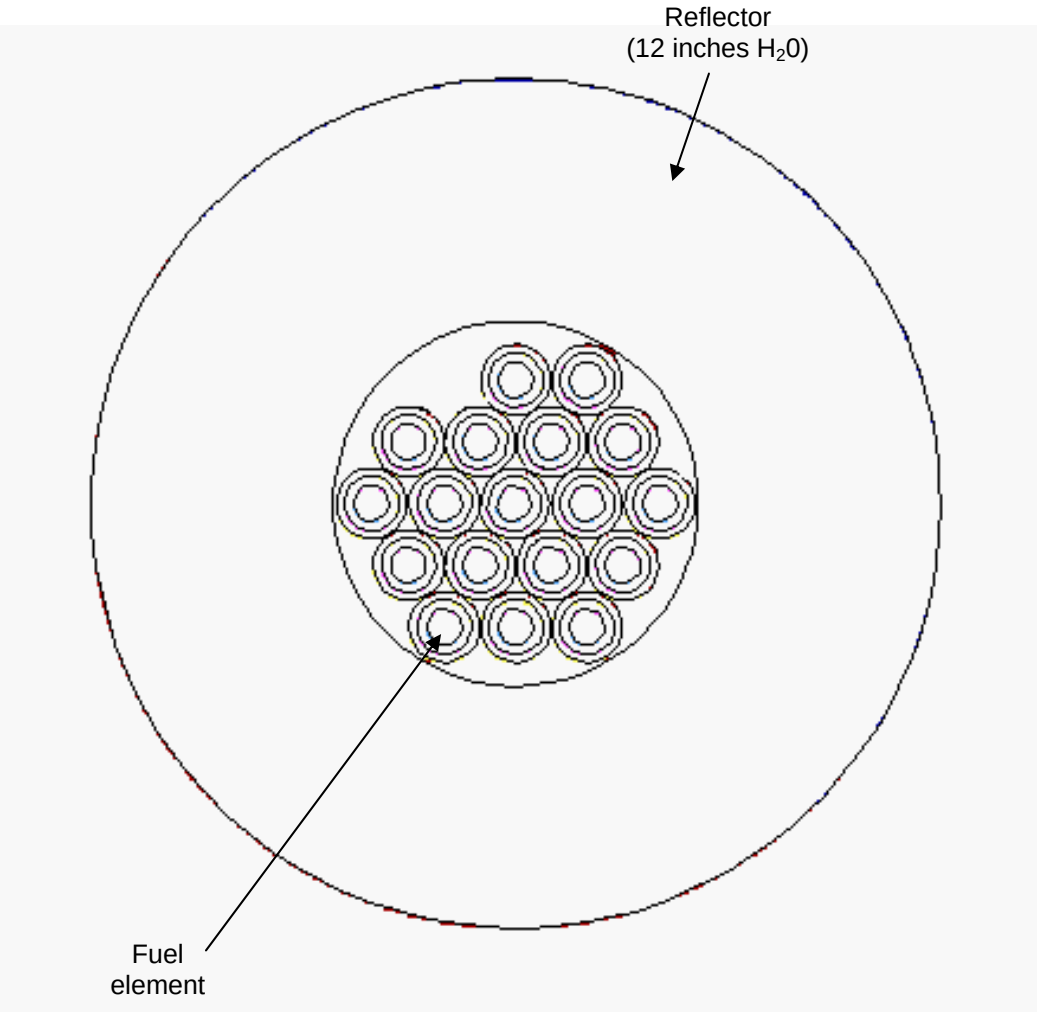


Figure 3.3-4
Cross Section View of MCNP Model with 6 Peach Bottom Fuel Elements in a Hexagonal Array within a Water Reflector

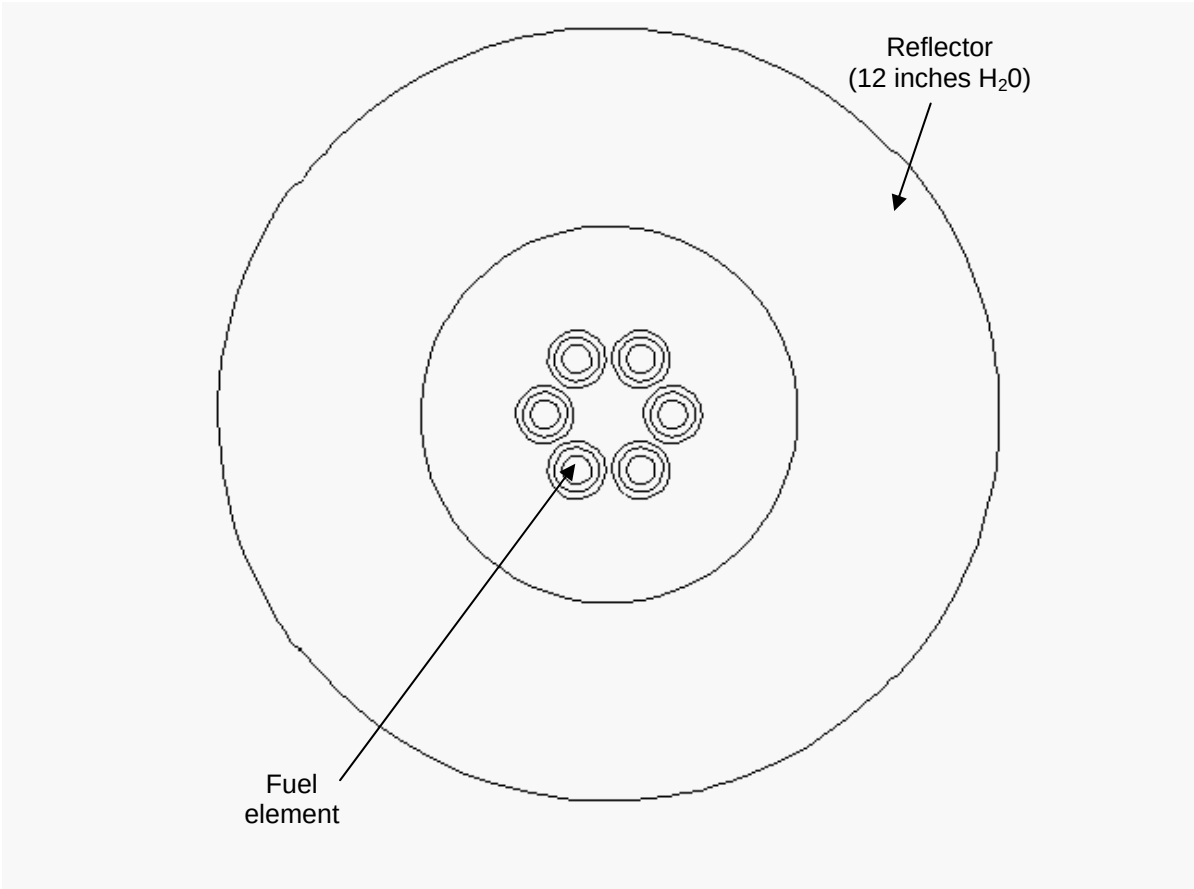
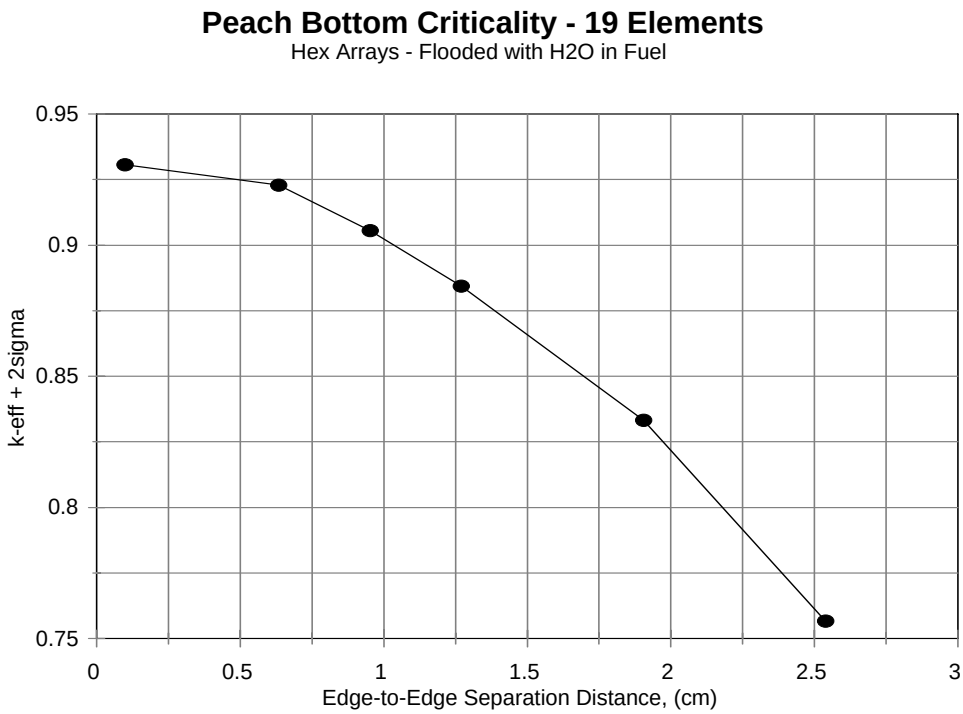


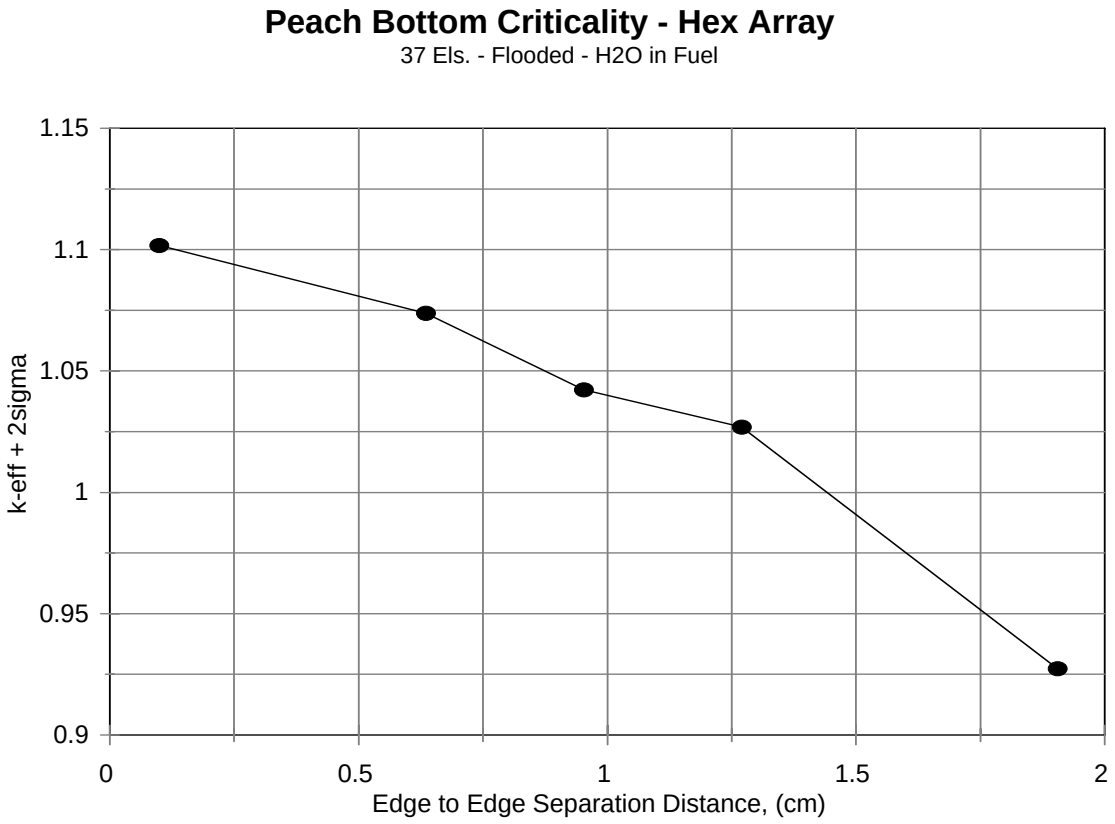
Figure 3.3-5
Calculated Criticality as a Function of Separation Distance for 19 Peach Bottom Fuel Elements in a Hexagonal Array



Note:

The fuel, the graphite reflectors, and the spine are assumed saturated with water. The array is fully flooded and water reflected.

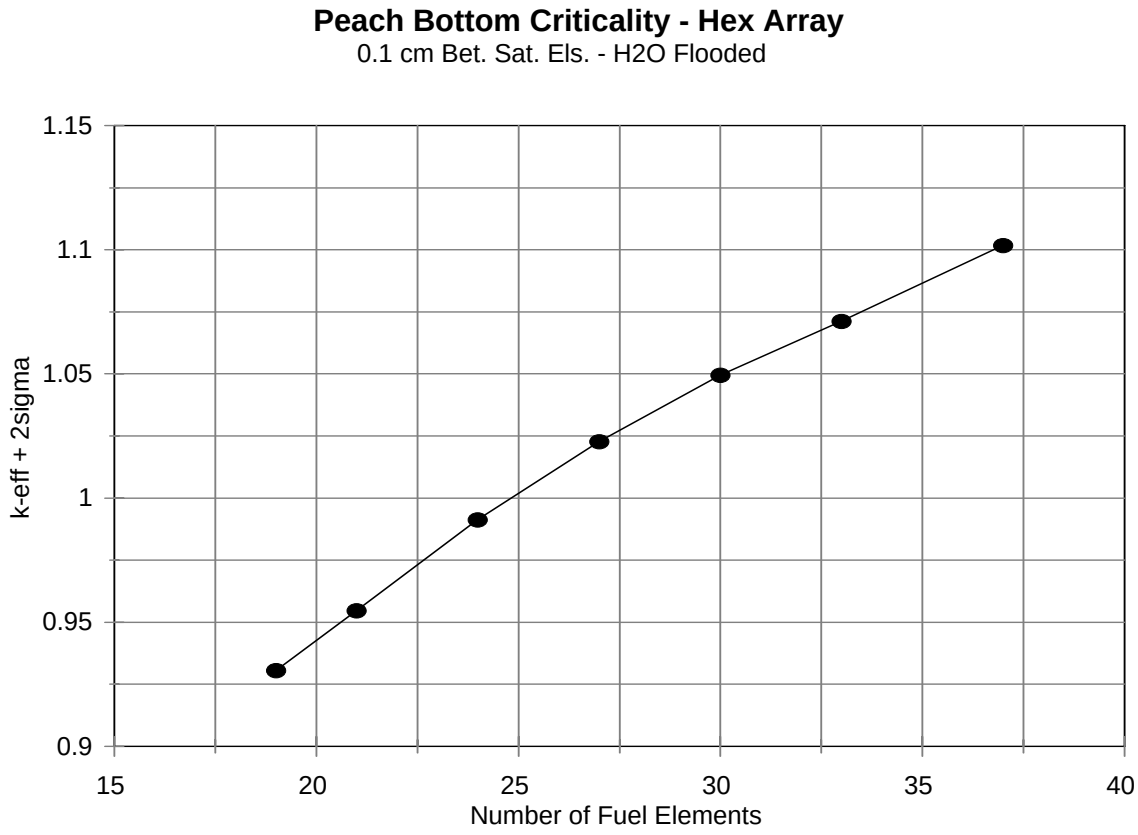
Figure 3.3-6
Calculated Criticality as a Function of Separation Distance for 37 Peach Bottom Fuel Elements in a Hexagonal Array



Note:

The fuel, the graphite reflectors, and the spine are assumed saturated with water. The array is fully flooded and water reflected.

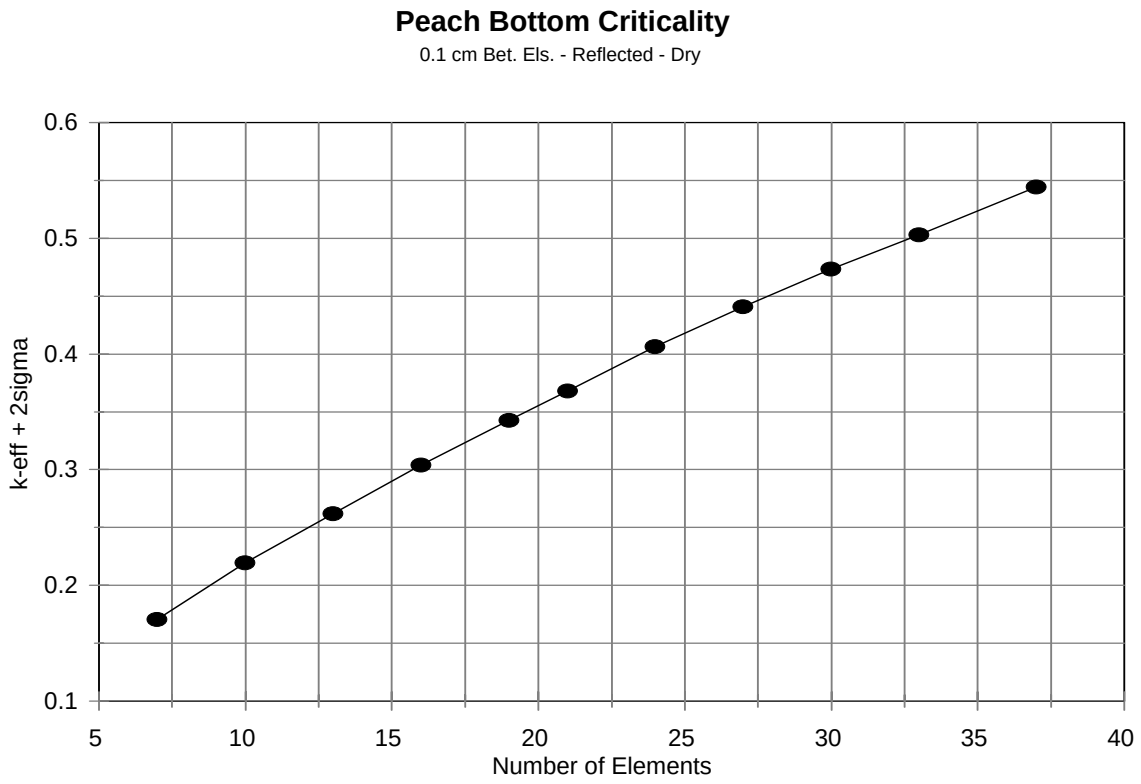
Figure 3.3-7
Calculated Criticality as a Function of Number of Fuel Elements for Peach Bottom Fuel Elements in a Hexagonal Array – Saturated and Flooded



Note:

The fuel, the graphite reflectors, and the spine are assumed saturated with water. The array is fully flooded and water reflected. The elements are separated by 0.1 cm edge to edge.

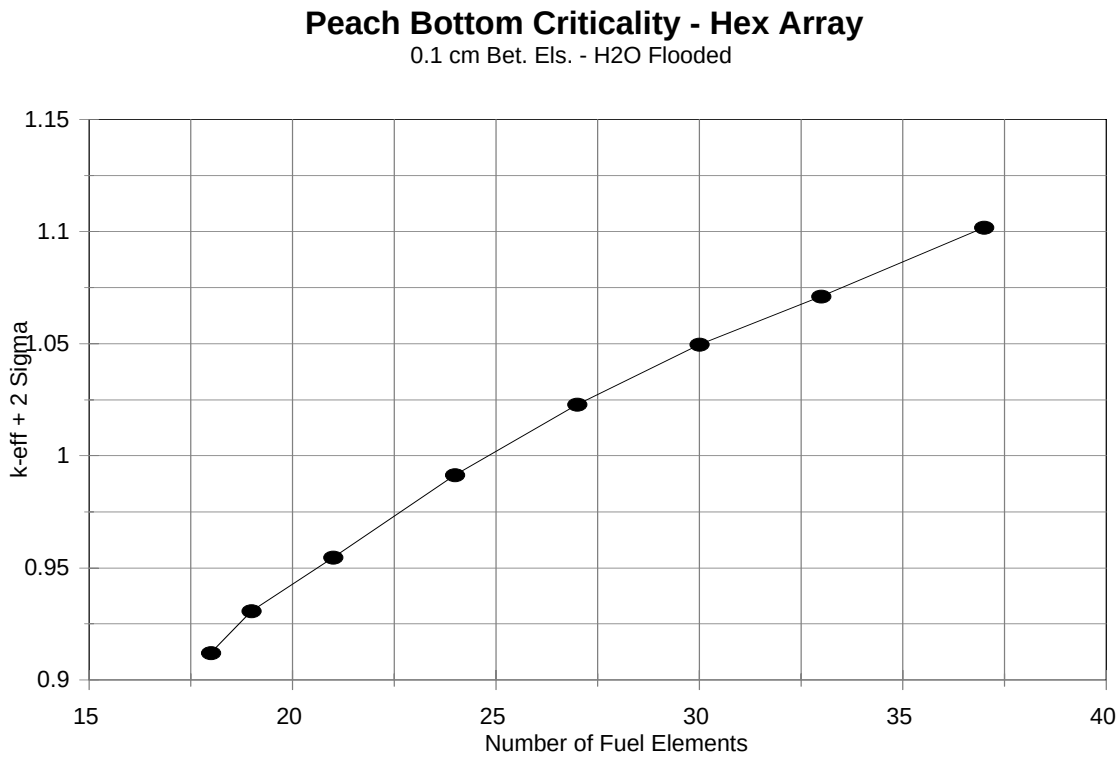
Figure 3.3-8
Calculated Criticality as a Function of Number of Fuel Elements for Peach Bottom Fuel Elements in a Hexagonal Array - Dry



Note:

The fuel, the graphite reflectors, and the spine are assumed dry. The array is water reflected with no water between the fuel elements. The elements are separated by 0.1 cm edge to edge.

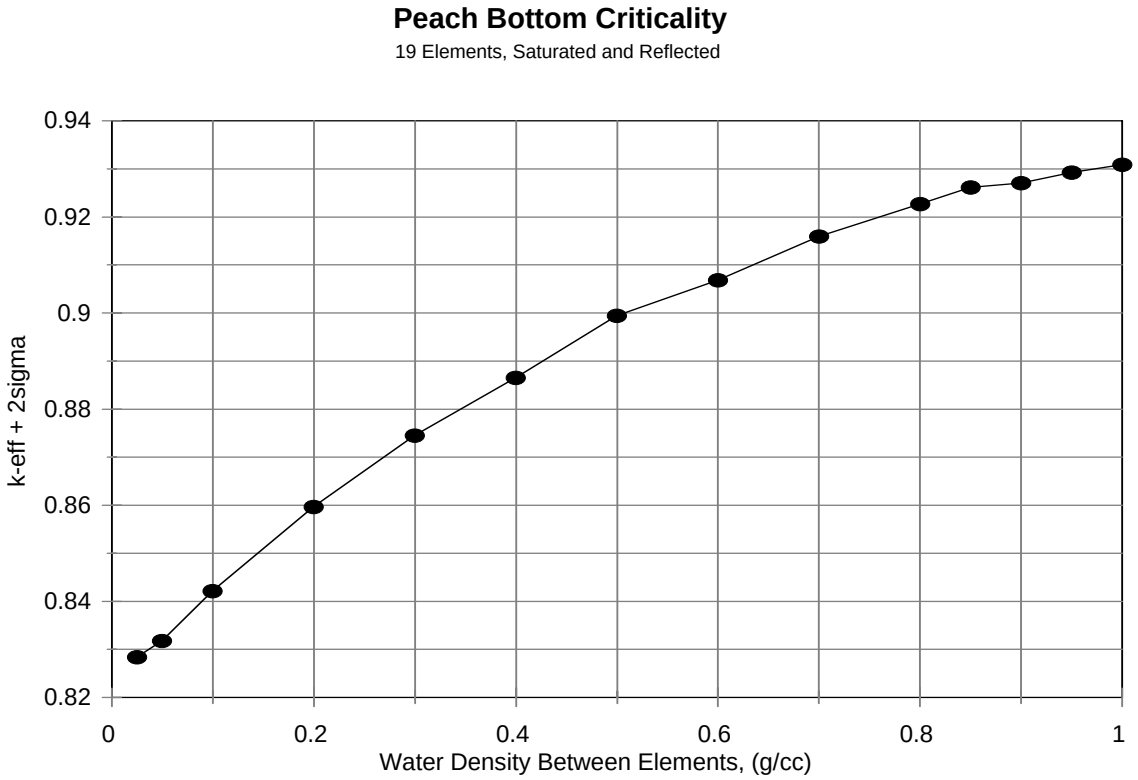
Figure 3.3-9
Calculated Criticality as a Function of Number of Fuel Elements for Peach Bottom Fuel Elements in a Hexagonal Array - Flooded



Note:

The fuel, the graphite reflectors, and the spine are saturated. The array is water reflected with full density water between the fuel elements. The elements are separated by 0.1 cm edge to edge The model for the 18 fuel elements was similar to that for the 19 elements except that an exterior element was removed.

Figure 3.3-10
Peach Bottom Criticality as a Function of Moderation



Note:

The model contains 19 fuel elements in a hexagonal array separated by 0.1 cm edge to edge. The array is fully reflected and the fuel elements are saturated.

Figure 3.4-1
Elevation View of Peach Bottom Fuel Elements in Storage Canister

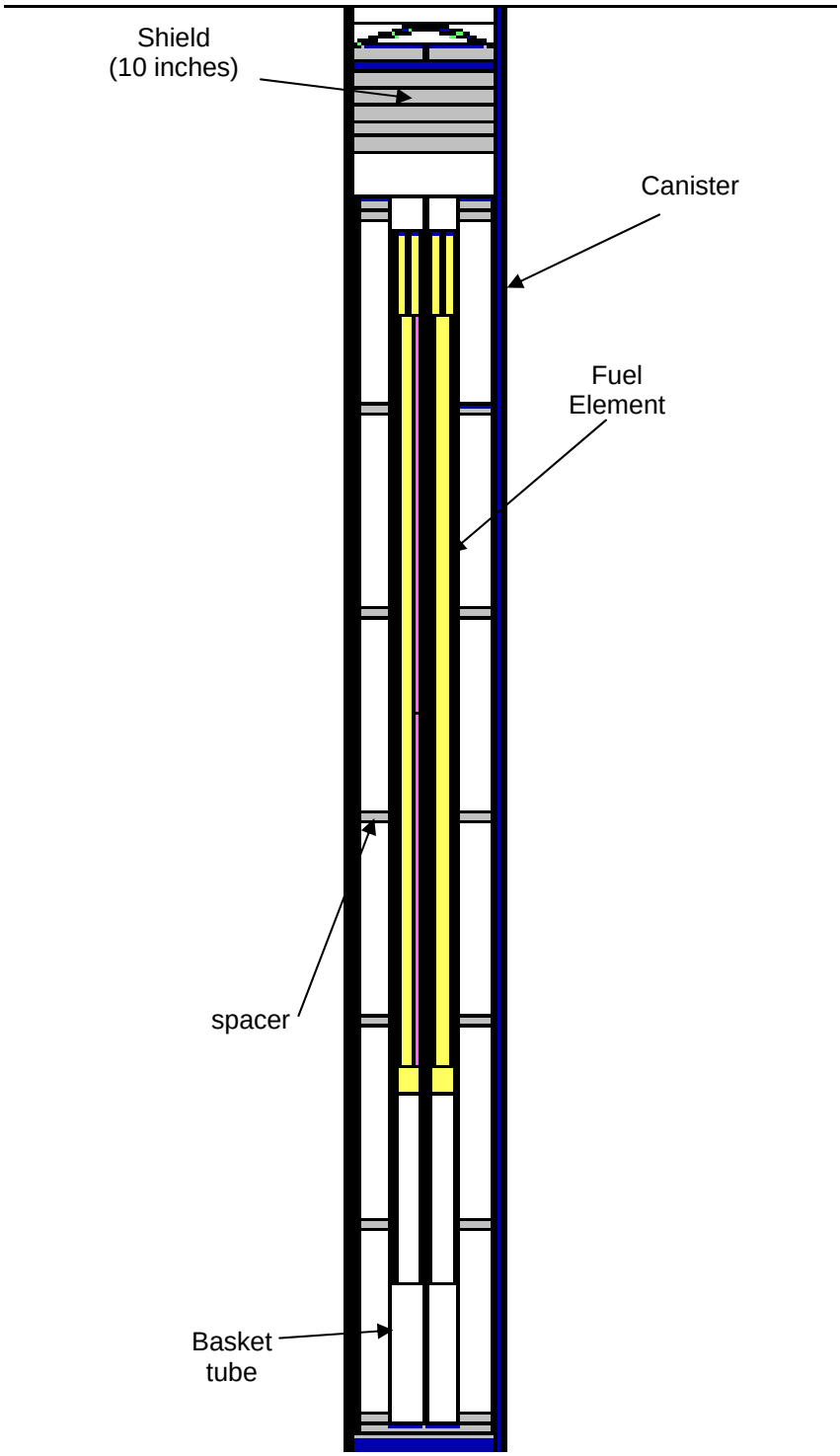


Figure 3.4-2
Elevation View of Peach Bottom Fuel Elements in Storage Canister and the Canister Storage Tube

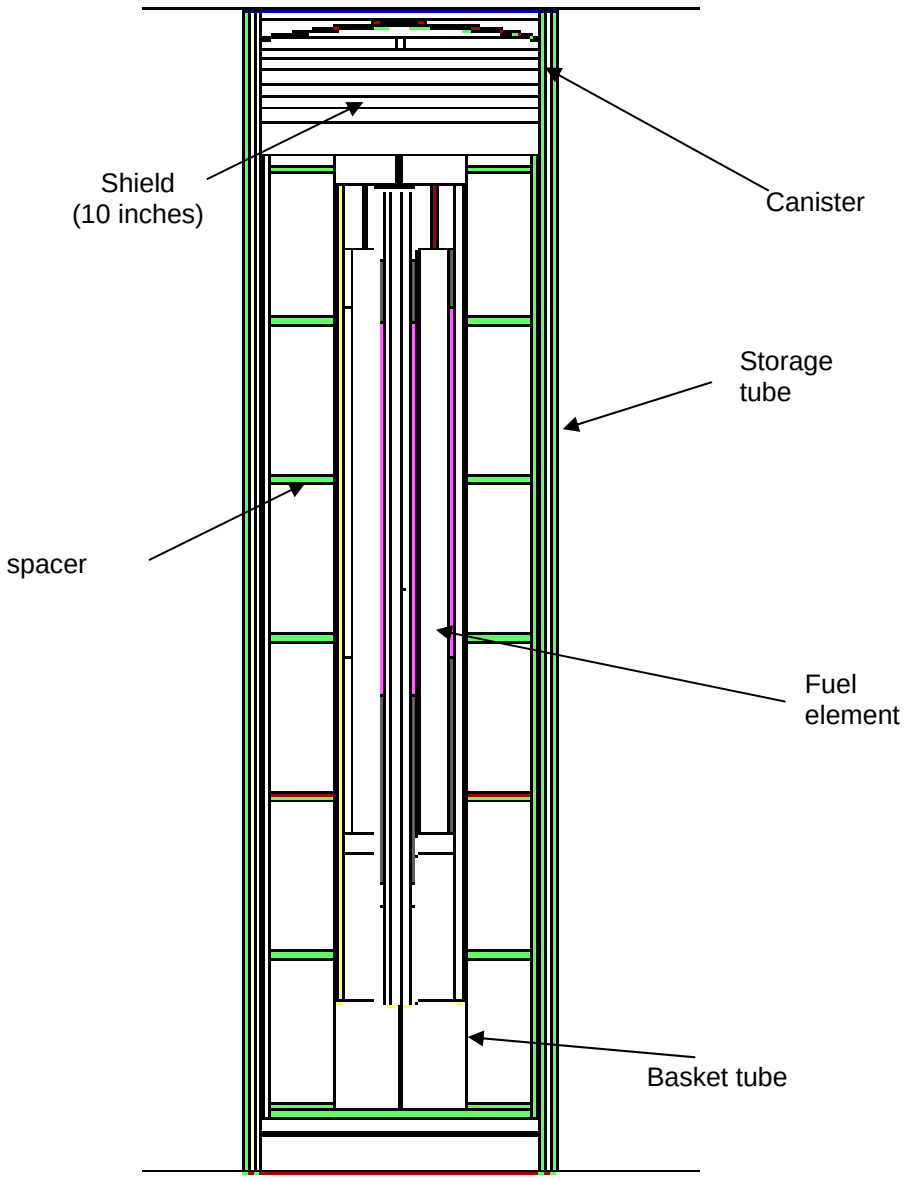


Figure 3.4-3
Cross Section through MCNP Model of the 18 Inch Diameter Basket Loaded with 10 Peach Bottom Fuel Elements

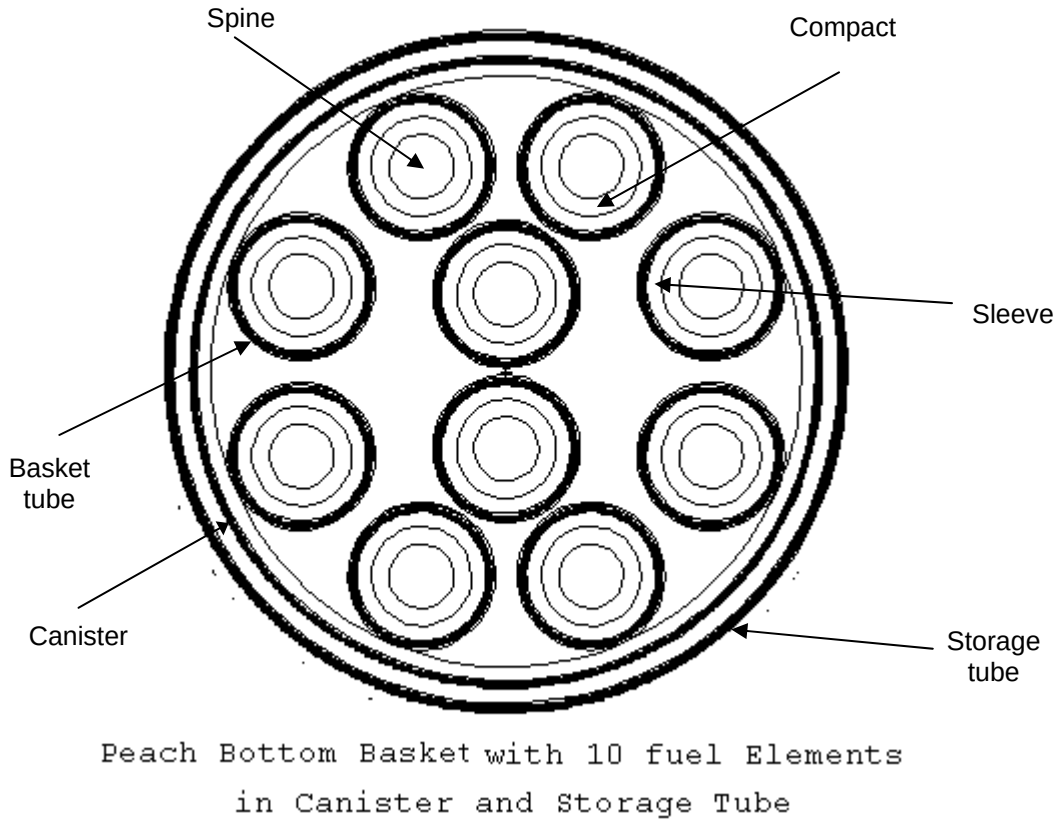


Figure 3.5-1
TRIGA Fuel Element (Figure 3-1, DOE Contract)

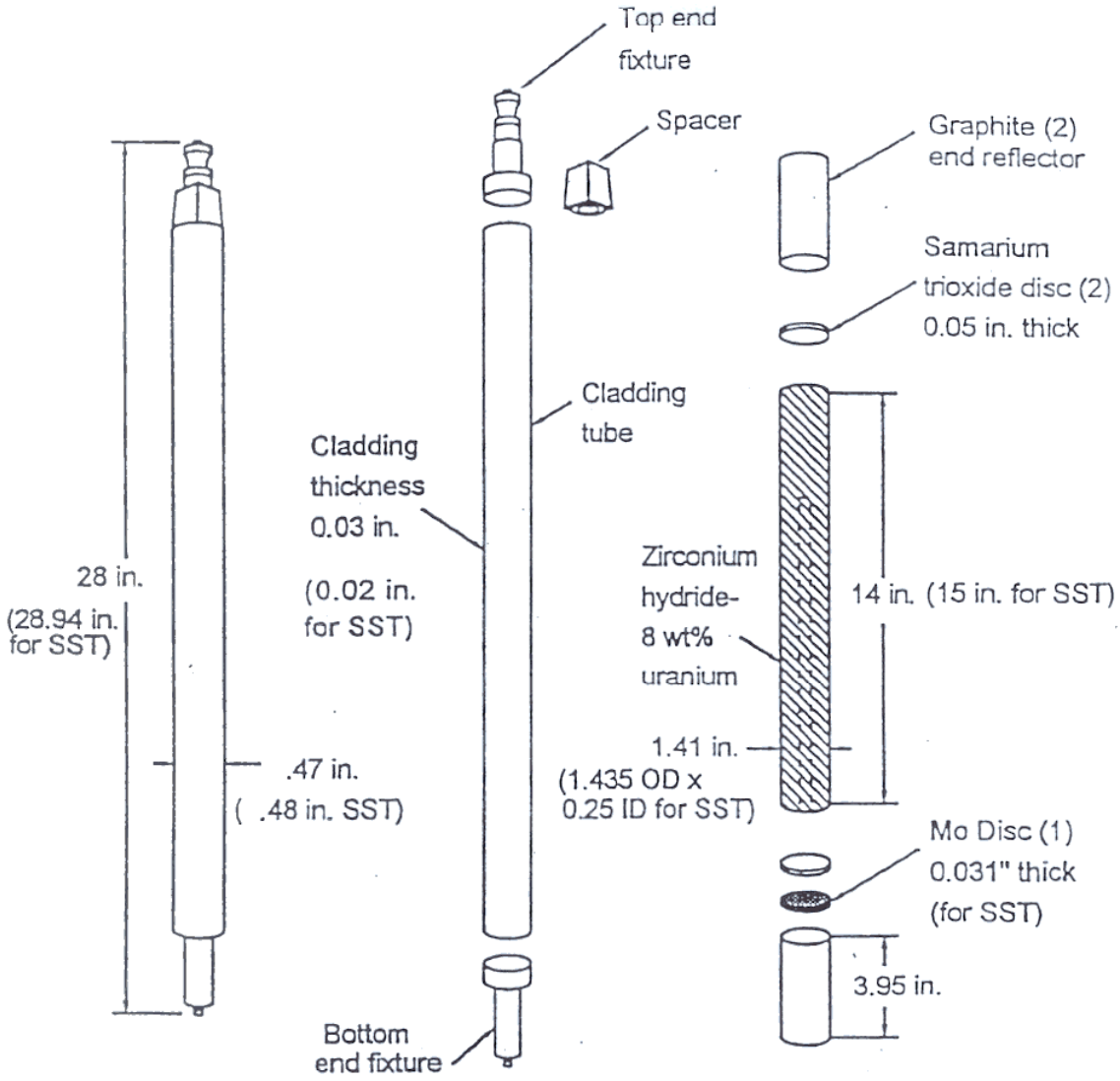


Figure 3.5-2
TRIGA Spent Fuel Basket

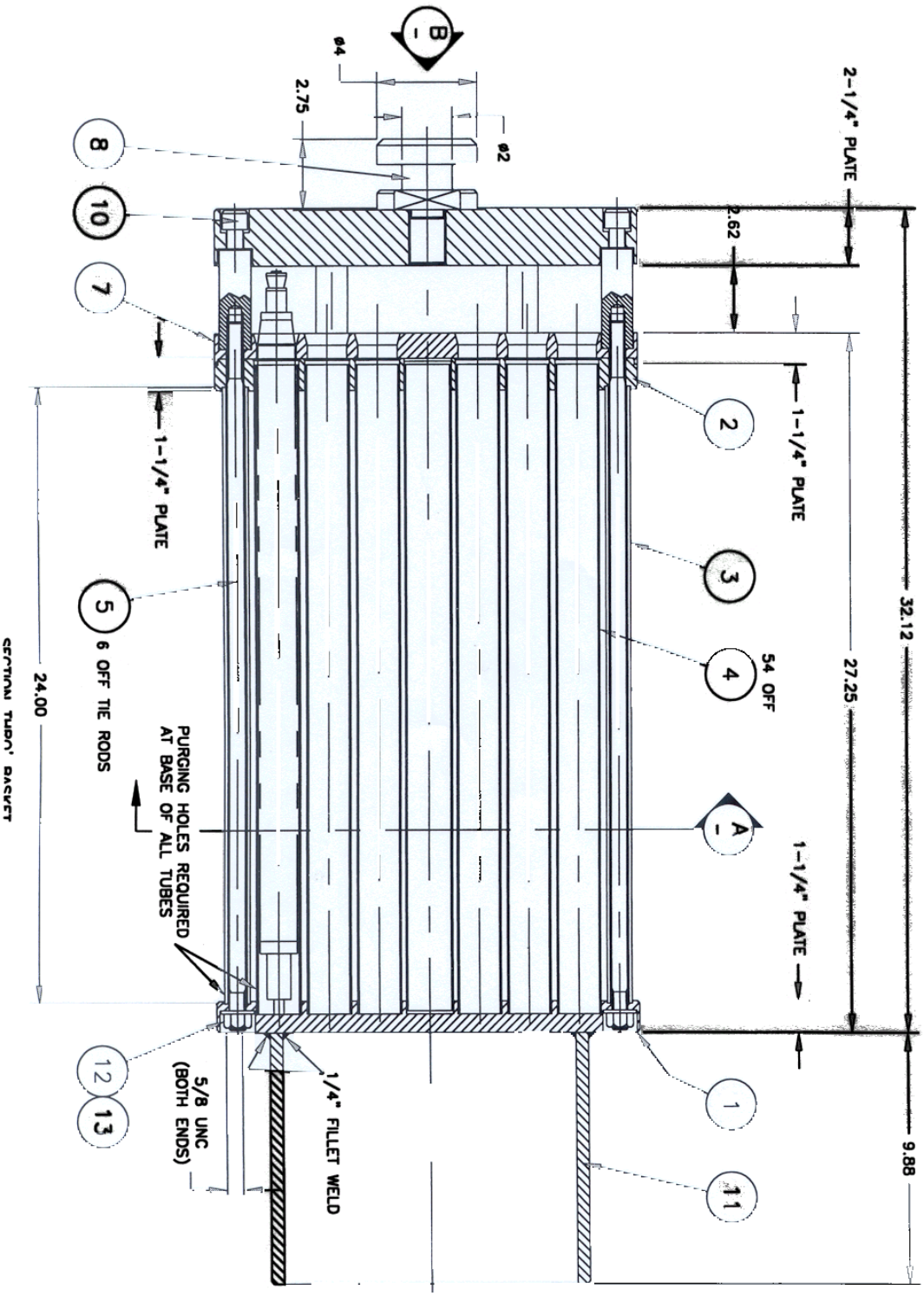


Figure 3.5-3
Two TRIGA Baskets in 18 Inch Canister

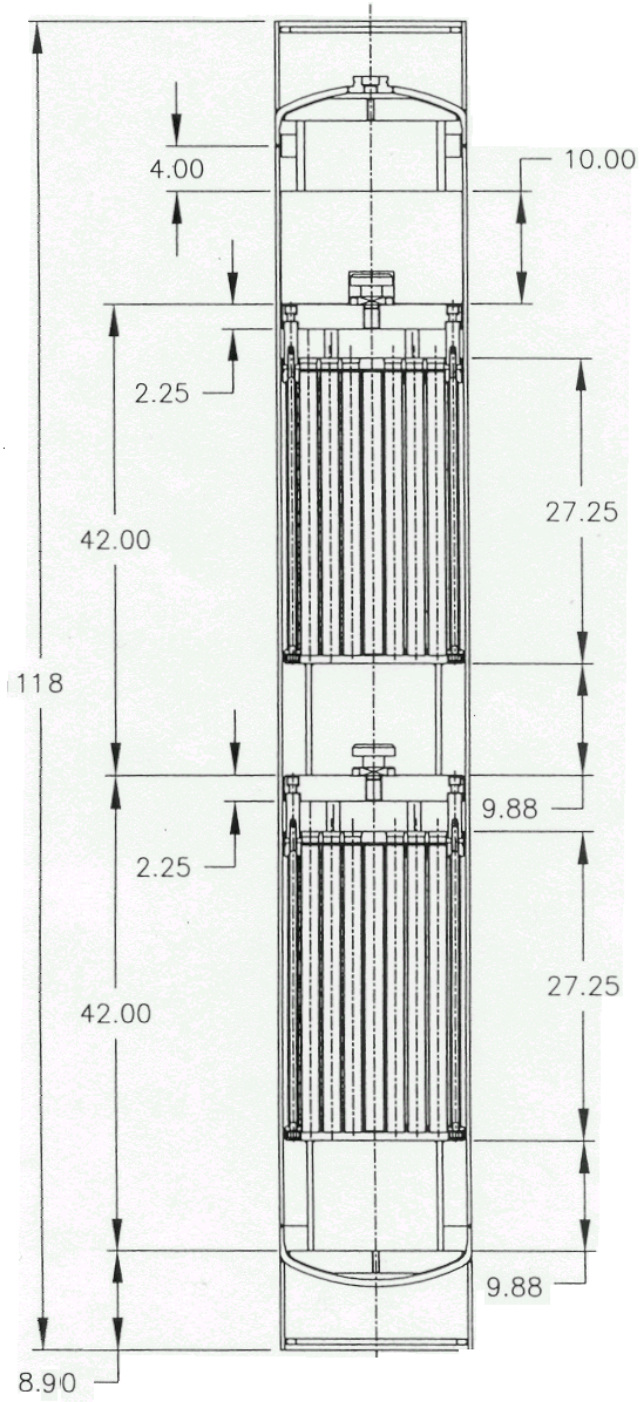


Figure 3.5-4
Cross Section from the MCNP Model for the Fueled Regions in the TRIGA Basket in the Storage Canister and Storage Tube

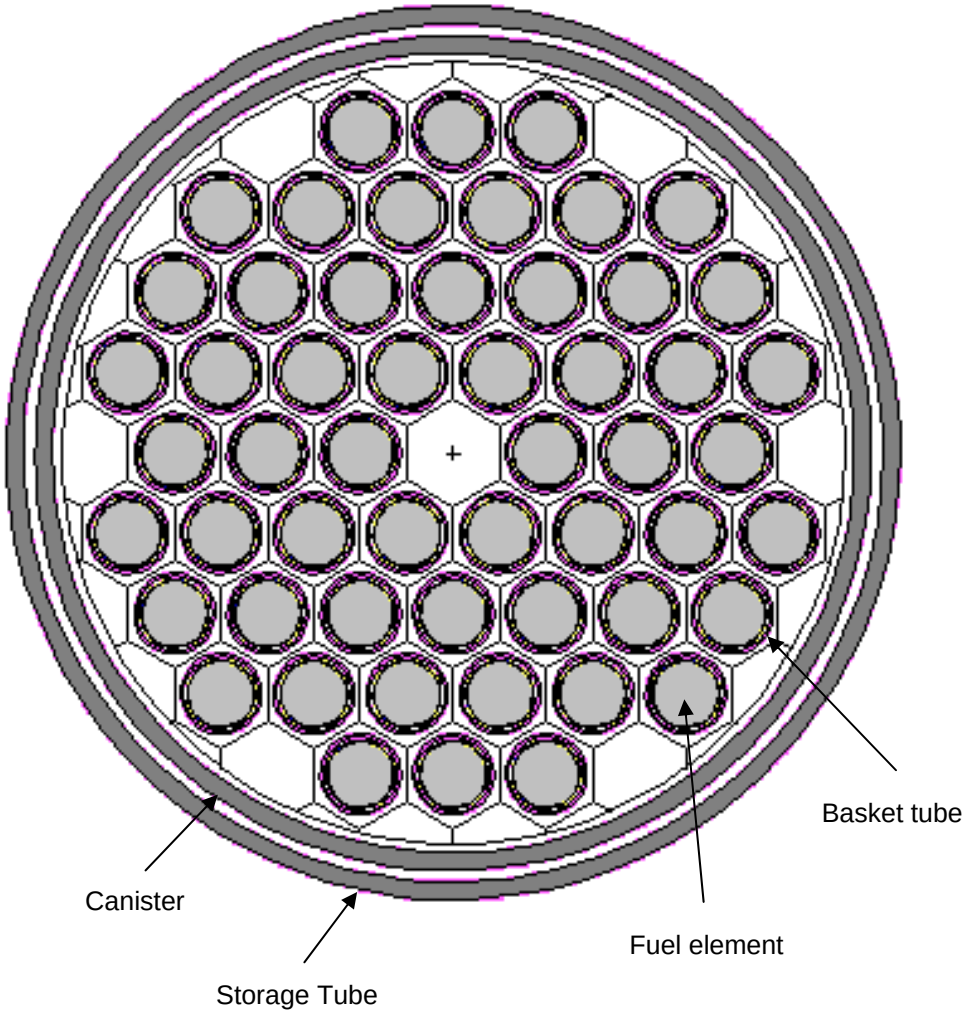


Figure 3.5-5
TRIGA and Peach Bottom ISF Fuel Canisters Showing Canister Dimensions and Spacing Used in Analysis

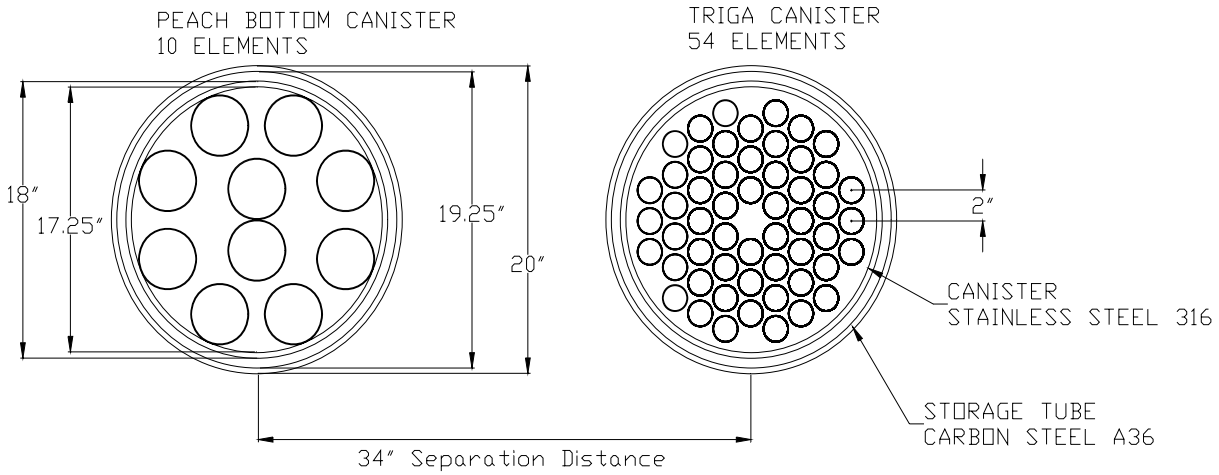


Figure 4.1-1
Water Moderated Reflector Rod Cell, Reflected on All 6 Surfaces

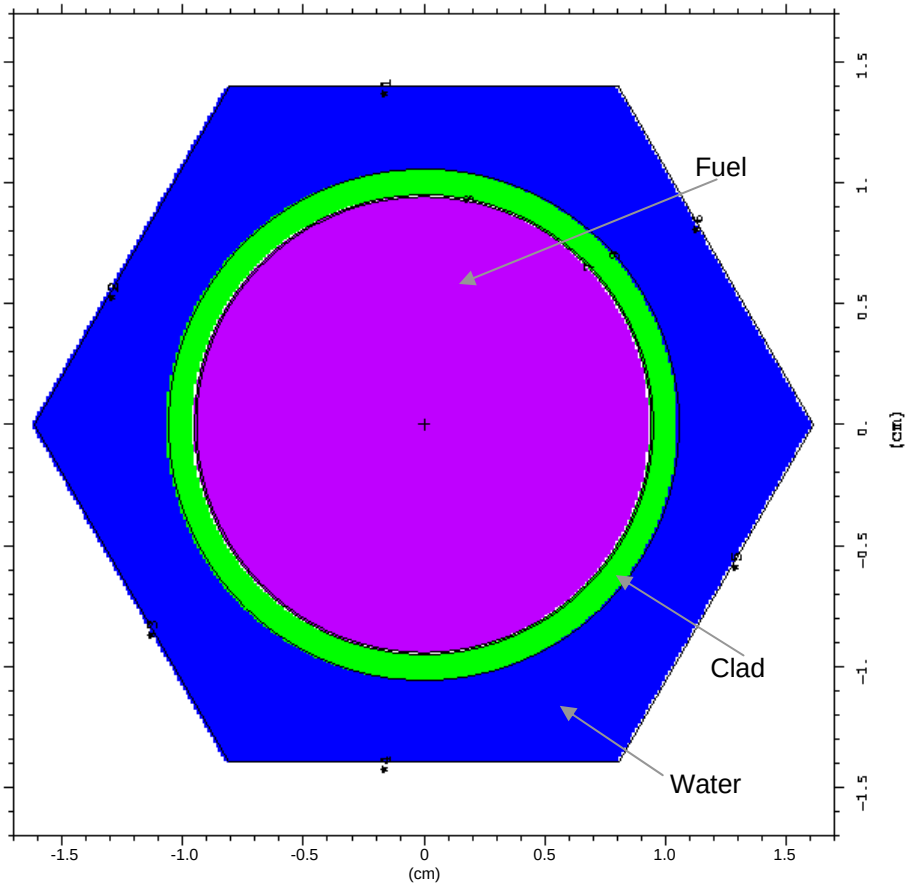


Figure 4.1-2
Axial Cut of Water Moderated Reflector Rod, Model Reflected on All Sides
(note scale difference)

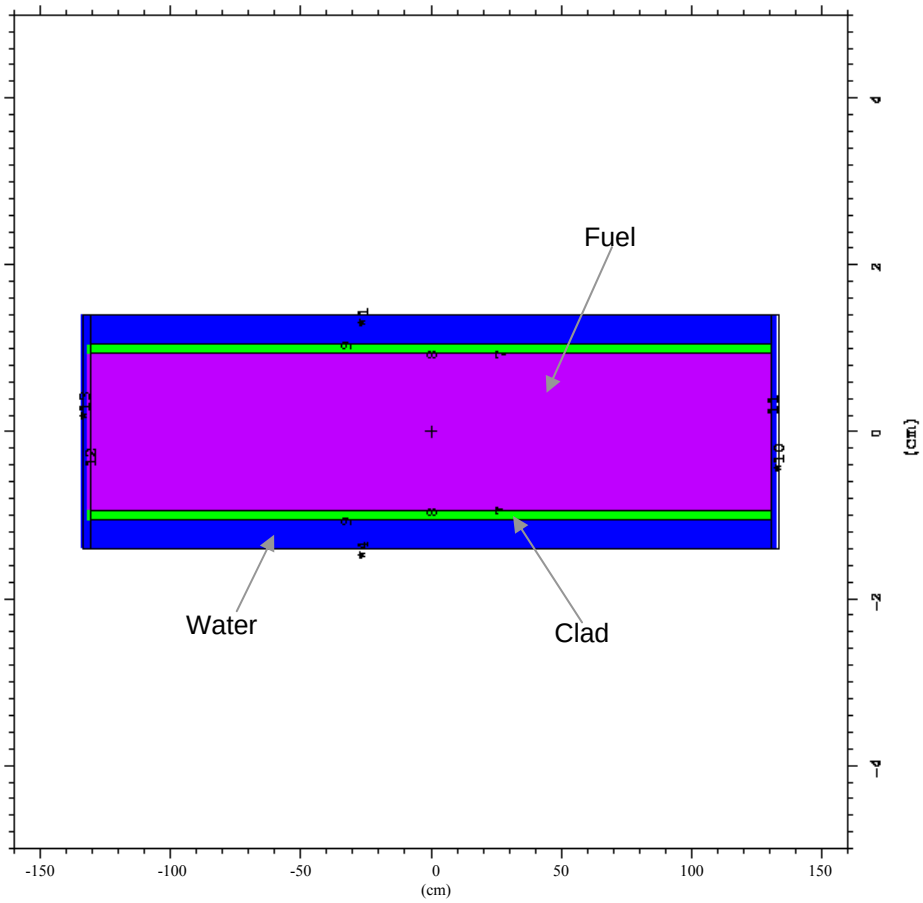
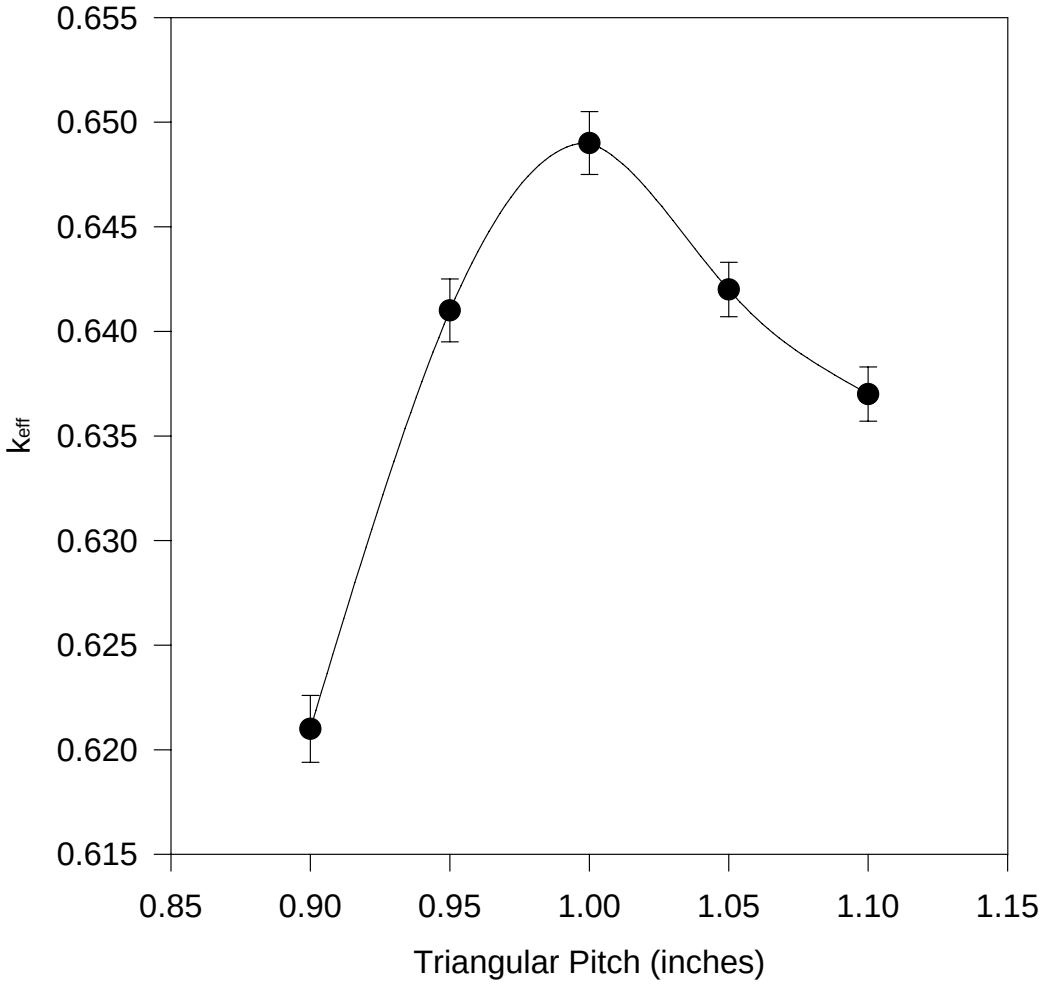


Figure 4.1-3
k_{eff} as a Function of Triangular Pitch
for Infinite Array of Water Moderated Shippingport Reflector Rods



Note:

Nominal +1σ uncertainty shown.

Figure 5.2-1
MCNP4B2
K_{eff} vs. U-235 Enrichment for Critical Experiments

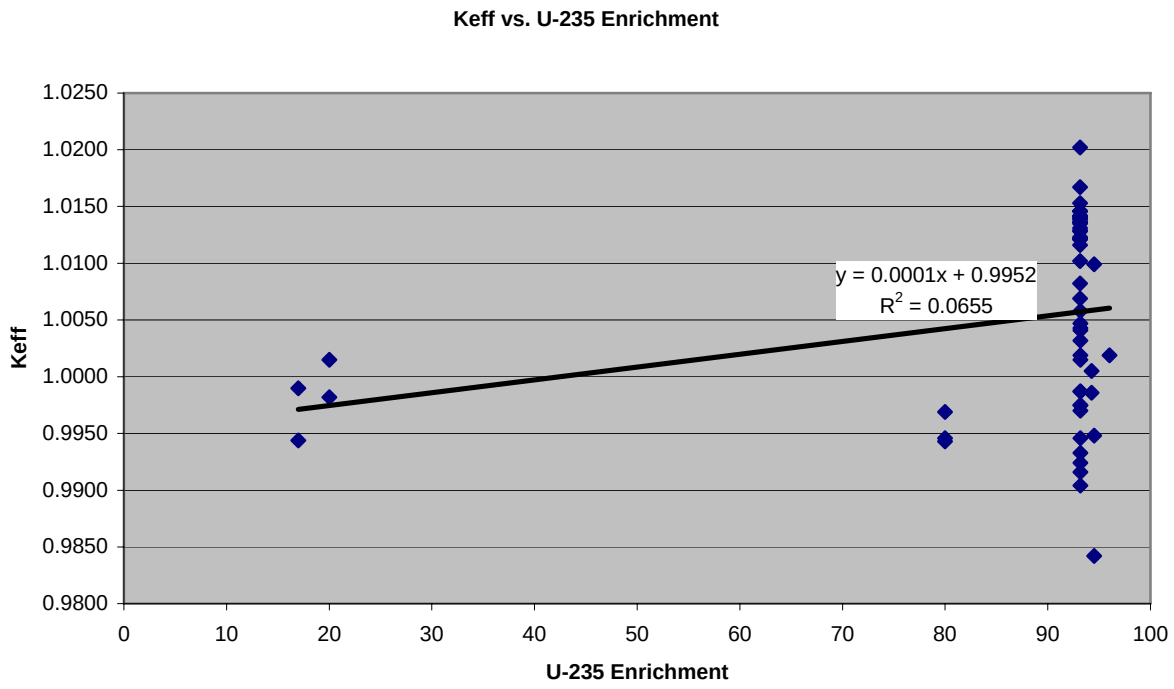


Figure 5.2-2
MCNP4B2
K_{eff} vs. EALF for Critical Experiments

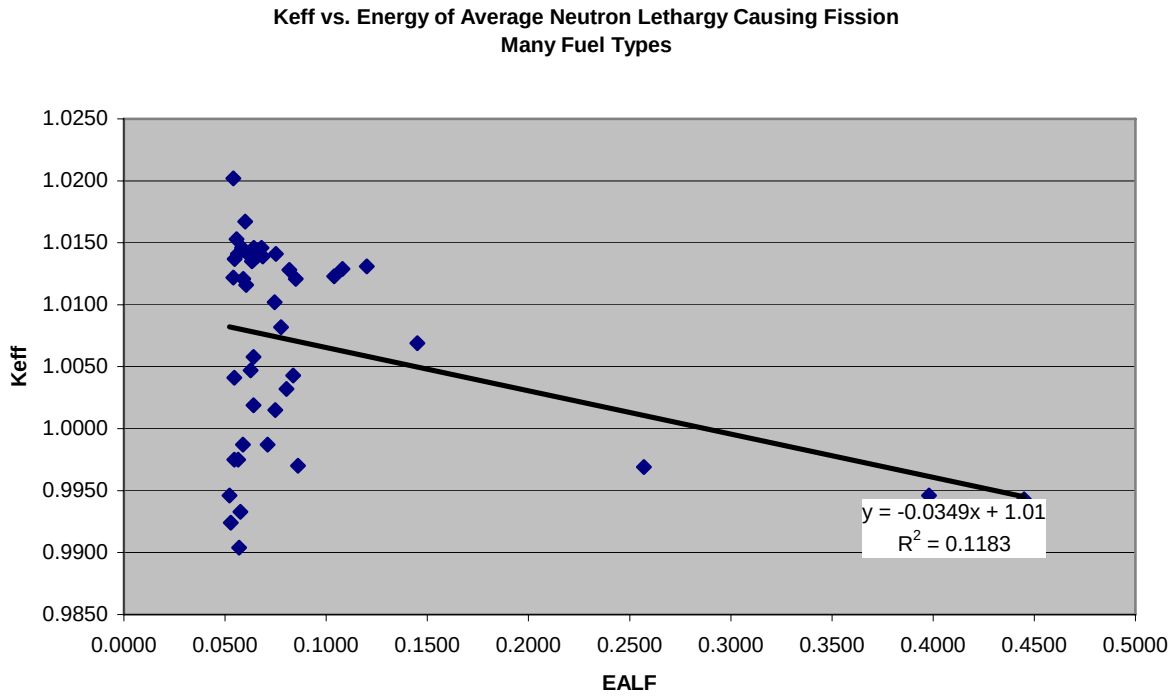


Figure 5.3-1
MCNP4C — TRIGA Cases
K_{eff} vs. U-235 Enrichment for Critical Experiments

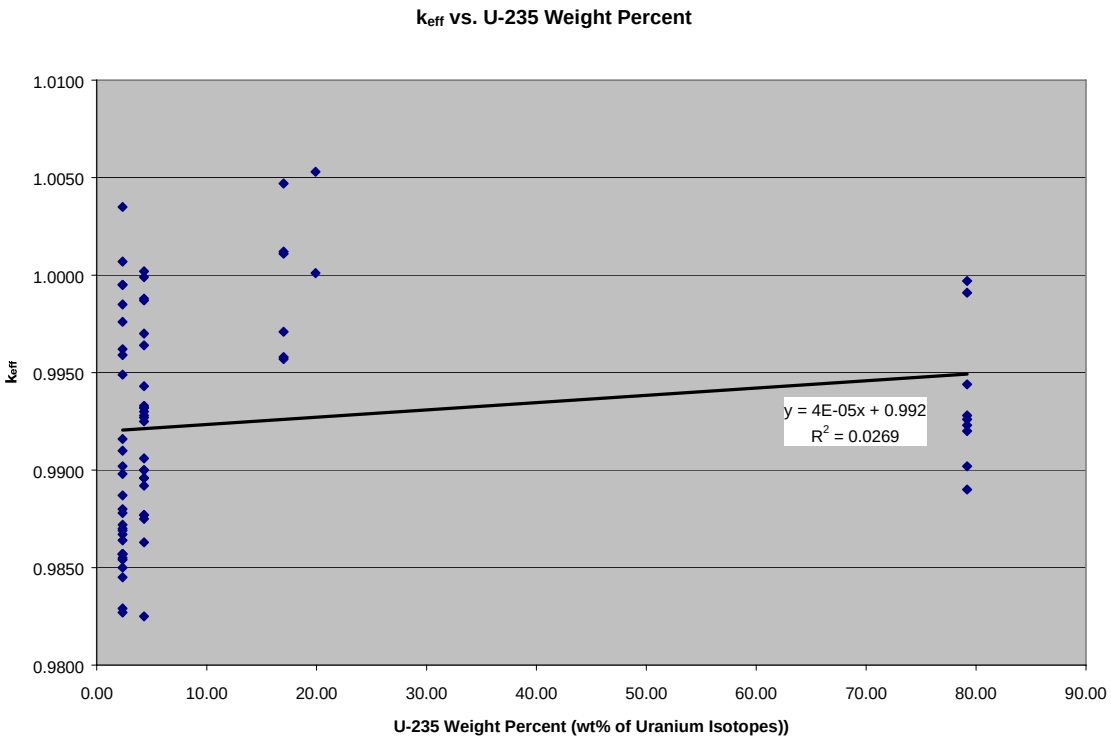


Figure 5.3-2
MCNP4C — TRIGA Cases
K_{eff} vs. EALF for Critical Experiments

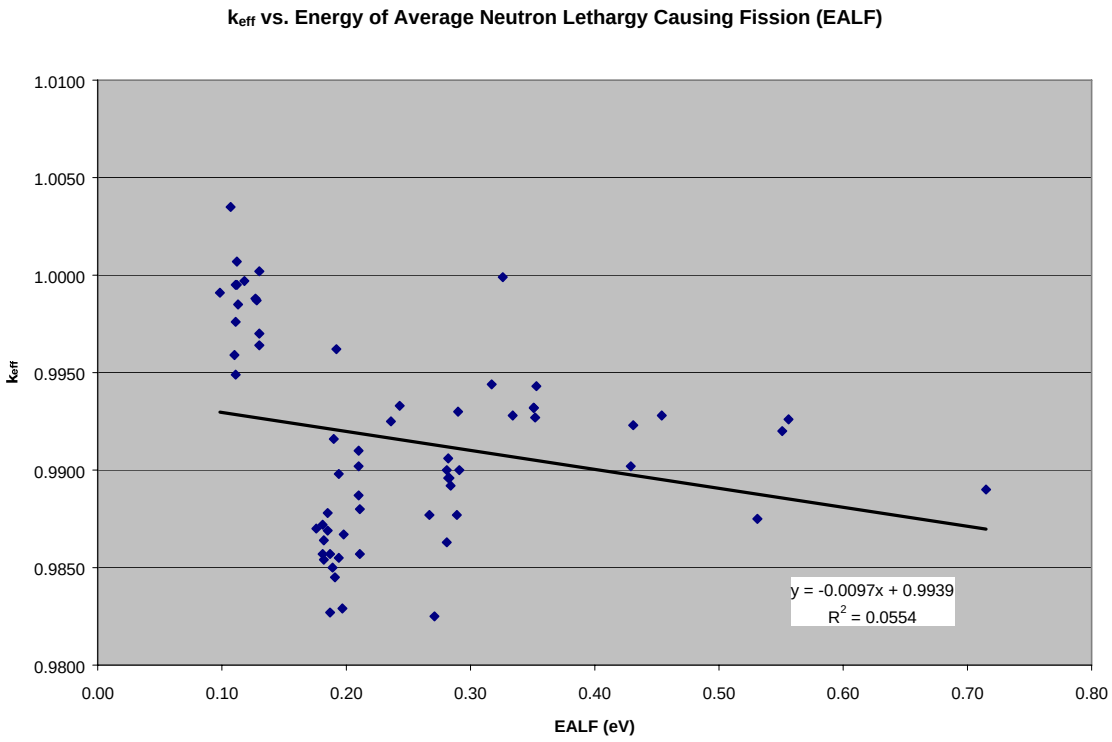


Figure 5.3-3
MCNP4C — TRIGA Cases
K_{eff} vs. AFGE for Critical Experiments

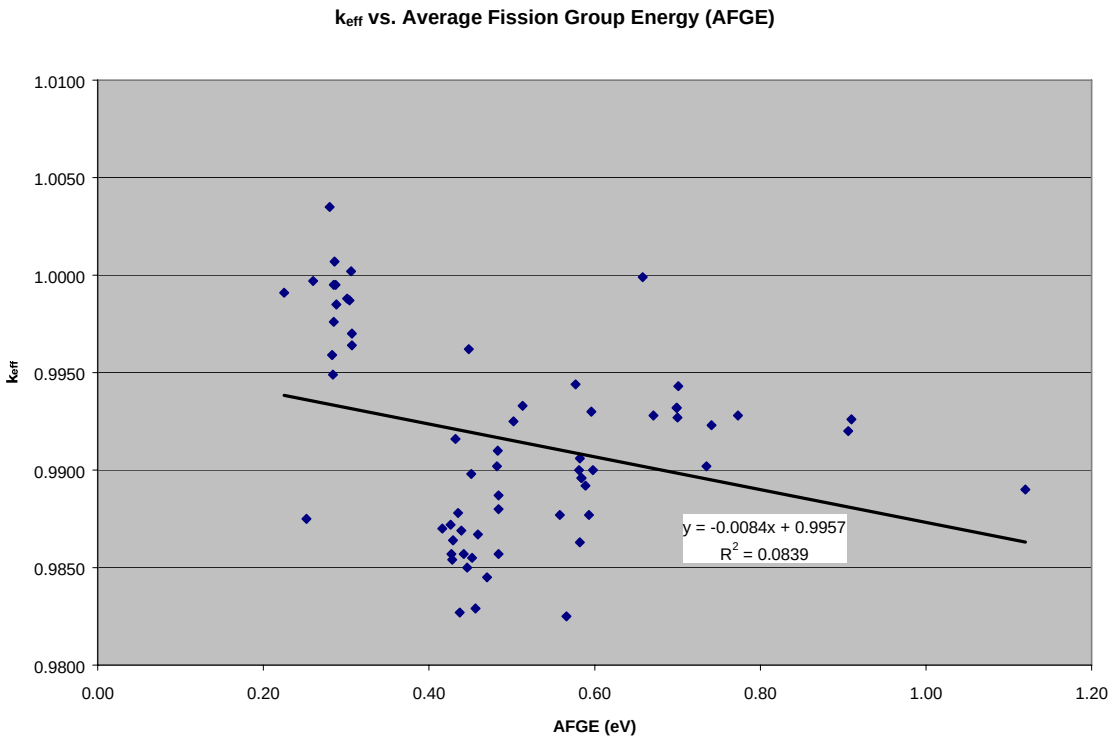


Figure 5.3-4
MCNP4C — TRIGA Cases
K_{eff} vs. Moderator / Fuel Volume Ratio for Critical Experiments

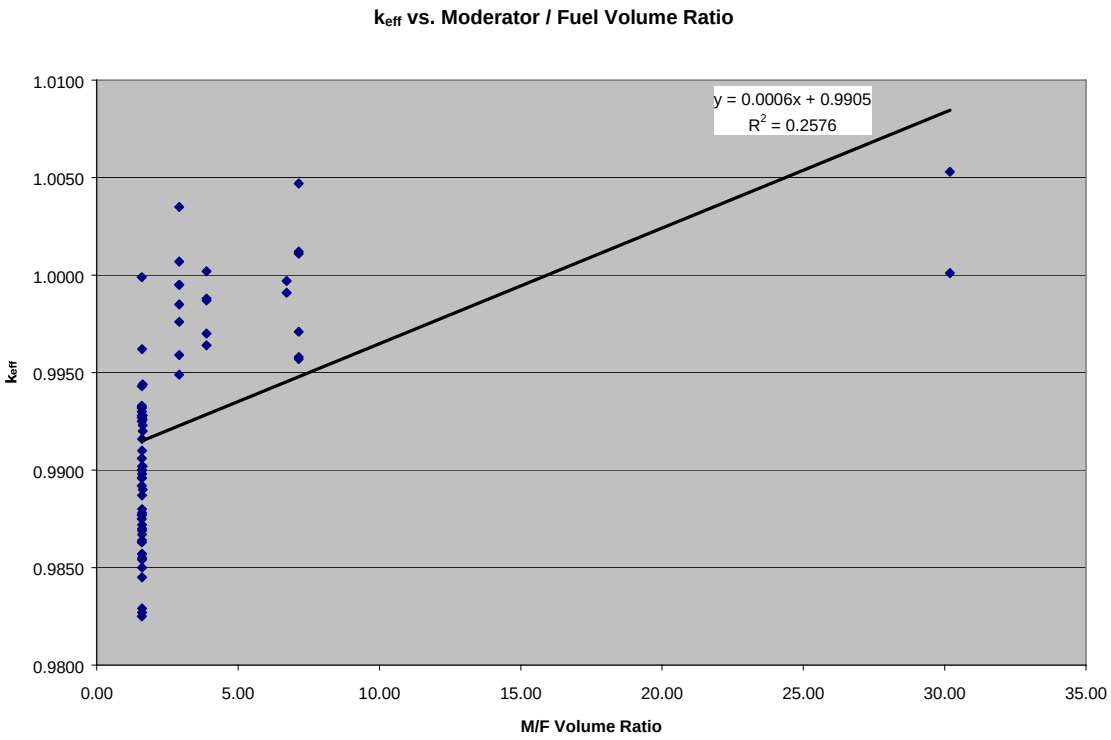


Figure 5.3-5
MCNP4C — Peach Bottom Cases
K_{eff} vs. U-235 Enrichment for Critical Experiments

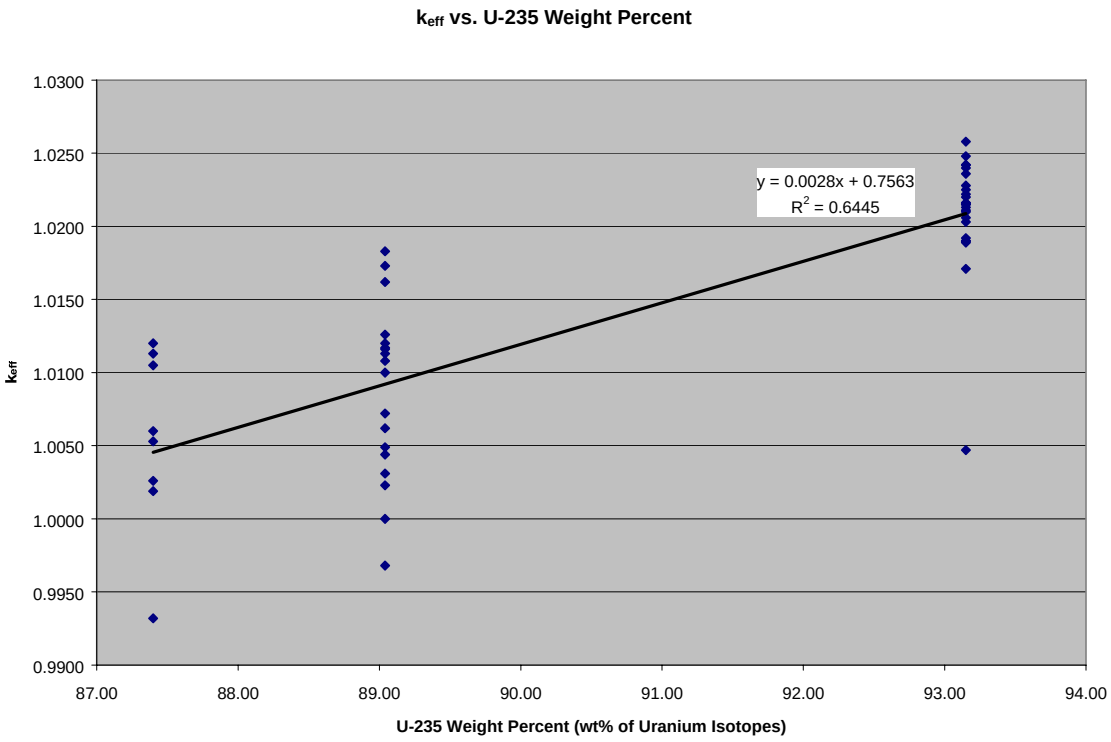


Figure 5.3-6
MCNP4C — Peach Bottom Cases
K_{eff} vs. EALF for Critical Experiments

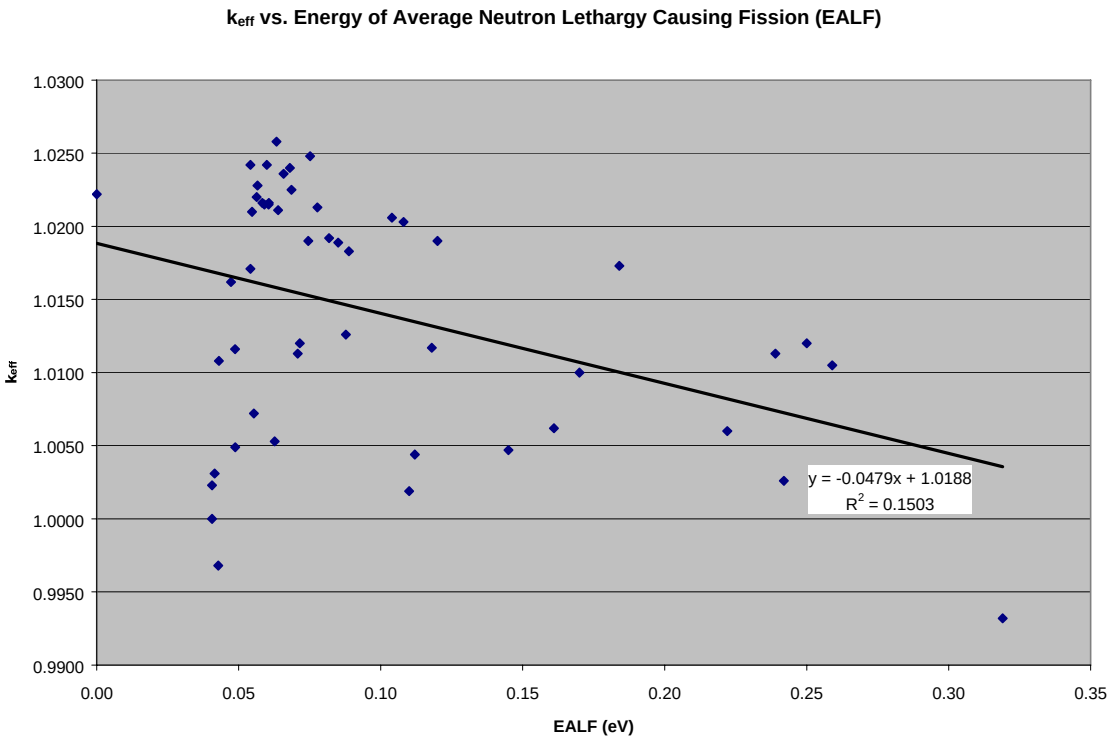


Figure 5.3-7
MCNP4C — Peach Bottom Cases
K_{eff} vs. AFGE for Critical Experiments

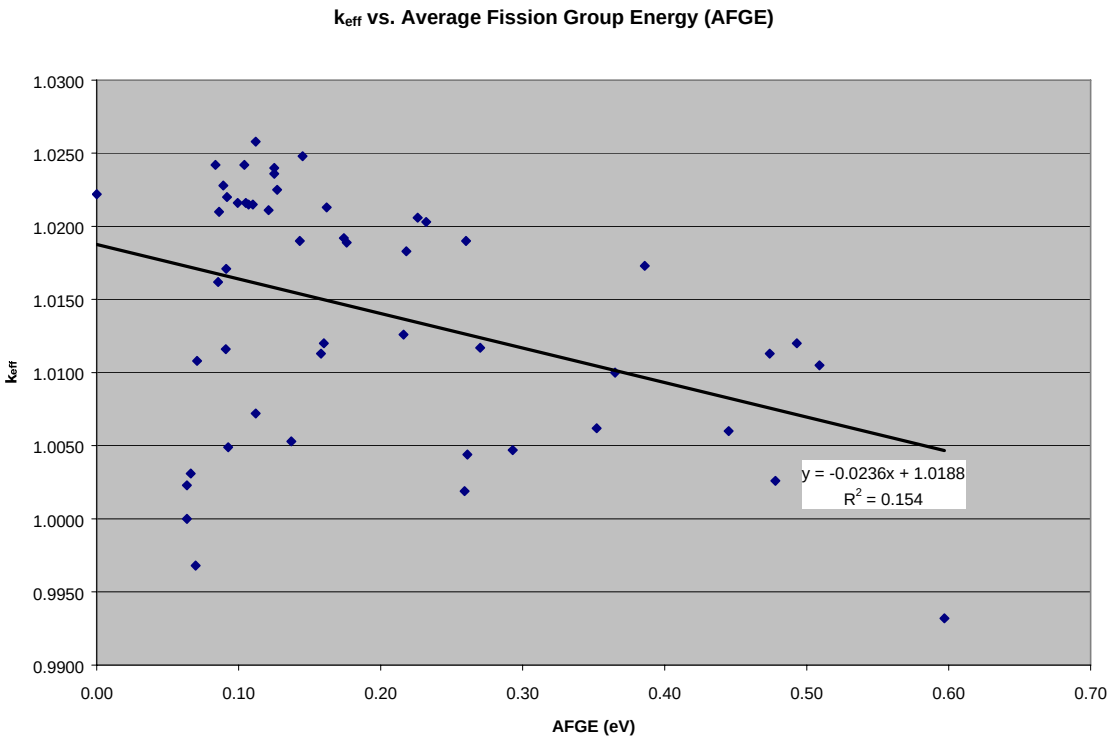
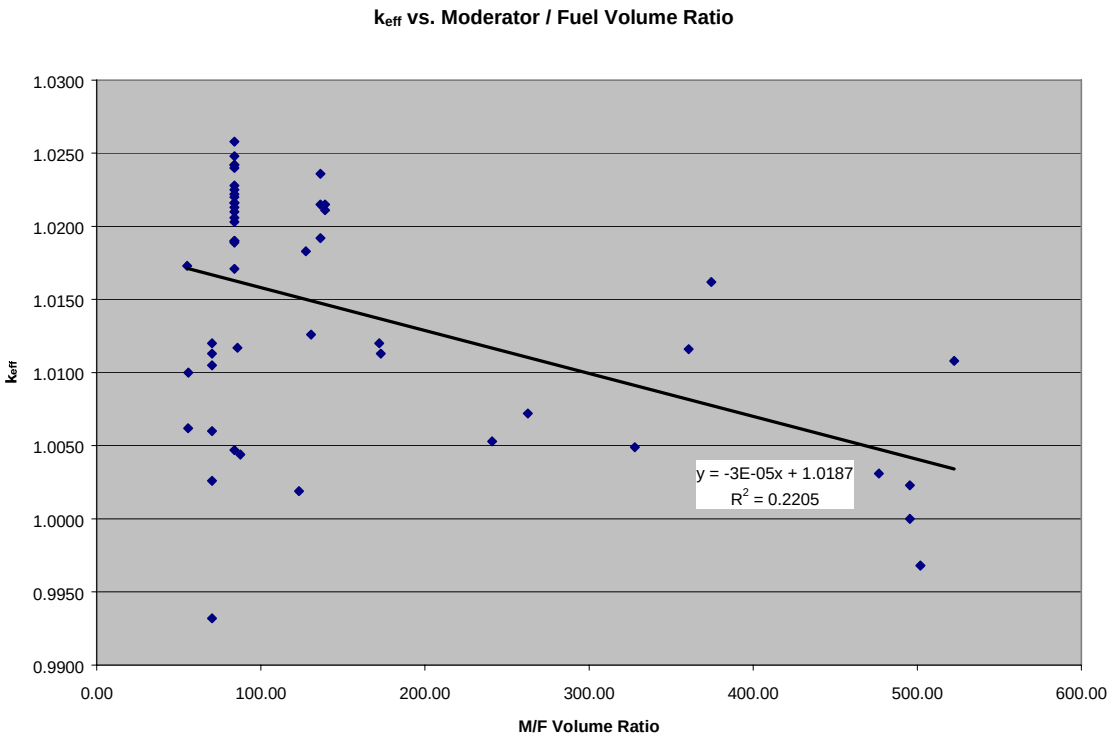



Figure 5.3-8
MCNP4C — Peach Bottom Cases
K_{eff} vs. Moderator / Fuel Volume Ratio for Critical Experiments