SANDIA REPORT
SAND97-2447 • UC-714
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Printed October 1997

ACRR Fuel Storage Racks Criticality Safety Analysis

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Distribution
Category UC-714

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Abstract

This document presents the criticality safety analysis for a new fuel storage rack to support modification of the Annular Core Research Reactor for production of molybdenum-99 at Sandia National Laboratories, Technical Area V facilities. Criticality calculations with the MCNP code investigated various contingencies for the criticality control parameters. Important contingencies included mix of fuel element types stored, water density due to air bubbles or water level for the over-moderated racks, interaction with existing fuel storage racks and fuel storage holsters in the fuel storage pool, neutron absorption of planned rack design and materials, and criticality changes due to manufacturing tolerances or damage. Some limitations or restrictions on use of the new fuel storage rack for storage operations were developed through the criticality analysis and are required to meet the double contingency requirements of criticality safety. As shown in the analysis, this system will remain subcritical under all credible upset conditions. Administrative controls are necessary for loading, moving, and handling the storage rack as well as for control of operations around it.

ACKNOWLEDGMENTS

The authors wish to acknowledge the help of Ed Parma for providing the basic MCNP model and Phil Cooper for his verification of the computations. Also, they wish to thank the Annular Core Research Reactor Committee and the Radiological and Criticality Safety Committee for their thorough review of the analysis in this report. Jeff Philbin and Gary Harms are also acknowledged for their technical review and numerous helpful comments.

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INTRODUCTION

Sandia National Laboratories (SNL) was selected by the U.S. Department of Energy (DOE) for production of medical radioisotopes in September 1996. The radioisotopes will be produced in nuclear reactor and hot cell facilities at the SNL Technical Area V site in Albuquerque, New Mexico. The first and most important radioisotope scheduled for production at SNL is molybdenum-99 (^{99}Mo). Nuclear reactor configuration is an important consideration for efficient and safe isotope production. This document reports the criticality safety analysis performed for a new fuel storage rack to be used in nuclear reactor core modifications.

Criticality safety analysis is mandated by DOE Order 5480.24 (DOE, 1992). The analysis documented in this report was performed as specified in the SNL environmental safety and health manual supplement on nuclear criticality safety (SNL, 1993). The analysis formed part of the basis for a safety review of the facility modification request to acquire the new fuel storage rack. The full criticality safety analysis was developed in multiple internal SNL reports and memorandums which have been consolidated in this document.

Criticality safety for the new fuel storage rack depends upon control of several parameters. Each parameter is a physical property whose value affects the nuclear reactivity of the fuel storage rack system. The control of criticality parameters for criticality safety is intended to be mostly through physical limitations of the new fuel storage rack design and construction. Administrative controls are necessary for loading, moving, and handling the storage rack as well as for control of operations around it.

The criticality analysis was conducted by calculational techniques.

DESCRIPTION

The ^{99}Mo activities will require significant changes to the Annular Core Research Reactor (ACRR) core hardware. These changes will require the removal and storage of the reactor fuel elements in the associated Gamma Irradiation Facility (GIF) pool. It was proposed that new fuel storage racks be designed and tested as part of the ^{99}Mo upgrades to the ACRR. These racks would be multifunctional; they are able to hold the ACRR BeO/UO_2 elements, the older Annular Core Pulsed Reactor (ACPR) ZrH-U fuel elements, nickel reflector elements, aluminum spacer elements, ^{99}Mo production UO_2 targets, or any combination of these. The purpose is to provide a capability for unloading the ACRR core and placing the elements in safe temporary storage. The ACRR currently has two previously approved ACPR storage racks, each with a capacity of 90 elements.

The current ACPR fuel element storage racks use boral sheets as a neutron absorber between each row of nine elements. The ACPR rack uses a rectangular pitch. The pitch within a row is 6.35 centimeter (cm) and the pitch between rows is ~9.6 cm. Each element is located in an individual aluminum tube for the current ACPR rack. The new ACRR fuel storage rack (FSR) design reduces the reliance on boral by using an all stainless steel construction. The new ACRR rack maintains the over moderated design of the ACPR rack with a rectangular 6.35 cm by 9 cm pitch. Each element is located in an individual stainless steel tube for the new ACRR FSR. Note that the original design, and some of the analysis, was for an aluminum and stainless steel rack.

Design of the new ACRR FSR was established by SNL drawing number R43471, ACRR Fuel Storage Container. The new ACRR FSR is illustrated in Figure 1. Dimensions of the main box are 67.5 cm wide by 91.5 cm long by 61 cm high (approximately 26.6 inches wide by 36 inches long by 24 inches high). Lifting points are located at each corner of the top. A bumper rail, measuring approximately 43 inches long by 27 inches wide, is mounted on the lifting points.

It is anticipated that the two existing ACPR and one new ACRR fuel storage racks will be used interchangeably to hold the fuel, reflector, spacer, and control elements. See Table 1 for a listing of the entire inventory. Both types of fuel elements are approximately 29 inches long and 1.5 inches in diameter so they extend beyond the top of the fuel storage racks (see Figure 2). The ACPR and the ACRR fuel storage racks will be used in the GIF pool for fuel storage. In order to hold the entire inventory during ACRR modifications, the fuel storage holsters in the GIF pool must be used to supplement the ACPR and ACRR fuel storage racks.

The location of the ACPR and the new ACRR fuel storage racks in the GIF pool is presented in Figure 3. This figure shows a plan view of the ACRR and GIF pool with fuel storage holsters and the two types of fuel storage racks. Fuel pass-through ports allow movement of individual fuel elements under water from the ACRR to the GIF pool. A 15-element transfer and storage rack (FER) for bulk transfer of fuel elements in air is also shown in the ACRR pool. The fuel ring external cavity (FREC) subcritical assembly of the ACRR, not needed for ^{99}Mo production, is shown in storage in the GIF pool. Figure 4 shows an elevation view of the combined ACRR and GIF pool facilities.

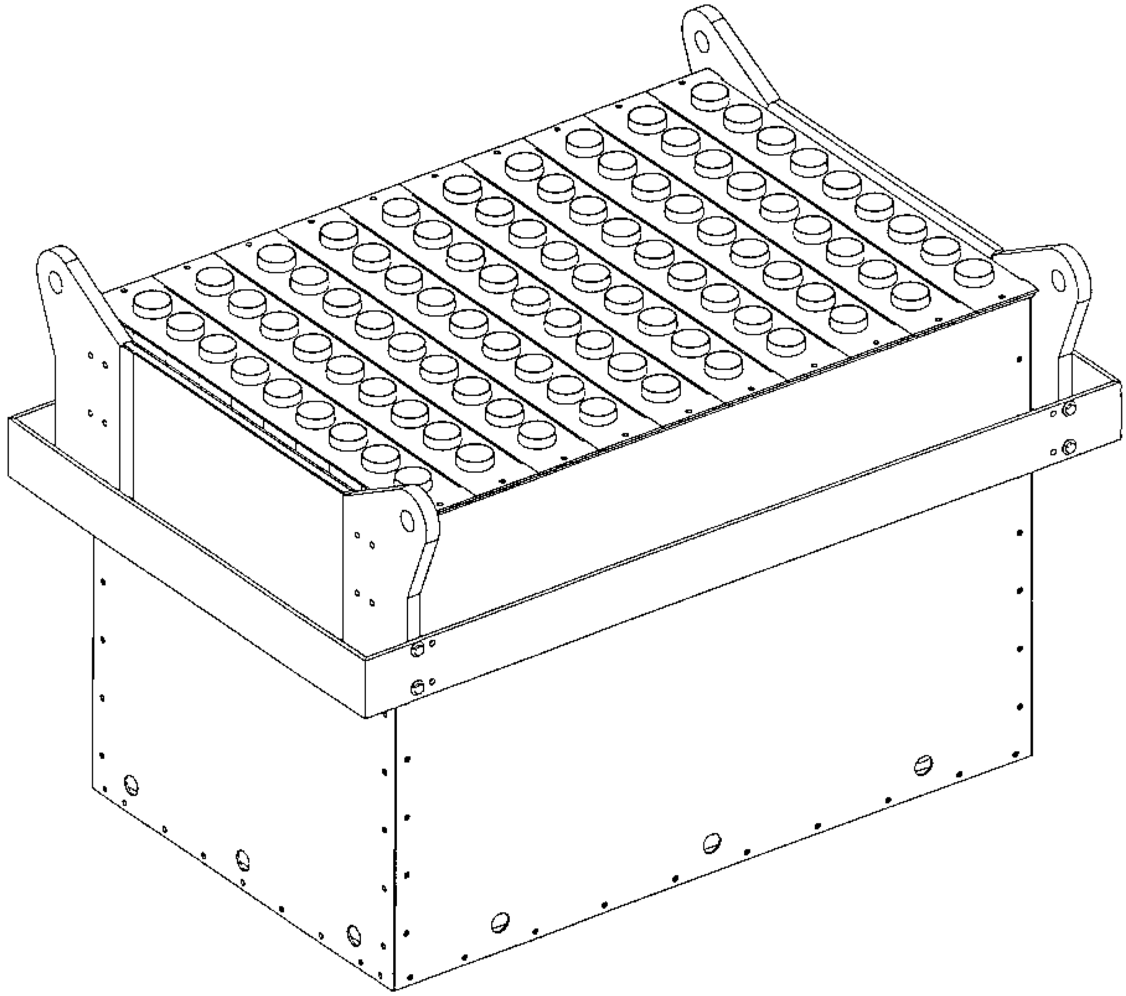


Figure 1. New ACRR fuel storage rack.

Table 1. Inventory of ACRR/ACPR core elements.

Fuel Element Description	Number of Elements
ACPR ZrH-U, 20 percent enriched (~54 grams (g) of ^{235}U)	~180
ACRR BeO-UO_2, 35 percent enriched (101 g of ^{235}U)	239
Nickel reflector elements	59
Aluminum spacer elements	10
Instrumented fuel elements, 35 percent enriched	5
Control elements	11
Cintichem ^{99}Mo UO_2 Targets, 93 percent enriched (< 33 g ^{235}U)	~36

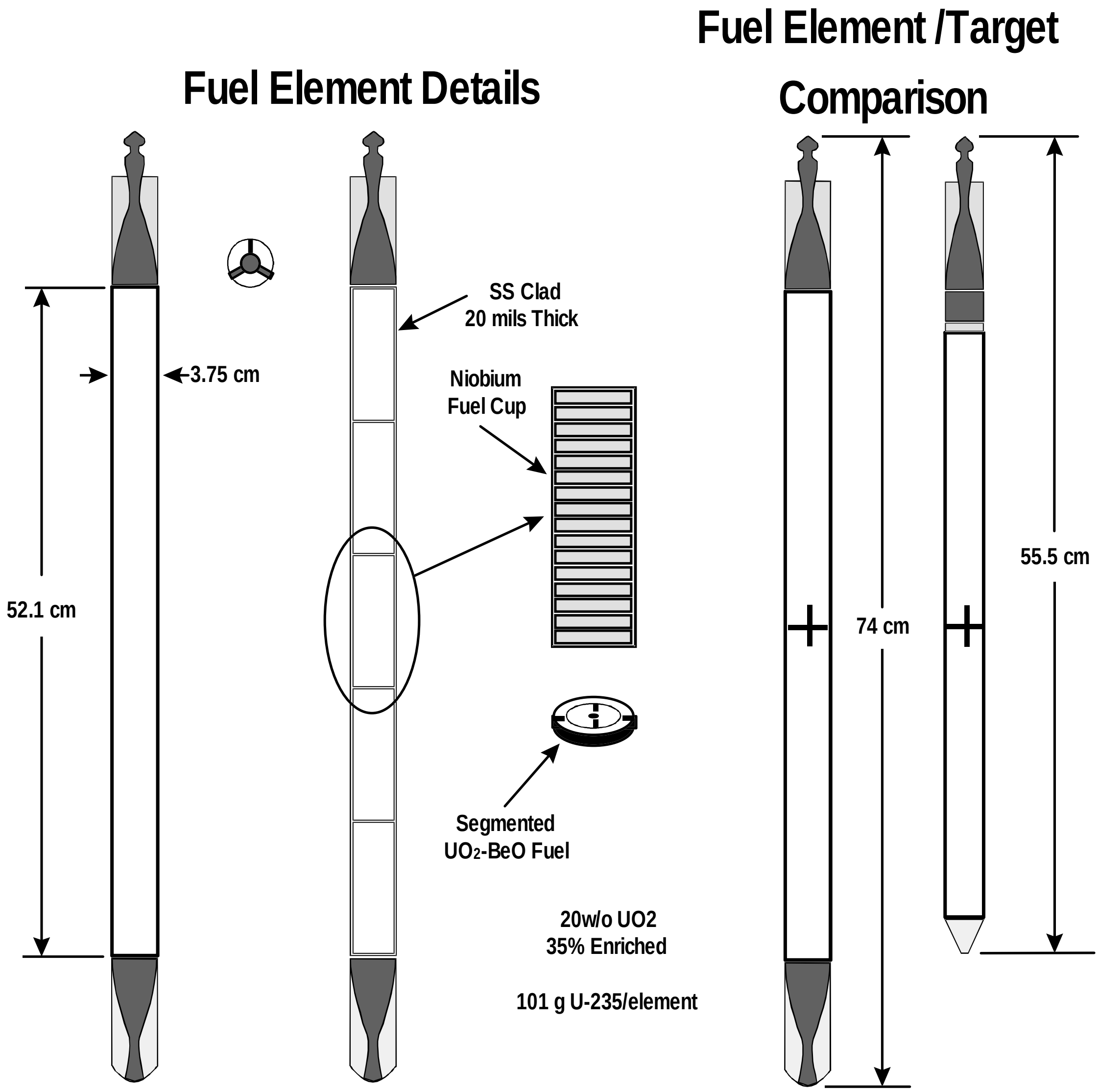


Figure 2. ACRR fuel elements and ^{99}Mo production targets.

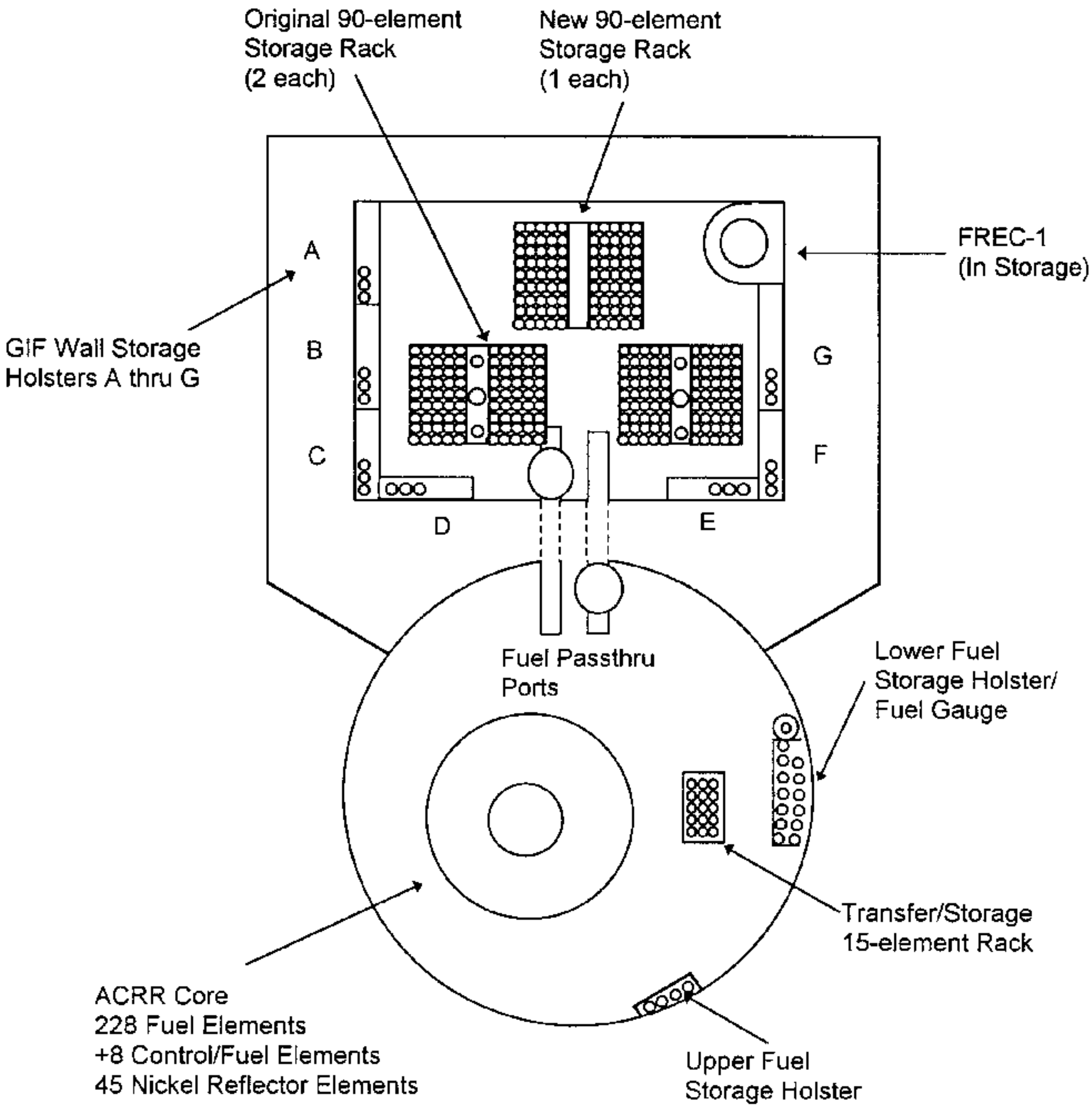


Figure 3. ACRR fuel storage racks and holsters.

The GIF holsters line three sides of the GIF pool at the bottom. The holsters form a planar array. Each holster has 15 storage locations. Each storage location holds two fuel pins stacked one on top of the other. The seven GIF holsters can hold a total of 210 fuel pins. The actual number of fuel pins currently stored is less because the ~15 fuel followed control rods occupy the space of two fuel pins. The holsters will be used to store the ~180 UZrH fuel elements and the fuel storage racks will hold the ~200 BeO/UO_2 fuel elements. Detailed drawings of the holsters are not available but measurements were made on the holsters where they protrude above the GIF pool water. For the calculations performed in this report, it was assumed that the holsters are constructed of aluminum tubing 4.4 cm (1.6 inches) in diameter with 0.165 cm (0.062 inch) wall thickness. The GIF holsters are approximately 5 feet, 8 inches high.

The fuel storage racks have external bumpers that limit how close a rack can be positioned to a wall or another rack. The holsters do not have bumpers and items pushed up against them, such as a fuel storage rack, are only about a centimeter from the edge of the fuel.

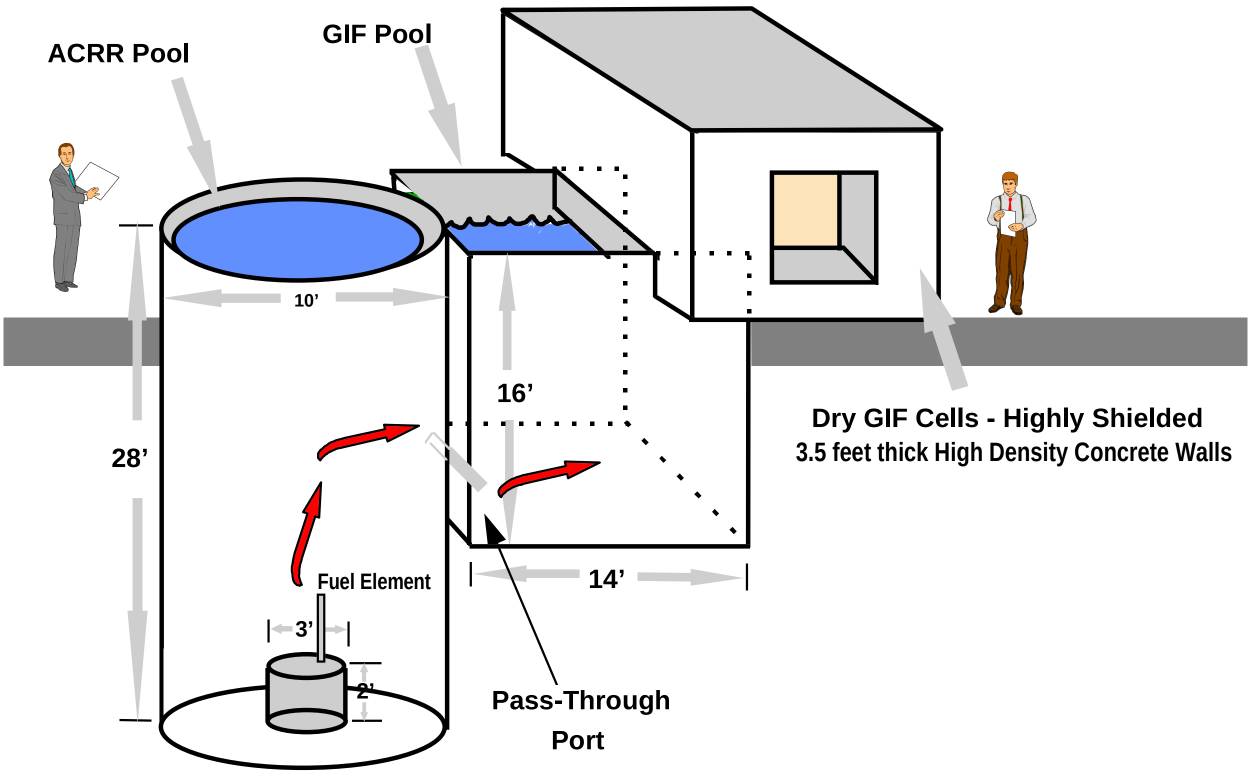


Figure 4. Combined ACRR and GIF pool facilities.

REQUIREMENTS DOCUMENTATION AND METHODOLOGY

Requirements for the criticality evaluation for the new ACRR FSR are given by ANSI/ANS-8.7, *Guide for Nuclear Criticality Safety in the Storage of Fissile Materials (R 1987)* (ANS, 1975) and ANSI/ANS-8.1 (ANS, 1983a). ANSI/ANS-8.7 lists several effective multiplication factor (k_{eff}) values applicable to subcritical fissile material storage systems but does not establish an acceptable subcritical value for the fuel storage operation. This document will analyze the criticality of normal conditions and postulated upset contingencies to establish that the proposed new ACRR FSR will remain subcritical. The criticality analysis was conducted by calculational techniques. A threshold of calculated $k_{eff} + 2\sigma \leq 0.95$ was used to indicate the limits of subcriticality where σ is the standard error of calculations.

Some limitations or restrictions on use of the FSR for storage operations were developed through the criticality analysis and are required to meet the double contingency requirements of criticality safety. Physical limitations inherent in the FSR design are preferred but some administrative controls are needed as well. Loading procedures and other operational procedures developed for the FSR will adhere to the administrative controls.

Once the operational limitations are established through this analysis, the new ACRR FSR will go through an approach to subcritical loading of fuel elements to verify the analysis and limitations. Requirements for the approach to subcritical loading operation are established by ANSI/ANS-8.6, *Safety in Conducting Subcritical Neutron-Multiplication Measurements in-Situ (R 1995)* (ANS, 1983b). Results of the approach to subcritical loading operation are not included in this analysis report. A similar approach to subcritical loading operation for the previously approved ACPR fuel element storage rack was conducted by Estes, Morris, and Philbin (1975) and analyzed independently by Parma (1995a). This criticality safety analysis documented in this report follows the guidelines of DOE-STD-3007-93 (DOE, 1993).

The criticality analysis of the new ACRR fuel storage racks was performed using the Monte Carlo neutron transport code MCNP versions 4A and 4xi (Briesmeister, 1986). The continuous energy cross sections from the DLC105C cross section set were used for these calculations. The computations were performed on a pentium PC, using version 4A, and on an RS/6000 computer, using version 4xi. Selected cases were run on both platforms as a cross check (Cooper, 1996). The test cases that accompany the DLC105C distribution were also run to verify the correct installation of the software. Appendix A contains sample MCNP inputs and outputs. Appendix B contains sample MCNP modeling geometry illustrations.

In addition, MCNP input decks from the International Criticality Safety Benchmark Evaluation Project (OECD-NEA, 1995) were run by Harms at SNL (Bodette, 1996a) on the two computer types. The results give further confidence that the codes have been correctly installed and that the cross section data sets are not corrupted. Comparing Harms' calculated k_{eff} to the true k_{eff} for the benchmark case of a flooded TOPAZ reactor (i.e. case HEU-COMP-INTER-001) allows derivation of a computer platform bias factor to apply to the criticality safety calculations. Based on this benchmark derivation of a computer platform bias factor, the MCNP results for the fuel storage racks and GIF holsters are approximately 0.3 percent low (Bodette, 1996a).

Conservative assumptions in the MCNP modeling ensure that calculated k_{eff} is higher than the actual k_{eff} (Cooper, 1996). An estimate of this modeling induced variation in k_{eff} was given by Parma (1995a) as +0.0014. This small variation is within the uncertainty of the MCNP calculations and was neglected in the analysis.

DISCUSSION OF CONTINGENCIES

Criticality Parameters

Criticality Safety for the new ACRR fuel storage rack depends upon control of several parameters. Each parameter is a physical property whose value affects the nuclear reactivity of the fuel storage rack system. The fuel storage rack parameters are mass, moderation, reflection, geometry, neutron absorbers, and interaction. The parameters are described as follows.

1. Mass fissile material is determined by the number and composition of elements stored in the rack.
2. Moderation is provided by spacing of elements in the rack and the medium between the elements.
3. Reflection is characterized by rack construction and clearance to other objects external to the rack
4. Geometry is the physical arrangement of elements in storage.
5. Neutron absorbers are those fissionable material mixture and other system materials which absorb neutrons.
6. Interaction is the transport of neutrons between the rack and adjacent racks or stored fuel elements.

Control measures intended to provide criticality safety are discussed in the next section.

Criticality Parameter Control

The control of criticality parameters for criticality safety is intended to be mostly through physical limitations of the new ACRR fuel storage rack design and construction. Thus, no operator intervention will be required during the unattended storage time. Administrative controls are necessary for loading, moving, and handling the storage rack as well as for control of operations around it. Controls for each criticality parameter are as follows.

Mass is physically limited to 90-elements per rack by the number of fuel pin holes in each rack.

Mass of fissile material in the Fuel Storage Racks is administratively controlled by allowing only one (1) UO_2/BeO [30 percent enriched] fuel pin or one (1) UZrH [20 percent enriched] fuel pin or one (1) Cintichem ^{99}Mo Target [93 percent enriched, < 33 grams (g) ^{235}U] per location for a total of 90 fuel pins per rack. Note that the storage of nickel reflector elements and aluminum spacer elements in the same rack is specifically allowed.

Moderation is physically controlled by the design of the rack which determines the fuel element pitch. The 6.35 cm by 9 cm pitch leads to an over moderated condition in the new ACRR FSR.

Moderation is administratively controlled by forbidding the introduction of voids (i.e., air bubbles or boiling) into a fuel storage rack. That is, pneumatic tools or other devices that could potentially introduce air voids into a fuel storage rack are forbidden in the vicinity of the racks. Note that the rack is designed with solid sides and bottom. Only the top of the rack has openings for the fuel elements. These design features make it difficult to blow air into the racks without deliberate intent. The pool temperature is administratively controlled below 60^{o}C which ensures that the fuel is cooled and vigorous boiling is precluded.

Reflection is physically controlled by the overall size of the rack which limits how close to a reflector, such as a concrete wall, the fuel can be.

Geometry is physically controlled by the configuration and fabrication of the fuel storage rack.

Neutron absorbers are physically controlled by the fabrication technique in which the boron/aluminum cermet is sandwiched between two aluminum plates. All computations were done assuming no boral was present. Therefore, the presence or absence of the boral is not a criticality concern. The stainless steel materials used to fabricate the ACRR fuel storage racks act as a neutron absorber. In order to maintain the integrity of the stainless steel the GIF pool water quality is administratively controlled.

Interaction is physically controlled by the overall size of the rack which limits how close other fuel racks can be to the fuel held in the rack.

Interaction is administratively controlled by setting stacking limits to a single layer.

Contingencies

A contingency is a possible but unlikely change in a condition/control important to the nuclear criticality safety of a fissionable material operation that would, if it occurred, reduce the number of barriers (either administrative or physical) that are intended to prevent an accidental nuclear criticality.

Various contingencies were analyzed to determine the effect of a loss of criticality control. The contingencies in Table 2 below represent key aspects of control for each criticality parameter. Analysis of each contingency is presented in the next section.

Table 2. Criticality control contingencies for analysis.

Control Parameter	Contingency
1. Loss of Mass control	1a. higher enrichment fuel pins
2. Loss of Moderation control	2a. interstitial moderation in rack
	2b. spacer pins in rack
3. Loss of Reflector control	3a. reflector elements placed in rack
	3b. rack placed near concrete wall
4. Loss of Geometry control	4a. rack hole spacing (i.e., pitch) is too small
	4b. outside dimensions of rack are too small
	4c. rack is crushed or dropped
5. Loss of Neutron absorbers	5a. boron leaches out of boral
	5b. stainless steel corrodes
6. Loss of Interaction control	6a. extended arrays
	6b. contents spill from a rack
	6c. racks are stacked

ANALYSIS AND RESULTS

Each criticality control contingency developed in the last section is analyzed here for the effect of loss of that control for the new ACRR FSR. The effect of the GIF holsters on criticality for the new ACRR FSR is analyzed as a basis for their use together in the GIF pool.

New ACRR fuel storage rack

Mass contingency 1a. higher enrichment fuel pins

All fuel pins currently located at the ACRR are less than 35 percent ^{235}U enrichment. The mass of ^{235}U in the ACRR UO_2/BeO fuel pins is typically 101 g. The ^{99}Mo UO_2 targets which could be used at the ACRR contain 93 percent ^{235}U enriched material. However, the quantity of ^{235}U in a single target is practically limited by the current fabrication process to about 30 g. Since the total mass of fissile material in the higher enriched ^{99}Mo UO_2 targets is one-third of that in a typical ACRR fuel pin, this is not a criticality hazard for ^{99}Mo UO_2 targets to be stored in the fuel storage racks.

A series of calculations has demonstrated subcriticality with 22 fuel pins of hypothetical 93 percent enriched UO_2-BeO elements (~269 g of ^{235}U for each element). Curve 2 in Figure 5 shows the results of these calculations for the 22 fuel pins with hypothetical 93 percent enriched UO_2-BeO. Eleven fuel pins were placed in the middle of a 90-element rack with the remaining pin locations filled by normal 35 percent enriched UO_2-BeO fuel pins. This rack was stacked on top of a similar rack containing another eleven over-enriched fuel pins. These two racks were placed in the middle of an array of other fuel storage racks containing normal fuel pins. The array was three racks wide by three racks long by two racks high (3x3x2 array). Even for this extreme case of rack interaction, the 22 fuel pins of hypothetical 93 percent enriched UO_2-BeO elements were not a criticality hazard at normal water density. None of the various configurations represented by the other curves of Figure 5 were a criticality hazard at normal water density.

Note that aluminum was specified in the computational models for Figure 5. The change to an all stainless steel construction for the fuel storage racks was made on the basis of the criticality hazard that could exist at low water densities (i.e. high void fractions) as born out in this figure. This issue is addressed further with respect to contingency 2a.

Moderation contingency 2a. interstitial moderation in rack

The current design is to have an over moderated array so that removing a pin or a set of pins would not lead to a critical configuration. This leads to a safe configuration when loading and unloading the fuel storage rack as designed under full water immersion. However, any situation which reduces the amount of moderator present could lead to a more critical configuration. Two situations were considered: 1) air or steam voids in the rack (perhaps from pneumatic equipment being operated in the tank or boiling) and 2) reducing the amount of water covering a rack (as when removing a loaded rack from the pool).

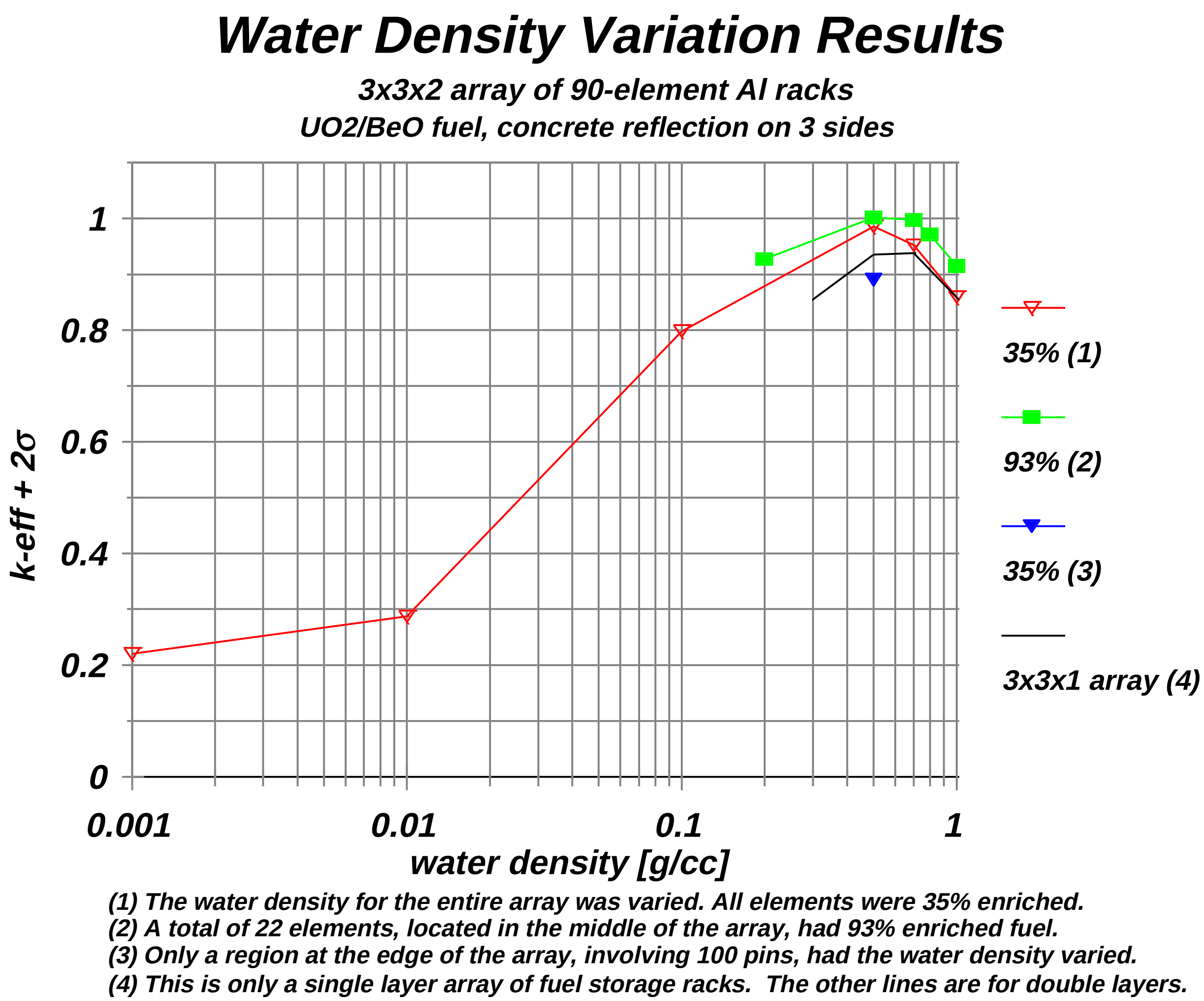


Figure 5. Water density variation results, 3x3x2 array of 90-element Al racks.

Situation 1 air/steam bubble voids in the rack. The Figure 6, curve 1 plot shows the results of calculations for uniformly varying the density of water moderator within an infinite planar array of stainless steel storage racks from 0.05 to 1 grams/cubic centimeter (g/cc). The plot clearly shows that the effective multiplication factor (k_{eff}) increases as the water density is decreased, as is expected from the over-moderated design. The peak k_{eff} is near a void fraction of 40 percent and is less than 0.95 even for the infinite planar array. The actual dimensions of the rack and pool limit the size of arrays to 3 by 3. The results are conservative in that the spacing between racks is zero in the infinite array model and the actual design of the racks ensures a minimum separation of 12 cm between racks (see curve 2). Therefore, the ACRR fuel storage racks are subcritical even with voids or bubbles in the racks.

Furthermore, it is unreasonable to assume that significant voiding would ever occur in a rack to an extent assumed in the calculations. The ACRR rack is designed with solid sides, bottom, and fuel pin tubes. The top of the rack only has openings for the fuel elements. These design features make it difficult to blow air into the racks without deliberate intent and modification to the racks.

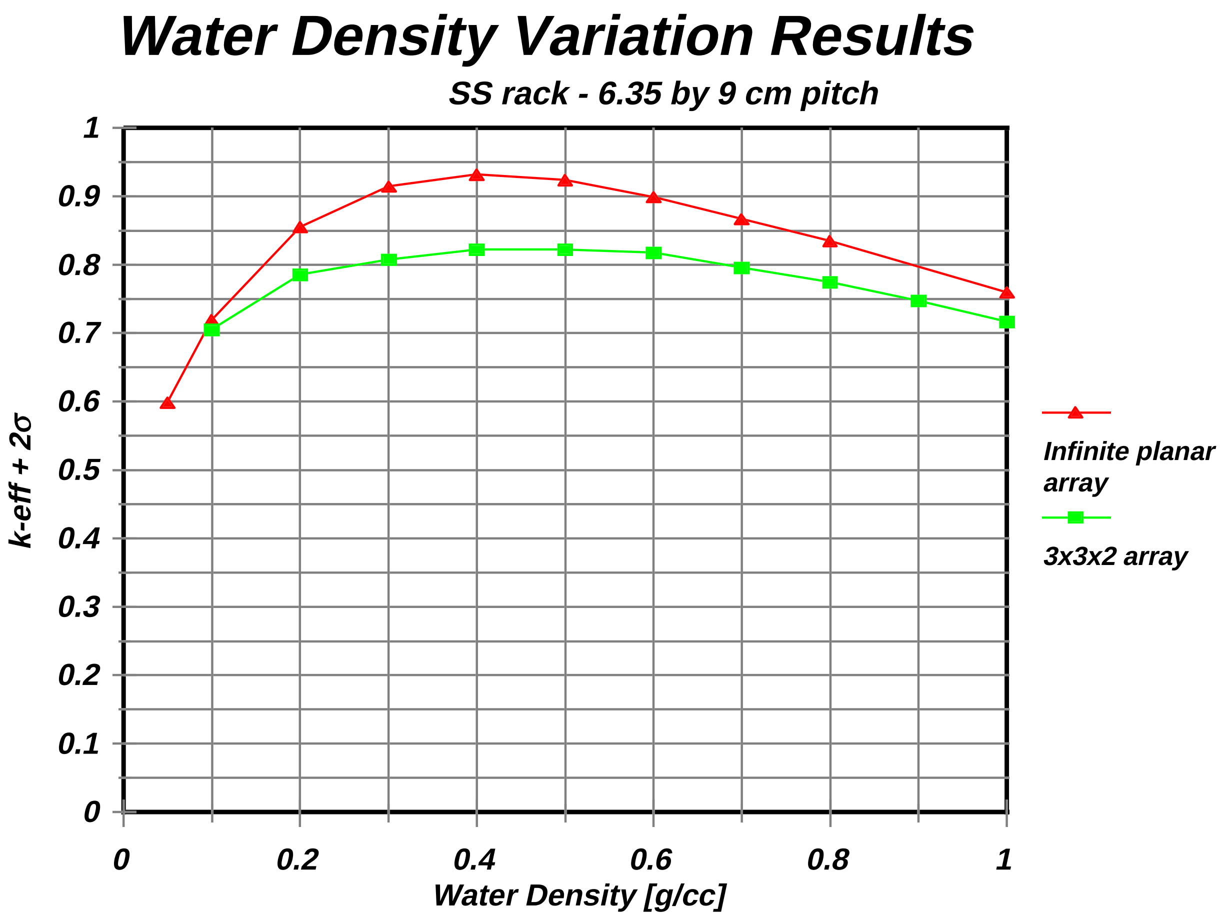
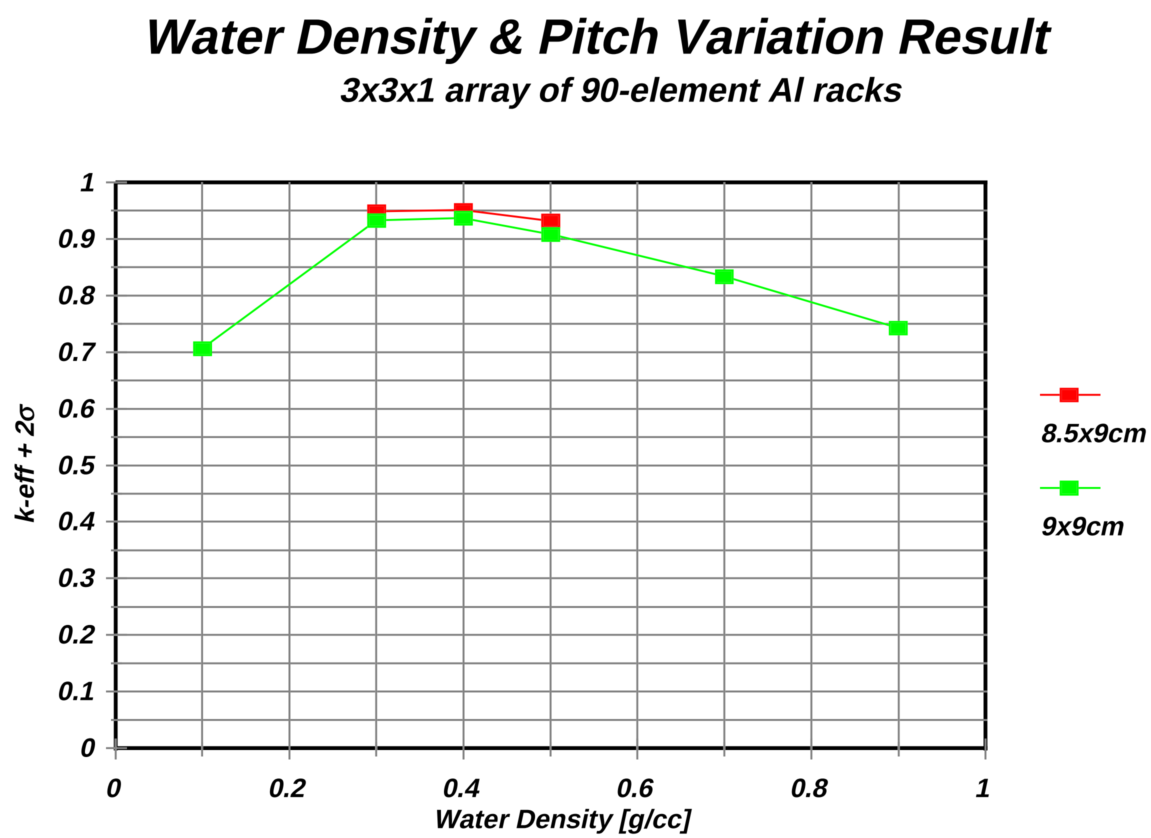


Figure 6. Water density variation results, infinite planar array of racks

Decay heat induced boiling has also been postulated as a possible mechanism for introducing voids into a fuel storage rack. Based on the Parma (1996) analysis this is not a credible scenario. The decay heat per element one hour after shutdown is less than 320 Watts and the pool temperature is administratively controlled to be less than 60^{o}C (to protect the resin beds in the cleanup loop). Based on these conditions the MASSFLOW code predicts the peak fuel cladding temperature to be 75^{o}C. The cladding temperature is well below the boiling point at Albuquerque conditions thus precluding boiling, even for this elevated pool temperature. The normal pool temperature is 28^{o}C, and for 320 Watt decay heat power per fuel pin, the peak cladding temperature would only be 48^{o}C. Again boiling is not possible at normal pool temperatures.

The GIF pool temperature remains close to 28^{o}C year-round with a heat load from the cobalt-60 sources of about 20 kW. This is without any active cooling and is due entirely to conduction to the surrounding soil and surface evaporation. A full 90-element rack, one hour after shutdown, represents about the same heat load as the cobalt-60 sources and would not increase the pool temperature significantly. It would take a reckless disregard for procedures and personal safety to even move 90 fuel elements from the ACRR into the GIF within an hour after shutdown. So, the 320 Watts decay heat power per fuel pin represents a worst case scenario which is unreasonable to achieve in practice. Boiling is not a credible mechanism for producing voids within the racks.

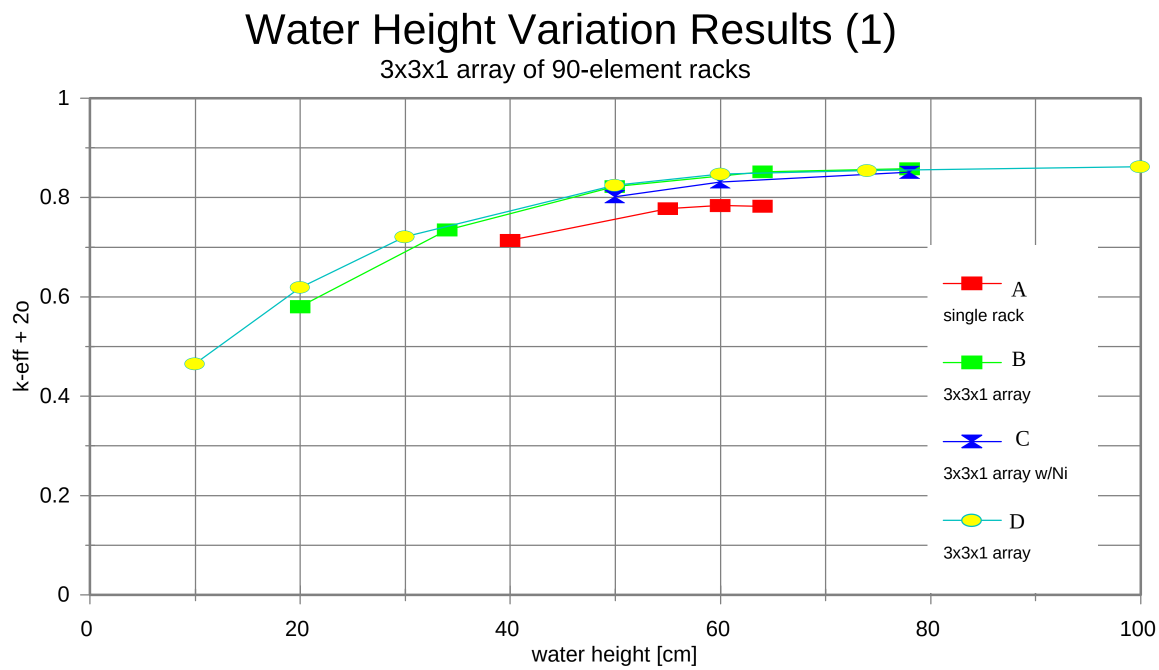
<u>Stainless Steel versus Aluminum</u>: The original design using aluminum construction had problems with voids (see Figure 5). A 3 by 3 by 1 array of aluminum racks could exceed the 0.95 threshold under severe voiding. Two options were considered to mitigate this: increase the pitch (see Figure 7) or use all stainless steel construction. As seen in Figure 7, simply increasing the pitch did not decrease k_{eff} of the rack array below 0.95 with enough margin for uncertainties. For that reason the racks are constructed of stainless steel with the resulting reduced k_{eff} as shown in Figure 6. All the other plots in this safety analysis are based on the original design in which the racks used aluminum. This represents a conservative overestimate of k-eff since aluminum does not absorb neutrons as significantly as stainless steel.



Simply increasing the pitch did not decrease k-eff of the rack array below 0.95 Note that the spacing between racks was only a few centimeters and not the >12 cm as used for the 6.35 by 9 cm pitch cases. The inter-rack spacing was eliminated in order to increase the pitch.

Figure 7. Water density and pitch variation results.

Situation 2 reducing the amount of water covering a rack. The Figure 8 and Figure 9 plots show the results of calculations in which the height of moderator in a 3 by 3 by 1 and a 3 by 3 by 2 array of aluminum storage racks was varied. These calculations model what might occur as the water was drained from the GIF pool. These plots show that a critical configuration does not occur by simply reducing the water level in the GIF pool.



A. The single rack was filled in a checker board pattern with 45 BeO/UO2 and 45 UZrH elements. There was no reflection other than the 9cm of water outside the rack where the bumper rails are.
B. The fuel storage racks in the 3 by 3 array were each filled with 90, BeO/UO2 elements. In addition to the 9 cm of water outside of each rack, three sides of the array were reflected by concrete.
C. Approximately 18 nickel elements were placed into each fuel storage racks on the outer row to act as reflectors.
D. The 3x3x1 array denoted by circles was fully water reflected.

Figure 8. Water height variation results (1).

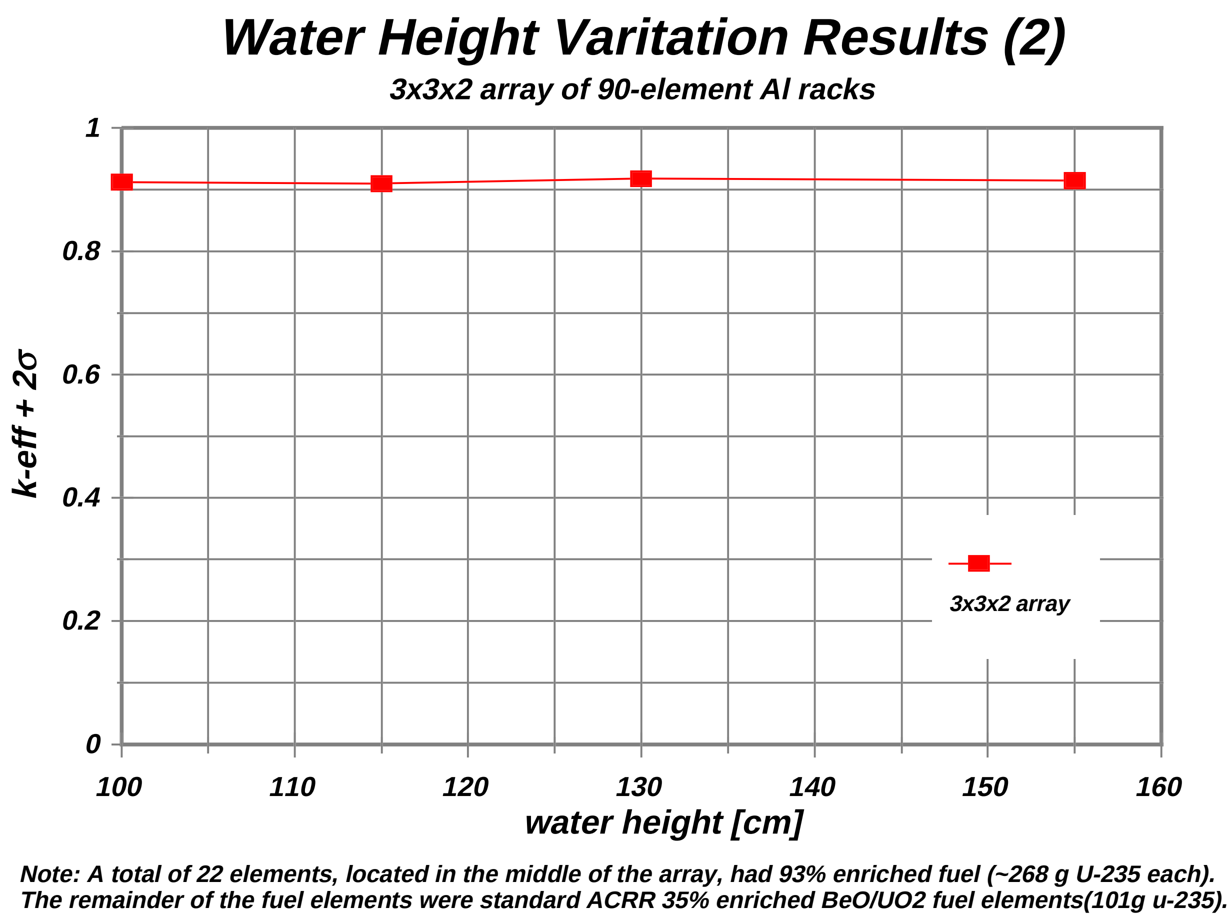
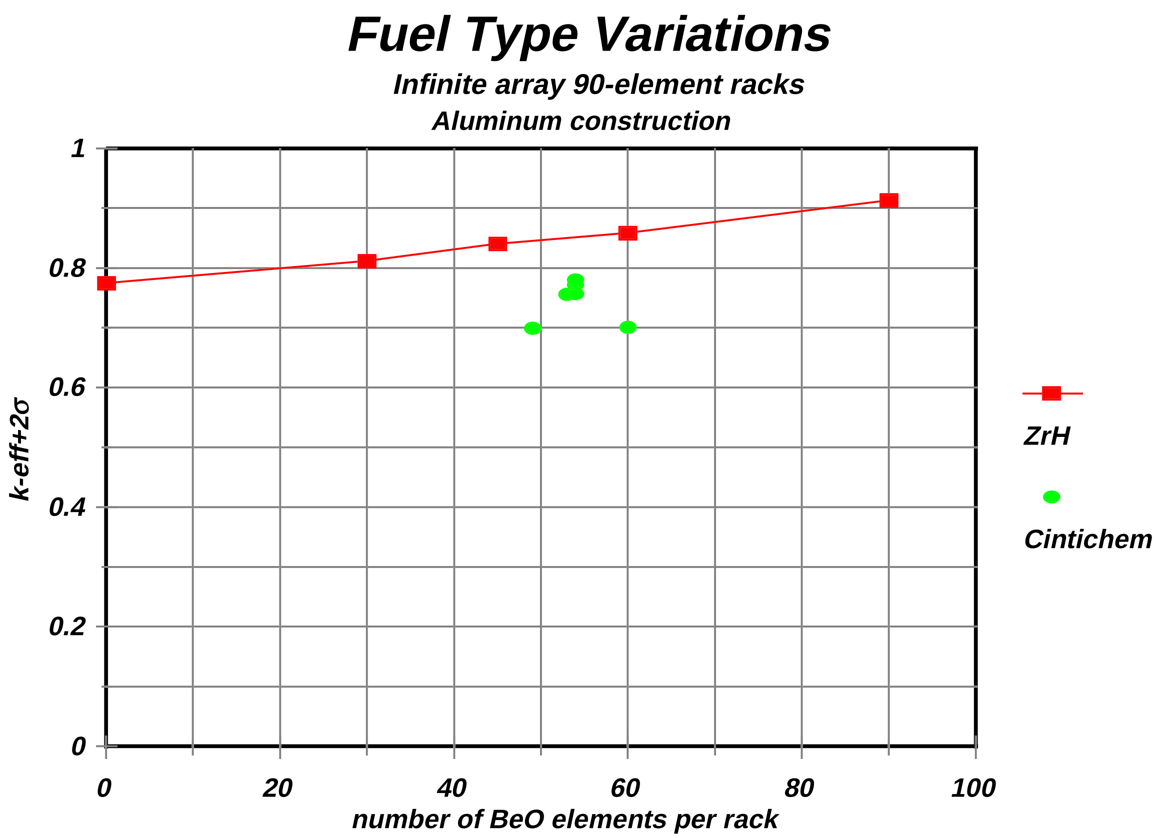


Figure 9. Water height variation results (2).

Moderation contingency 2b. spacer pins in rack

The presence of spacer pins (that is, solid aluminum or air filled pins) would not lead to a critical configuration. First, though the rack is over moderated, spacer pins do not reduce the amount of moderator present any more than adding a fuel pin. Second, spacer pins would decrease the fissile loading in the rack which always yields a safer configuration. This is demonstrated by Figure 10. Replacing the BeO/UO_2 fuel with the ACPR ZrH fuel (see curve 1) yields a safer configuration since there is less fissile material present. Similarly, replacing the BeO/UO_2 fuel pins with Cintichem ^{99}Mo production targets yields an even lower value for k-eff. The Cintichem ^{99}Mo production targets have less fissile material than the ACPR ZrH fuel. Therefore, space pins in the rack do not represent a criticality hazard.



The calculations were done for a single rack with specular reflection on all sides. The rack was completely filled in a checker board pattern with BeO/UO2 and either UZrH fuel elements or Cintichem targets.

Figure 10. Fuel type variations.

Reflector contingency 3a. reflector elements placed in rack

It is anticipated that the nickel reflector elements will be stored in the same rack as the fuel. Curve 3 in the Figure 8 plot demonstrates that the nickel reflector elements do not lead to a more reactive configuration. Adding nickel elements reduces the amount of fissile material (cf. Contingency 2b) and leads to a less reactive configuration. Nickel elements do not reduce the amount of moderator present any more than adding a fuel pin.

Reflector contingency 3b. rack placed near concrete wall

The fuel storage racks are designed to be fully flooded, water reflected on five sides and bottom reflected by stainless steel and concrete. Placing a fully loaded fuel storage rack in a corner of the GIF pool would mean that two sides and the bottom are reflected by stainless steel and concrete. All computations involving arrays of racks were done with concrete reflection on two sides and the bottom. The stainless steel of the pool liner was neglected in the "aluminum rack" calculations in order to be conservative. Contingency 3b is implicitly included in the results for the other contingencies. For example, the 100 cm datum point of curve 4 in Figure 8 was fully water reflected on one side and top. It was also concrete/water reflected on the other sides and bottom. Therefore, fully reflected arrays, whether by water or concrete, are subcritical.

Geometry contingency 4a. rack hole spacing (i.e., pitch) is too small

Design specifications and quality assurance (QA) procurement controls will limit the magnitude of the pitch variations to those of normal manufacturing tolerances (i.e., ~0.030 inch). The plot of Figure 11 (Parma, 1995b) is directly relevant in demonstrating the sensitivity to pitch variations for the ACRR fuel storage racks. Using the slope of the ACRR fuel curve near 7 cm, a 0.030 inch variation in the pitch would lead to a 0.4 percent variation in k_{eff}. This is approximately the same magnitude as the error in the calculations. Normal manufacturing tolerances will not lead to a compromise in the criticality safety of the fuel storage racks.

Geometry contingency 4b. outside dimensions of rack are too small

Design specifications and QA procurement controls will limit the magnitude of the variation in the overall, outside dimensions to those of normal manufacturing tolerances (i.e., ~0.030 inch). The net result, if all racks were undersized, is a reduction in the spacing between two adjacent racks by 0.060 inch. Figure 12 shows the results of gross variations in the rack-to-rack spacing. Based on these results, the variation in k_{eff} is less than 0.1 percent for normal manufacturing tolerances and does not compromise the criticality safety of the fuel storage racks.

Geometry contingency 4c. rack is crushed or dropped

A crushed rack could lead to more optimum moderation and/or loss of the neutron absorber. A dropped or tipped over rack could lead to many fuel pins laying together on the bottom of the pool. Either of these situations could lead to a critical configuration. The plot of Figure 11 shows that an optimum configuration of 36 ACRR fuel pins is considered critical (i.e., $k_{eff} + 2\sigma > 0.95$). Therefore, in order to avoid a criticality hazard when moving a rack with fuel pins in it, a rack shall not be lifted or moved with more than 15 fuel pins in it (Bodette, 1996b).

The likelihood of anything falling from a crane onto the racks and crushing them is incredible. The ACRR crane rigging and hoisting procedures require a minimum of a two-point lift and a safety factor of 10 even under a single point failure. Normal lifts with two points have a safety factor of 20 while industry standards generally allow a safety factor of 5 without any assumed failures.

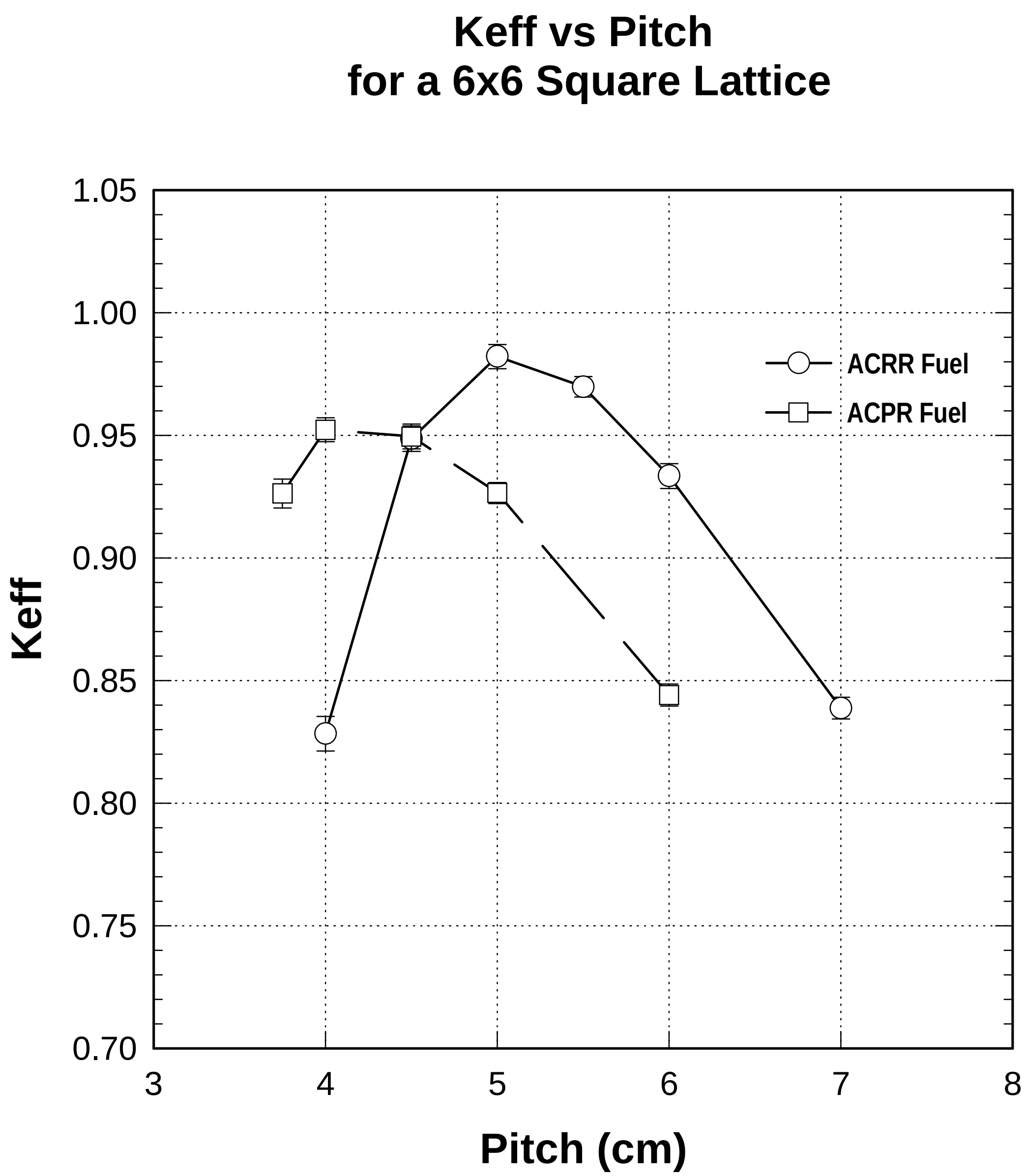
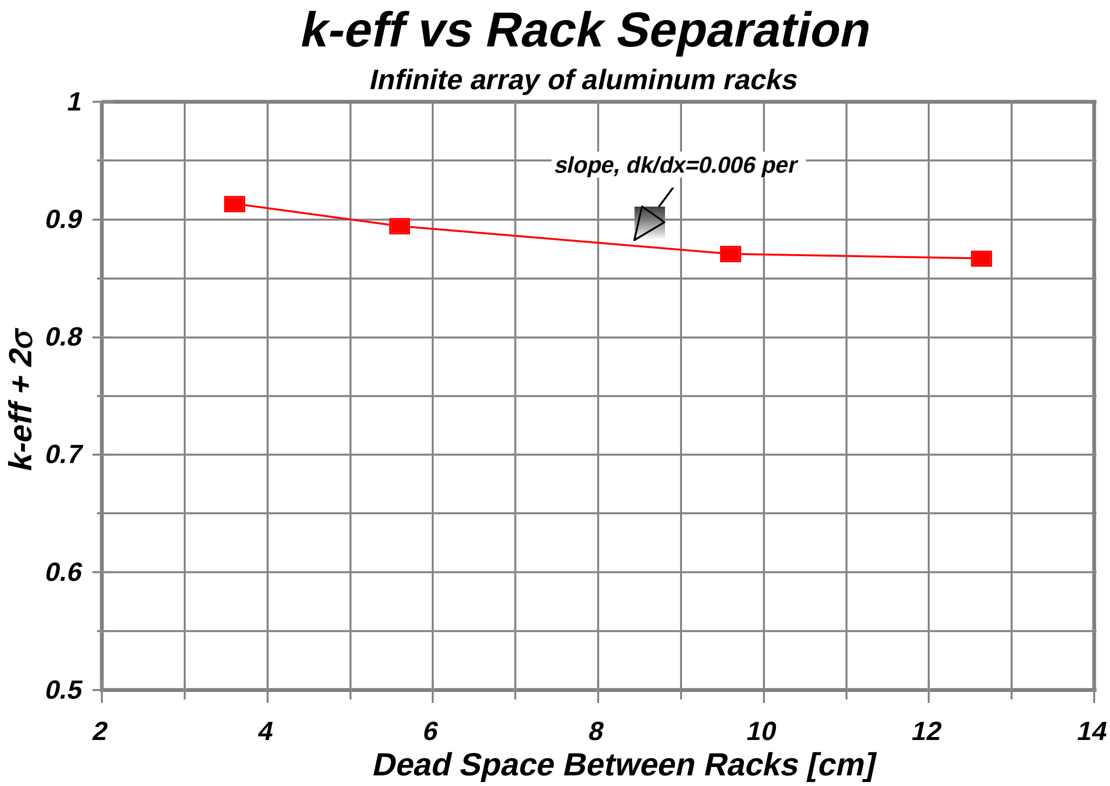


Figure 11. K_{eff} vs. pitch for a 6x6 square lattice.



The dead space between racks is that region on the outside of the racks which is not filled with fuel elements. The new ACRR fuel racks have a dead space on the four sides corresponding to one empty fuel element cell. This gives a water filled region between racks of 12.7cm on two sides and 18cm on the other two sides. This physical separation is engineered using aluminum bumpers.

Figure 12. K_{eff} vs. rack separation.

Neutron absorbers contingency 5a. boron leaches out of boral

In order to ensure a subcritical configuration for contingency 2a, the racks were redesigned to have a full stainless steel construction. The original design called for aluminum tubes to hold each element and these are now stainless steel as are all other metal parts of the rack. Boral is used in the ACPR fuel storage rack and provision for its use in the new ACRR fuel storage rack exists (Bodette, 1996e). The criticality safety of the ACRR fuel storage rack does not depend on the presence of boral, but does depend on the stainless steel. The stability of boral and stainless steel in spent fuel pools has been examined in several reports. Boral in water was examined by Brooks and Perkins (1978) in Report No. 577. Boral is rated by this report as stable in a typical spent fuel pool environment for more than the 40-year design life of the boiling water reactor (BWR) spent fuel storage racks it was being considered for. Similar conclusions regarding stainless steels are also made in BNL-NUREG-22866 (Weeks, 1977) and BNL-NUREG-28937 (or CONF-810402-16) (Czajkowski et al., 1981) provided that good water quality is maintained and that steps are taken to prevent “contamination of the pool with harmful impurities such as sulfur compounds or chloride compounds.” See Table 3 for typical spent fuel pool chemistry.

Table 3. Typical spent fuel pool chemistry.
(From BNL-NUREG-28937)

Characteristic	Typical Value
Conductivity (micro-mho/cm)	<5
Chloride (parts per million [ppm])	<0.1
pH	5.6 - 8.6
SiO_2 (ppm)	<0.5
Temperature	<52° C

It should be noted that measurements and calculations for the ACPR fuel-element storage racks without Boral do indicate there may be a criticality concern in the unlikely event that the Boral leaches out completely. However, there is no criticality concern for the ACRR fuel storage racks with respect to corrosion of the stainless steel. The ACRR fuel storage racks are doubly contingent safe since corrosion alone is not enough to cause criticality. Reduced water density or another contingency would need to be invoked for a criticality.

Neutron absorbers contingency 5b. stainless steel corrodes

See Contingency 5a and Contingency 5a/5b in the next section of this report which deals with the GIF fuel holsters.

Interaction contingency 6a and 6c. extended arrays and stacked racks

The case of placing racks next to each other to form a large three-dimensional array has been examined in contingencies 1a, 2a, 3a, 4a and 4b. Contingencies 4a and 4b used infinite array calculations which demonstrated that extended arrays are criticality safe at normal water density. Even for the unreasonable case of uniformly distributed air voids (i.e., contingency 2a) a double layer 3 by 3 array of stainless steel fuel storage racks is subcritical. The overall size of a rack is 67.5 cm (wide) by 91.5 cm (long) by 61 cm (high). The fuel pins stick up above the top of the rack by about 15 cm so that stacking the racks is not practical without the possibility of damaging the fuel pins. The GIF pool dimensions are 244 cm (8 feet) by ~360 cm (~12 feet). The size of an array of racks is physically limited to ~3 by 3 in a single, horizontal plane (see Figure 3 of GIF pool). The current inventory of uranium bearing elements would fill less than 5 racks. Thus, in order to fill the 3 by 3 by 2 arrays analyzed in contingencies 1a, 2a, and 3a would require twice the current inventory of fuel elements. Based on these observations, placing racks together in a large extended array inside the GIF pool is doubly contingent safe with respect to criticality. There is also the possible interaction of the FSRs with the “holsters” which line the walls of the GIF pool. The GIF holsters and their interaction with the FSRs is considered in great detail in the next section of this report.

Interaction contingency 6b. contents spill from a rack

See Contingency 4c.

GIF holsters

Until now the Fuel Storage Racks (FSRs) have been considered independently of any other fuel storage in the GIF pool. The walls of the GIF pool are lined with fuel storage tubes commonly refered to as holsters. . Due to the physical size of the pool and the presence of the holsters it is necessary to consider that the FRSs will be placed up against the GIF holsters (Bodette, 1996c). The most limiting contingencies for the FSR were 2a Loss of Moderation Control: interstitial moderation in the rack and 6a Loss of Interaction control: extended arrays. Air bubble voids in the racks were demonstrated to lead to a more reactive configuration. Voids combined with an extended array of racks are the relevant contingencies to the current situation of the GIF holsters and the FRSs.

Mass contingency 1a. higher enrichment fuel pins

The issue with higher enrichment fuel pins is the increased fissile material, that is ^{235}U. The UZrH fuel currently stored in the GIF holsters is 20 percent enriched and contains approximately 54 grams (g) of ^{235}U. The BeO/UO2 fuel elements are 35 percent enriched and contain approximately 101 g of ^{235}U. The issue here is replacing the UZrH fuel in the GIF holsters with the BeO/UO2 fuel. Figure 13 shows the results of filling the GIF holsters with UZrH and BeO/UO2 fuel. The GIF holsters were modeled as an infinite planar array. The GIF holsters are subcritical with either fuel element type loading.

Note also in Figure 13 that the GIF holsters are clearly under-moderated since lowering the water density (i.e. decreasing the amount of moderator present) leads to a lower k_{eff}.

Moderation contingency 2a. interstitial moderation in rack

Water is used to isolate the fuel within the rack (i.e. over-moderated) and outside the rack. The bumper on the outside of the Fuel Storage Racks serves to isolate the racks from nearby fissile material by interposing a water barrier/absorber between them. Should the water density decrease due to air voids, for example, k_{eff} increases.

Figure 14 is a composite of results where the water density has been uniformly varied in different arrays of fuel elements. The first two curves of Figure 14, “Infinite planar array” and “3x3x2 array”, respectively, are from Figure 6. The MCNP models for these two curves did not include the stainless steel walls, top, and bottom of the FSR, but did include the stainless steel tubes holding each element. The first two curves do not include the GIF holsters.

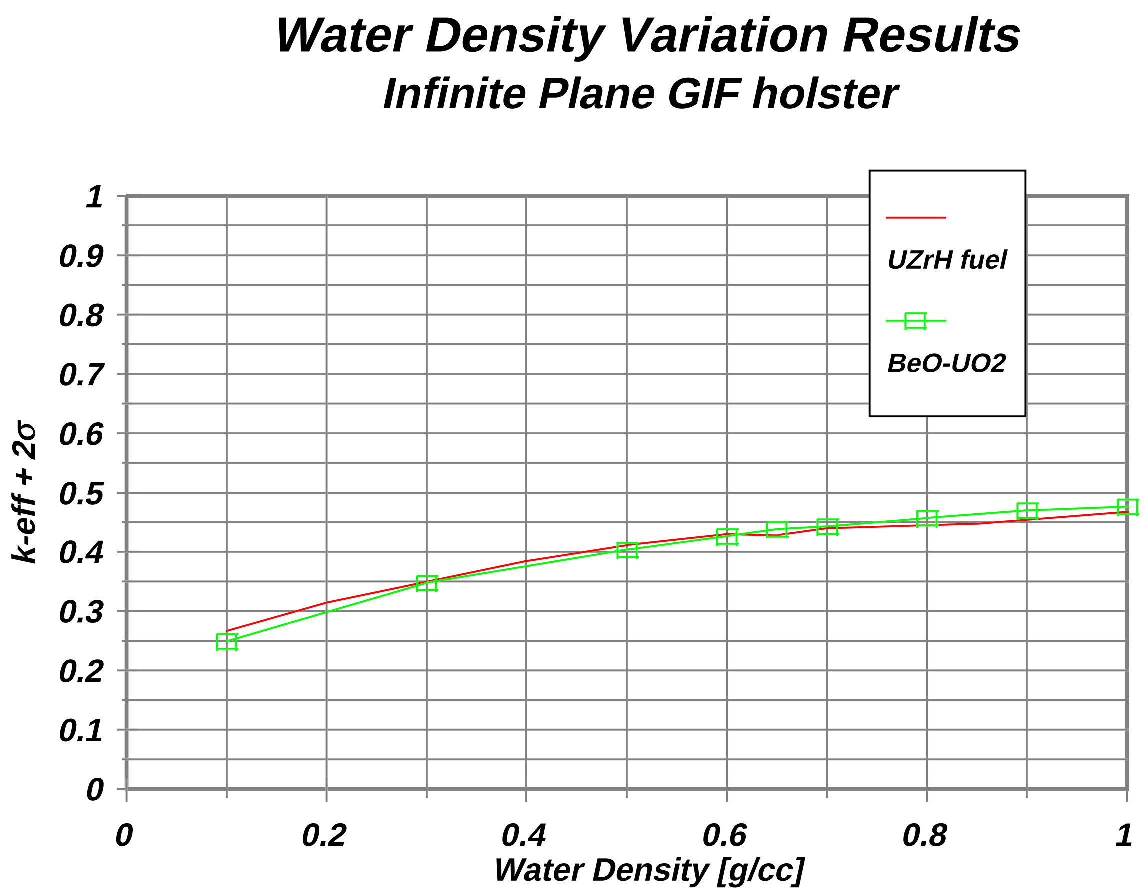
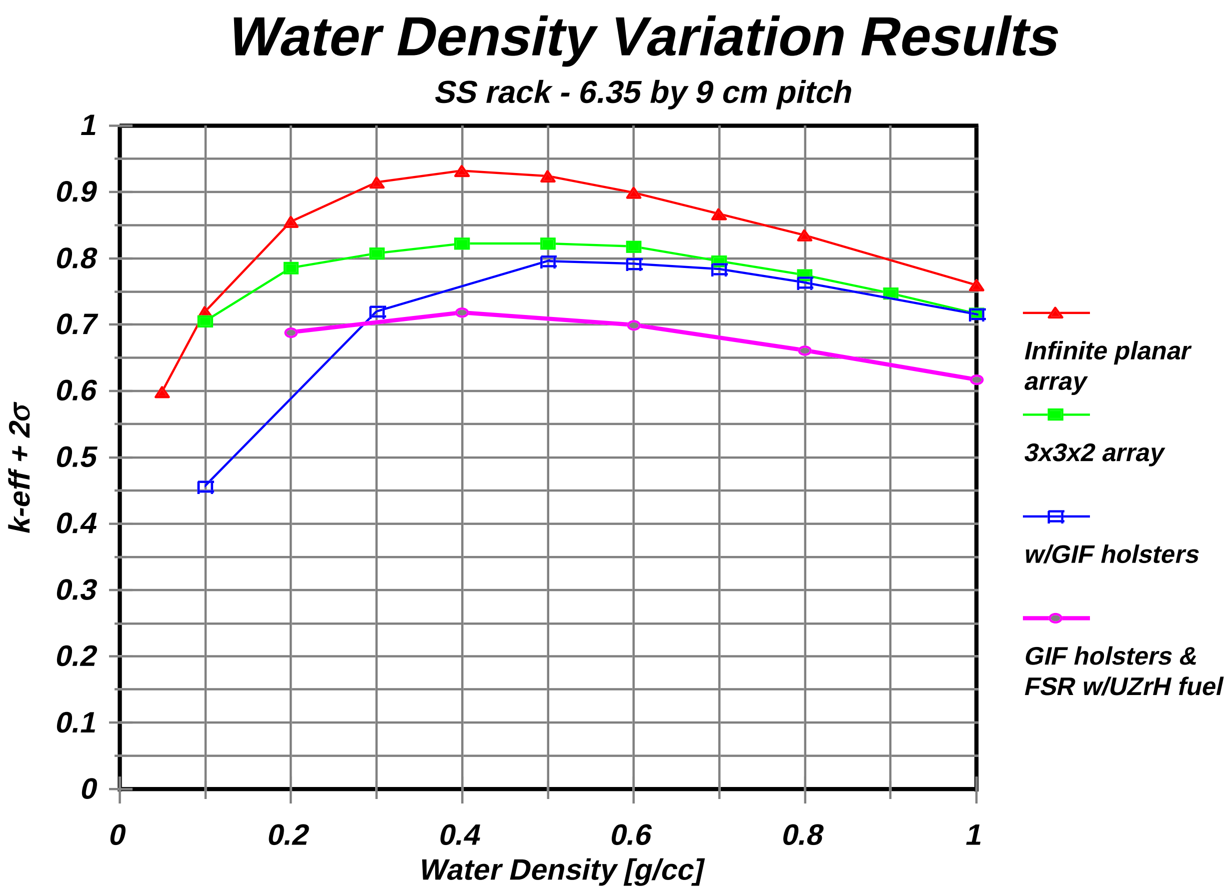


Figure 13. Water density variation results, infinite plane GIF holster.

The third curve of Figure 14 includes the GIF holsters with two FSRs, end-to-end, pushed against the holsters in a corner (see Figure B-4). The MCNP model included the stainless steel walls, top, and bottom of the FSR using an infinitely tall wall around each FSR. Also included is the stainless steel lining the GIF pool. A specular reflection boundary condition runs down the centerline of the pool.

The fourth curve of Figure 14 is an attempt to perform a bounding calculation using an infinite array geometry. The MCNP model includes the GIF holsters with a FSR pushed up against them. The only stainless steel wall of the FSR accounted for is the one directly between the FSR and the GIF holsters. The specular reflection boundary condition specified for the three water bound sides effectively creates an infinitely long, narrow GIF pool. The fourth side, that which has the GIF holsters, is reflected by more than 50 cm of concrete. The top is reflected by 1.3 m of water and the bottom is reflected by 40 cm of concrete below a ¼ inch stainless steel plate.

The physical layout is similar to that depicted in Figure B-8, except that Figure B-8 includes stainless steel plates between the rows of fuel pins which this calculation did not.



Curve 1: Infinite planar array of FSR's with BeO/UO2 fuel and no GIF holsters; Curve 2: A 3 by 3 by 2 high array of FSR's with BeO/UO2 fuel and no GIF holsters; Curve 3: Two FSR's with BeO/UO2 fuel and GIF holsters with UZrH fuel; Curve 4: Infinite array with a FSR up against GIF holster and UZrH fuel in all locations .

Figure 14. Water density variation results, SS rack, 6.35 by 9 cm pitch.

Figure 15 compares the UZrH fuel and the BeO/UO2 fuel for the same bounding geometry (like Figure B-8) as for curve 4 in Figure 14. The effect of the stainless steel tubes around each fuel pin can be appreciated by comparing curves 2 & 3 of Figure 15. The BeO/UO_2 fuel is more reactive than the UZrH fuel. This is expected since the BeO/UO_2 has a higher fissile loading.

Based on the results presented in Figures 14 and 15, uniformly reducing the water density when the FRSs are placed up next to the GIF holsters does not lead to a critical configuration.

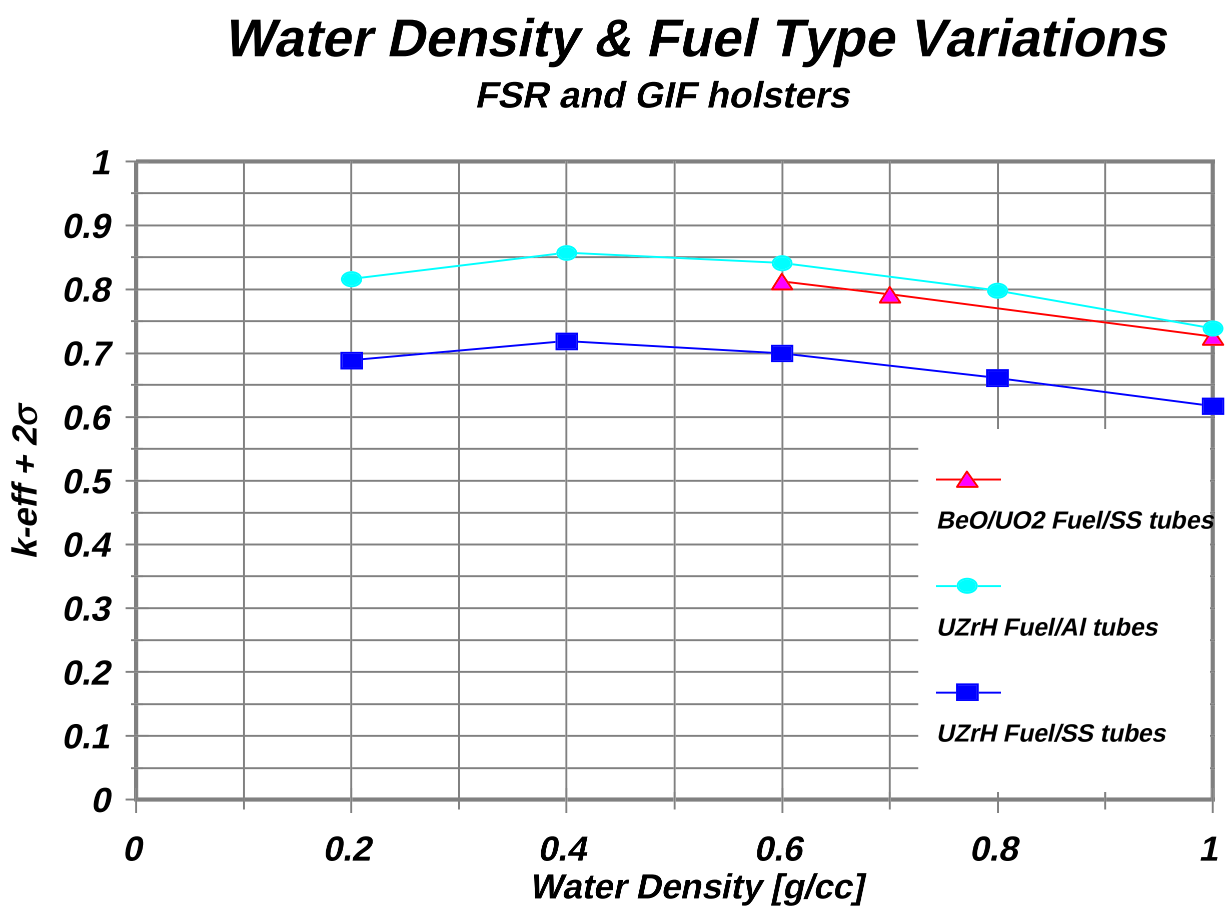


Figure 15. Water density and fuel type variations, FSR and GIF holsters.

Moderation contingency 2b. spacer pins in rack

Placing spacer pins either in the GIF holsters or in the FSR reduces the amount of fissile material present and leads to a safer configuration as already demonstrated in Figure 10.

Reflector contingency 3a. reflector elements placed in rack

See Contingency 2b.

Reflector contingency 3b. rack placed near concrete wall

The presence of the concrete floor and walls has been explicitly included in the models for Contingencies 1a and 2a.

Geometry contingency 4a, 4b, and 4c. rack hole spacing (i.e., pitch) is too small, outside dimensions of rack are too small, and rack is crushed or dropped

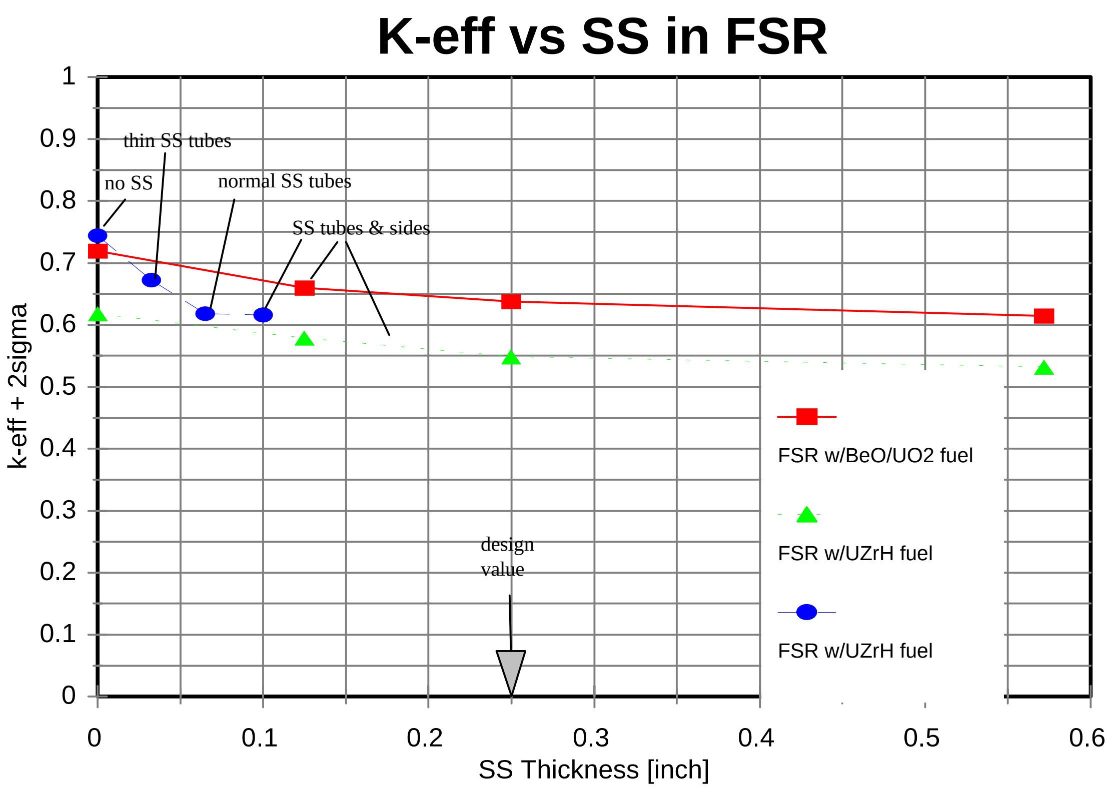
No new issues are raised with respect to these three contingencies because of the GIF holsters. The analysis in the new ACRR fuel storage rack analysis section stands.

Neutron absorbers contingency 5a and 5b. boron leaches out of boral and stainless steel corrodes

No boron has been included in the calculational models used for the analysis presented in this report. The stainless steel materials of construction have been included in the calculational models in order to ensure a subcritical configuration for Contingency 2a when the water density is reduced. Corrosion of the stainless steel does not lead to a critical configuration by itself. It was pointed out in the new ACRR fuel storage rack analysis section that maintaining good water quality and removing potential sources of sulfur or chloride contaminants is important to preventing corrosion.

Per the request of the ACRR ^{99}Mo Project/Reactor Operations Team, the effect of adding stainless steel absorber plates to the new 90-element rack has been considered (Bodette, 1996d). The calculational model used is shown in Figure B-8. The GIF Holsters lining one side were filled with the ACPR UZrH fuel while the 90-element rack is filled with either the ACRR BeO/UO2 fuel or the ACPR UZrH fuel. The three water sides had specular reflection boundary conditions. The concrete wall has more than 50 cm of concrete reflector, the floor incorporates 40 cm of concrete reflector and the top has 130 cm of water reflector. The specular boundary conditions effectively generate an infinitely long, narrow GIF pool. The same fuel element models used in the new ACRR fuel storage rack analysis section were used in this analysis. The stainless steel plates were placed between the rows of fuel elements (see Figure B-8) in the MCNP model as they would be in the actual FSR.

Figure 16 shows the effect on k_{eff} of including the various stainless steel features of the fuel storage racks and of adding stainless steel plates. The third curve starts with just aluminum tubes around each fuel element. The next two points use 0.03 inch and 0.065 inch thick stainless steel tubes around each fuel element in the FSR. The fourth point on the curve includes the stainless steel sides of the FSR as well. The first and second curves look at adding stainless steel plates between the rows of fuel elements in the FSR. These two curves demonstrate that the first quarter-inch of plate accomplishes most of the k_{eff} reduction that is possible. In conclusion, adding the stainless steel plates between the rows of fuel elements in the new stainless steel 90-element ACRR fuel storage rack does improve the subcritical margin. Also, if **all** the stainless steel were lost due to corrosion, the array of FSRs and GIF holsters is still safe (i.e. k_{eff} is less than 0.95).



The MCNP calculation modeled the FSR against the GIF holster as an infinite linear array (see Figure B-8). The first two curves consider the effect of adding different thicknesses of SS absorber plates between the rows of fuel elements in the FSR. The third curve shows the effect of the various SS components in the FSR.

Figure 16. K_{eff} vs. SS in FSR.

Interaction contingency 6a. extended arrays

Placing a FSR up against the GIF holsters effectively increases the size of the FSR. The GIF holsters have a tighter pitch than the Fuel Storage Racks so that placing a FSR up against the GIF holsters is not the same as placing two FRSs together. This contingency has been addressed in Contingency 1a. Figures 14 and 15 show the result of calculations where a FSR is placed next to the GIF holsters. The FSR is loaded with either BeO/UO2 or UZrH fuel and the GIF holsters are loaded with the UZrH fuel. Based on the results shown in Contingencies 2a, 5a/5b (above) and in Contingency 6c (below) placing the Fuel Storage Racks up against the GIF holsters is doubly contingent safe with respect to criticality.

Interaction contingency 6b. contents spill from a rack

No new issues are raised with respect to this contingency because of the GIF holsters. The analysis in the new ACRR fuel storage rack analysis section of this report stands.

Interaction contingency 6c. stacked racks

The new issue here is that the GIF holsters store fuel pins in a two-high configuration while the FSR is designed for a one-high configuration. This contingency was modeled as shown in Figures B-4 and B-6 for the criticality calculations called **2HiGIF***x* in Table 4. The top had 200 cm of water reflector and two sides as well as the bottom had a concrete reflector of at least 50 cm thickness. The short side of water has 60 cm thick water reflector. The long side of water was given a specular boundary condition, effectively producing a mirror image of the array for a total of eight racks in the GIF pool. The highest calculated $k_{eff} + 2\sigma$ for this configuration is 0.7183 which is less than 0.95 Therefore, if the administrative controls are violated and the Fuel Storage Racks are stacked two-high up against the GIF holsters the array is subcritical and doubly contingent safe.

Table 4. FSR stacked two high and placed up against the GIF holsters.

Input Deck	Comments	$k_{eff} + 2\sigma$
2HiGIF1	UZrH in GIF holsters; BeO/UO2 in SS FRSs	0.7176
2HiGIF2	UZrH in GIF holsters; every third position is empty (i.e. water filled); BeO/UO2 in SS FRSs	0.7157
2HiGIF3	BeO/UO2 in GIF holsters; BeO/UO2 in SS FRSs	0.7183

DESIGN FEATURES AND ADMINISTRATIVELY CONTROLLED LIMITS AND REQUIREMENTS

The following limitations shall be incorporating into any operating/handling procedures for the use of the new ACRR fuel storage racks. These limitations were developed through the criticality analysis and are required to meet the double contingency requirements of criticality safety.

Limitations

1. The loading of the ACRR fuel storage rack shall be limited to 90 elements per rack.
2. Only the following elements are approved for storage in the ACRR fuel storage rack:
   - 35 percent enriched UO_2/BeO, ACRR fuel elements with ~101 grams (g) of ^{235}U;
   - 20 percent enriched UZrH, ACPR fuel elements;
   - 35 percent enriched UO_2/BeO, ACRR fuel followed control elements;
   - 35 percent enriched UO_2/BeO, ACRR fueled instrument elements;
   - 93 percent enriched UO_2 Cintichem Targets with less than 33 g ^{235}U;
   - fueled and unfueled control and instrumented elements with < 101 g ^{235}U;
   - nickel reflector elements; and
   - aluminum or void reflector elements.
3. Racks shall not be stacked. Racks can only be arranged in one-high arrays.
4. This analysis is restricted to storage in the GIF pool and a separate analysis is required when using the racks in any location other than the GIF pool (e.g., the ACRR pool).
5. Pneumatic tools or other devices that could potentially introduce air voids into a fuel storage rack are forbidden in the vicinity of the racks.
6. Modified or damaged racks (e.g., severe corrosion, dents, or missing parts) shall not be used without a criticality safety review and approval.
7. A rack shall not be lifted or moved with more than 15 fuel pins in it.

Clarifications

1. Racks which do not contain any fissile material are not bound by the above restrictions.
2. The ACRR fuel storage rack can be used to move up to 15 fuel pins between the ACRR pool and the GIF pool.
3. Elements of all allowed types may be mixed freely within a rack based on criticality safety. However, this is discouraged from a quality assurance tracking stand point since it increases the possibility of snatching the wrong element when loading the core or the fuel ring external cavity (FREC) subcritical assembly of the ACRR.

SUMMARY AND CONCLUSIONS

Criticality safety for the new ACRR fuel storage rack (FSR) depends upon control of several parameters. Each parameter is a physical property whose value affects the nuclear reactivity of the fuel storage rack system. The control of criticality parameters for criticality safety is intended to be mostly through physical limitations of the new fuel storage rack design and construction.

Some limitations or restrictions on use of the FSR for storage operations were developed through the criticality analysis and are required to meet the double contingency requirements of criticality safety. As shown in the analysis, this system will remain subcritical under all credible upset conditions. Administrative controls are necessary for loading, moving, and handling the storage rack as well as for control of operations around it. The administrative controls or limitations must be incorporated into any operating/handling procedures for the use of the new ACRR fuel storage racks.

The most limiting contingencies for the FSR were 2a loss of moderation control: interstitial moderation in the rack and 6a loss of interaction control: extended arrays. Air bubble voids in the racks were demonstrated to lead to a more reactive configuration. The physical construction of the FSR with solid sides and bottom makes the introduction of air bubbles incredible without intentional acts and modifications to the rack. Voids combined with an extended array of racks are the relevant contingencies for use of the FSRs with the GIF holsters in the GIF pool. Due to the physical size of the pool and the presence of the holsters, the FSRs must be placed against the GIF holsters containing fuel elements. Even under the combined effects of Contingencies 2a and 6a (i.e. interstitially moderated and extended arrays) the FSRs and GIF holsters are subcritical as demonstrated in Figure 14.

The new ACRR FSR will go through an approach to subcritical loading of fuel elements to verify the analysis and limitations before fuel storage operations begin.

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Appendix A

Sample MCNP Input and Output

Tables

Table A-1. Sample MCNP input for infinite array, 90-element storage rack.

```
Infinite Array, 90-element storage rack, size sensitivity
c
c       Ed's corrected mass BeO fuel model
c       full new rack, fully submerged
c       6.35cm by 9cm pitch, specular reflection
c
c       ----------
c       cell cards
c       ----------
c
c               fuel lattice            U02/BeO acrr fuel model
c
9       0                 -109    126     -127            u=l     imp:n=l   $ central void
10      1       -3.3447   109     -110    126     -127    u=l     imp:n=l   $ uo2-beo fuel
11      0                 110     -111    126     -127    u=l     imp:n=l   $ void
12      4       -8.4      111     -112    126     -127    u=l     imp:n=l   $ niobium
13      0                 112     -113    126     -127    u=l     imp:n=l   $ void gap
14      7       -2.80     -115            125     -126    u=l     imp:n=l   $ beo plug
15      7       -2.80     -115            127     -128    u=l     imp:n=l   $ beo plug
16      0                 -113    121     -126    #14     u=l     imp:n=l   $ void
17      0                 -113    -122    127     #15     u=l     imp:n=l   $ void
18      3       -8.03     113     -114    121     -122    u=l     imp:n=l   $ ss3O4
19      2       -1.0      -114    122                     u=l     imp:n=l   $ upper water
20      2       -1.0      -114    -121                    u=l     imp:n=l   $ low water
21      2       -1.0      114     -116                    u=l     imp:n=l   $ water
22      8       -2.7      116     -117                    u=l     imp:n=l   $ al tube
23      2       -1.0      117                             u=l     imp:n=l   $ water
c
c               define a rectangular box with approximate
c               size of fuel storage rack
c
I       0                         -301    302     -303    304     -312    311     fill=2  imp:n=l
c
c               define a square pitched lattice to hold fuel elements
c
2       -1.0                      -101    102     -103    104             trcl=(O.O -4.5 0.0)  lat=l
        u=2     imp:n=l   fill  -7:7  -7:7  0:0
        2  2  2  2  2  2  2  2  2  2  2  2  2  2  2
        2  2  2  2  2  2  2  2  2  2  2  2  2  2  2
        2  2  2  2  2  2  2  2  2  2  2  2  2  2  2
        2  2  2  1  1  1  1  1  1  1  1  1  2  2  2
        2  2  2  1  1  1  1  1  1  1  1  1  2  2  2
        2  2  2  1  1  1  1  1  1  1  1  1  2  2  2
        2  2  2  1  1  1  1  1  1  1  1  1  2  2  2
        2  2  2  1  1  1  1  1  1  1  1  1  2  2  2
        2  2  2  1  1  1  1  1  1  1  1  1  2  2  2
        2  2  2  1  1  1  1  1  1  1  1  1  2  2  2
        2  2  2  1  1  1  1  1  1  1  1  1  2  2  2
        2  2  2  1  1  1  1  1  1  1  1  1  2  2  2
        2  2  2  1  1  1  1  1  1  1  1  1  2  2  2
        2  2  2  2  2  2  2  2  2  2  2  2  2  2  2
        2  2  2  2  2  2  2  2  2  2  2  2  2  2  2
c
c       define slightly bigger rectangular box around the rack
c       originally Ed was going to put SS in this region to model
c       actual storage racks.
```

Table A-1. Sample MCNP input for infinite array, 90-element storage rack. (continued)

```
3        2 -1.0     -401 402 -403 404 -412 411
                    (301:-302:303:-304:312:-311)  imp:n=l
c
c        define rest of universe with zero neutron importance
4        0          401:-402:403:-404:412:-411  imp:n=O
c
c        -------------
c        surface cards
c        -------------
c
c        fuel lattice
c
c        fixed
101      px 3,175
102      px -3. 175
c        can vary
c        103                 py 3.5179
c        104                 py -3.5179
103      py         4.5      $ 9cm pitch
104      py         -4.5
c
c        fuel       pins
109      CZ         0.2413
110      CZ         1.684
111      CZ         1.72025
112      CZ         1.77125
113      CZ         1.82225
114      CZ         1.87325
115      CZ         1.487
116      CZ         2.0574
117      CZ         2.2225
c
c        fuel pin vertical dimensions
121      pz         5.08
122      pz         69.22
125      pz         10.085
126      pz         11.99
127      pz         64.24
128      pz         66.145
c
c        storage rack dimensions
c
301      px         29.21
302      px         -29.21
303      py         43.18
304      py         -43.18
311      pz         0
312      pz         71.76
c
c        outer dimensions of storage rack w/specular reflection
*401     px         35.5
*402     px         -35.5
*403     py         49.5
*404     py         -49.5
*411     pz         -2.0
*412     pz         74.0
```

Table A-1. Sample MCNP input for infinite array, 90-element storage rack. (continued)

```
c
c       ---------
c       materials
c       ---------
c       uo2-beo fuel (3.276 g/cc)
c       ml      4009.50c -0.27958   8016.50c -0.52162       92235.50c -6.3958e-2
c               92238.50c -1.2238e-1 92234.50c -4.5605e-4 92236.50c -4.363le-4
c               41093.50c -0.01157
c
c       uo2-beo fuel (3.276 g/cc w/o hole, no nb mixed in, correct u-235)
ml      4009.50c -0.282817      8016.50c -0.527675      92235.50c -6.6309e-2
        92238.50c -1.22309e-1 92234.50c -4.5482e-4 92236.50c -4.3587e-4
c       no nb mixed in      41093.50c -0.01157
c
c       water (I g/cc)
m2      1001.50c 2          8016.50c 1
c
c       ss 304 (7.95 g/cc)
m3      14000.50c -0.0059  24000.50c -0.1853  25055.50c -0.017
        26000.55c -0.6884  28000.50c -0.1034
c
c       niobium (8.4 g/cc)
m4      41093.50c 1
c
c       b4c poison (2.48 g/cc)
c   m5  6000.50c 0.2        5010.50c 0.1592     5011.55c 0.6408
c
c       nickel reflector (8.9 g/cc)
c  m6   28000.50c 1
c
c       beo (2.8 g/cc)
m7      4009.50c 0.5        8016.50c 0.5
c
c       al 6061 (2.7 g/cc)
m8      12000.50c -0.01     13027.50c -0.968    14000.50c -0.006
        24000.50c -0.0035  25055.50c -0.0015  26000.55c -0.007
        29000.50c -0.004
c
c       s(a,b) identifiers
c
mtl     beo.Olt
mt2     lwtr.Olt
mt7     beo.Olt
c
c imp:n 1 16r 0
mode    n
kcode   600 0.9 3 250
ksrc    0 4.2 50 0 22.2 60 19 -22.2 40 0 -31.2 60
print   10 60 100 110
```

Table A-2. Sample MCNP input and output for the new FSR in the corner of the GIF holsters.

```
lmcnp     version 4a     ld=10/01/93                    06/21/96 08:02:57
********************************************************                                          probid      06/21/96 08:02:57
  inp=inpol mctal=mctal0l outp=outpol

                    New FSR w/BeO in corner of GIF; Holsters w/ZrH low water density
          c
          c
          c         ----------
          c         cell cards
          c
          c
          c
          c         define limits to problem space
          1         0               -100:102:-103:106:-107:108 imp:n=O
          2         0               100 -101 104 -106 107 -108 imp:n=l fill=13
          3         0               101 -102 105 -106 107 -108 imp:n=l fill=12
          c
          4         12    -2.37     100 -101 103 -104 107 -108 imp:n=l    $ concrete         corner filler
          c
          5         12    -2.37     101 -102 103 -105 107 -108 imp:n=l    fill=14
          14        2     -0.6      -251 2S2 -2S3 254 trcl=(3.175     4.5  0) lat=l u=12
                                    imp:n=l fill=0:28 0:29 0:0
                                2 7 7 7 7 7 7 7 7 7 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
                                8 1 1 1 1 1 1 1 1 1 5 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
                                8 1 1 1 1 1 1 1 1 1 5 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
                                8 1 1 1 1 1 1 1 1 1 5 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
                                8 1 1 1 1 1 1 1 1 1 5 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
                                8 1 1 1 1 1 1 1 1 1 5 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
                                8 1 1 1 1 1 1 1 1 1 5 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
                                8 1 1 1 1 1 1 1 1 1 5 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
                                8 1 1 1 1 1 1 1 1 1 5 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
                                8 1 1 1 1 1 1 1 1 1 5 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
                                8 1 1 1 1 1 1 1 1 1 5 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
                                2 9 9 9 9 9 9 9 9 9 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
                                2 7 7 7 7 7 7 7 7 7 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
                                8 1 1 1 1 1 1 1 1 1 5 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
                                8 1 1 1 1 1 1 1 1 1 5 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
                                8 1 1 1 1 1 1 1 1 1 5 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
                                8 1 1 1 1 1 1 1 1 1 5 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
                                8 1 1 1 1 1 1 1 1 1 5 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
```

Table A-2. Sample MCNP input and output for the new FSR in the corner of the GIF holsters. (continued)

```
                    8 1 1 1 1 1 1 1 1 1 5 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
                    8 1 1 1 1 1 1 1 1 1 5 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
                    8 1 1 1 1 1 1 1 1 1 5 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
                    8 1 1 1 1 1 1 1 1 1 5 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
                    8 1 1 1 1 1 1 1 1 1 5 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
                    2 9 9 9 9 9 9 9 9 9 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
                    2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
                    2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
                    2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
                    2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
                    2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
                    2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
c
15  2   -0.6    -401   402  -403   404  trcl=(-2.858 2.858 0)  lat=l  u=13 &
                imp:n=l fill=3
c
17  2   -0.6    -411   412  -413   414  trcl=(2.858 -2.858 0)  lat=l  u=14 &
                imp:n=l fill= -2:31 0:0 0:0 10 10 10
                10  10  10  10  10  10  10 10  10  10  &
                10  10  10  10  10   4   4   4   4   4
                 4   4   4   4   4   4   4 10 10  10  10
c
28  2   -0.6           119                  u=2 imp:n=l     $ water
29  3   -7.86          120  -119            u=2 imp:n=l     $ SS pool bottom
30  12  -2.37               -120            u=2 imp:n=l     $ concrete
c
c   FSR SS wall
32  2   -0.6          -160   119            u=8 imp:n=l     $water
33  2   -0.6           161   119            u=8 imp:n=l     $water
34  3   -7.86          120  -119            u=8 imp:n=l     $ SS pool bottom
35  12  -2.37         -120                  u=8 imp:n=l     $concrete
36  3   -7.86          160  -161   119      u=8 imp:n=l     $ SS wall of FSR
c
c
c
c   fuel (acpr- UZRH - 12wt%U (20% enriched) 6.61g/cc)
c
39  10  -6.SO   -209         226    -227    u=3 imp:n=l     $ Zr
40  9   -6.112   209  -210   226    -227    u=3 imp:n=l     $ UZRH fuel
41  11  -1.6    -210         225    -226    u=3 imp:n=l     $ low c plug
```

Table A-2. Sample MCNP input and output for the new FSR in the corner of the GIF holsters. (continued)

```
42  11  -1.6   -210         227   -228     u=3 irnp:n=l     $ up c plug
43  0          -210         228   -229     u=3 imp:n=l      $ up void
44  0           210  -211   225   -229     u=3 imp:n=l      $ void gap
45  3   -7.86  -211         224   -225     u=3 imp:n=l      $ low ss3O4
46  3   -7.86   -21         229   -230     u=3 imp:n=l      $ up ss3O4
47  3   -7.86   211  -212   224   -230     u=3 iinp:n=l     $ ss3O4 clad
48  3   -7.86  -213         230   -234     u=3 imp:n=l      $ SS Tri-flute
49  2   -0.6    213  -212   230   -234     u=3 iinp:n=l     $ upper water
50  2   -0.6   -212         119   -224     u=3 imp:n=l      $ low water
51  2   -0.6    212  -116   119            u=3 imp:n=l      $ water
52  8   -2.7    116  -117   119            u=3 iinp:n=l     $ al tube
c
53  2   -0.6    117   119   152                       u=3 imp:n=l     $ water
54  3   -7.86         120   153   -152                u=3 imp:n=l     $SS pool liner
55  12  -2.37                     -153                u=3 imp:n=l     $wall concrete
c
56  3   -7.86   120  -119   152                       u=3 imp:n=l     $SS pool bottom
57  12  -2.37        -120   153                       u=3 imp:n=l     $lower concrete
c
60  10  -6.50  -209   236  -237            u=3 imp:n=l      $ Zr
61  9   -6.112  209  -210   236   -237     u=3 imp:n=l      $ UZRH fuel
62  11  -1.6   -210         235   -236     u=3 imp:n=l      $ low c plug
63  11  -1.6   -210         237   -238     u=3 imp:n=l      $ up c plug
64  0          -210         238   -239     u=3 imp:n=l      $ up void
65  0           210  -211   235   -239     u=3 imp:n=l      $ void gap
66  3   -7.86  -211         234   -235     u=3 imp:n=l      $ low ss3O4
67  3   -7.86  -211         239   -240     u=3 imp:n=l      $ up ss3O4
68  3   -7.86   211  -212   234   -240     u=3 imp:n=l      $ ss3O4 clad
69  2   -0.6   -212         240            u=3 imp:n=l      $ upper water
c
c   empty GIF holsters
80  2   -0.6          119   154                       u=4 imp:n=l     $ water
81  3   -7.86         120   155   -154                u=4 imp:n=l     $SS pool liner
82  12  -2.37              -155                       u=4 imp:n=l     $wall concrete
c
83  3   -7.86   120  -119   154                       u=4 imp:n=l     $SS pool bottom
84  12  -2.37        -120   155                       u=4 imp:n=l     $lower concrete
c
c   SS  sides to FSR
100 2   -0.6   -162   119                  u=7 iinp:n=l     $water
```

Table A-2. Sample MCNP input and output for the new FSR in the corner of the GIF holsters. (continued)

```
101 2   -0.6    163   119                  u=7 imp:n=l      $water
102 3   -7.86   120  -119                  u=7 imp:n=l      $ SS pool bottom
```

```
103  12   -2.37            -120                       u=7 imp:n=l          $concrete
104  3    -7.86     162    -163     119               u=7 imp:n=l          $ SS wall of FSR
c
110  2    -0.6      166     119                       u=9 imp:n=l          $water
111  2    -0.6     -167     119                       u=9 imp:n=l          $water
112  3    -7.86     120    -119                       u=9 imp:n=l          $ SS pool bottom
113  12   -2.37            -120                       u=9 imp:n=l          $concrete
114  3    -7.86    -166     167     119               u=9 imp:n=l          $ SS wall of FSR
c
120  2    -0.6     -164     119                       u=5 imp:n=l          $water
121  2    -0.6      165     119                       u=5 imp:n=l          $water
122  3    -7.86     120    -119                       u=5 imp:n=l          $ SS pool bottom
123  12   -2.37            -120                       u=5 imp:n=l          $concrete
124  3    -7.86     164    -165     119               u=5 imp:n=l          $ SS wall of FSR
c
c    fuel (acpr -UZRH - 12wt%U (20% enriched) 6.61g/cc)
c
127  10   -6.50    -209             226      -227     u=10 imp:n=l         $ Zr
128  9    -6.112    209    -210     226      -227     u=10 imp:n=l         $ UZRH fuel
129  11   -1.6     -210             225      -226     u=10 imp:n=l         $ low c plug
130  11   -1.6     -210             227      -228     u=10 imp:n=l         $ up c plug
131  0             -210             228      -229     u=10 imp:n=l         $ up void
132  0              210    -211     225      -229     u=10 imp:n=l         $ void gap
133  3    -7.86    -211             224      -225     u=10 imp:n=l         $ low ss3O4
134  3    -7.86    -211             229      -230     u=10 imp:n=l         $ up ss3O4
135  3    -7.86     211    -212     224      -230     u=10 imp:n=l         $ ss3O4 clad
136  3    -7.86    -213             230      -234     u=10 imp:n=l         $ SS Tri-flute
137  2    -0.6      213    -212     230      -234     u=10 imp:n=l         $ upper water
138  2    -0.6     -212             119      -224     u=10 imp:n=l         $ low water
139  2    -0.6      212    -116     119               u=10 imp:n=l         $ water
140  8    -2.7      116    -117     119               u=10 imp:n=l         $ al tube
c
153  2    -0.6      117     119     154               u=10 imp:n=l         $ water
154  3    -7.86             120     155      -154     u=10 iinp:n=l        $SS pool liner
155  12   -2.37                              -155     u=10 imp:n=l         $wall concrete
c
156  3    -7.86     120    -119     154               u=10 imp:n=l         $SS pool bottom
157  12   -2.37            -120     155               u=10 imp:n=l         $lower concrete
```

Table A-2. Sample MCNP input and output for the new FSR in the corner of the GIF holsters. (continued)

```
c
160  10   -6.50    -209             236      -237     u=10 imp:n=l         $ Zr
161  9    -6.112    209    -210     236      -237     u=10 imp:n=l         $ UZRH fuel
162  11   -1.6     -210             235      -236     u=10 imp:n=l         $ low c plug
```

```
163  11   -1.6     -210            237     -238        u=10 imp:n=l        $ up c plug
164  0             -210            238     -239        u=10 imp:n=l        $ up void
165  0              210    -211    235     -239        u=10 imp:n=l        $ void gap
166  3    -7.86    -211            234     -235        u=10 imp:n=l        $ low ss3O4
167  3    -7.86    -211            239     -240        u=10 imp:n=l        $ up ss3O4
168  3    7.86      211    -212    234     -240        u=10 imp:n=l        $ ss3O4 clad
169  2    -0.6     -212            240                 u=10 imp:n=l        $ upper water
c
c
c      fuel (acrr) U02-BeO
c
209  0             -109     126    -127                u=l imp:n=l
210  1    -3.3447  109     -110    126     -127        u=l imp:n=l         $ uo2-beo fuel
211  0              110    -111    126     -127        u=l imp:n=l         $ void
212  4    -8.4      111    -112    126     -127        u=l iinp:n=l        $ niobium
213  0              112    -113    126     -127        u=l imp:n=l         $ void gap
214  7    -2.80    -115            125     -126        u=l imp:n=l         $ beo plug
215  7    -2.80    -115            127     -128        u=l imp:n=l         $ beo plug
216  3    -7.86    -113     121    -126    #214        u=l irrip:n=l       $ ss
217  3    -7.86    -113    -122    127     #21S        u=l imp:n=l         $ ss
218  3    -7.86     113    -114    121     -122        u=l  imp:n=l        $ ss3O4
219  2    -0.6     -114     122                        u=l  imp:n=l        $ upper water
220  2    -0.6     -114    -121             119        u=l  imp:n=l        $ low water
221  2    -0.6      114    -116    -129     119        u=l imp:n=l         $ water
222  8    -2.7      116    -117             119        u=l imp:n=l         $ al tube
223  2    -0.6      117            -129     119        u=l imp:n=l         $ water
224  2    -0.6      117             129                u=l imp:n=l         $ above water
225  2    -0.6      114    -116     129                u=l irnp:n=l        $ above water
226  3     -7.86    120    -119                        u=l imp:n=l         $ SS pool bottom
227  12   -2.37    -120                                u=l imp:n=l         $ concrete
c
c      -----------end of cell cards----------

c
c      -------------
c      surface cards
```

Table A-2. Sample MCNP input and output for the new FSR in the corner of the GIF holsters. (continued)

```
c      -------------
c      boxes around FSR and GIF holsters
100  px -60      $ North
101  px 00.5
*102 px 122.  $ South
103  py -60.0   $ West
```

```
104  py -5.6
105  py 0.05
106  py 269.5    $ East
107  pz -40.
108  pz 350.0
c
c
109  cz 0.2413          $ Beo fuel
110  cz 1.684
111  cz 1.7202S
112  cz 1.77125
113  cz 1.82225
114  cz 1.8732S
115  cz 1.487
116  cz 2.0574
117  cz 2.2225
c
119  pz 0               $ bottom of pool
120  pz -0.635          $ Ss pool liner
c
121 pz 5.08
122  pz 69.22
125  pz 10.085
126  pz 11.99
127  pz 64.24
128  pz 66.145
129  pz 50.0
c
152  px -5.0            $ SS GIF pool wall liner
153  px -5.635          $ concrete 1/4 inch thick
154  py -5.0
155  py -5.635
c
160  px 2.54          $ for SS on FSR
```

Table A-2. Sample MCNP input and output for the new FSR in the corner of the GIF holsters. (continued)

```
161  px 2.86
162  py 4.182
163  py 4.7
164  px -2.86
165  px -2.54
166  py -4.182
167  py -4.9
c
```

```
209  cz 0.3175           $ UZRH fuel
210  cz 1.779
211  cz 1.822
212  cz 1.873
213  cz 0.75             $ SS in Tri-flutes
c
c      224  pz 0.0
c      225  pz 1.28
c      226  pz 10.18
c      227  pz 48.28
c      228  pz 57.18
c      229  pz 57.815
c      230  pz 59.085
c
224  pz 6.99             $ low SS
225  pz 8.27           $ low graphite plug
226  pz 17.17          $start of fuel
227  pz 55.27          $end of fuel
228  pz 64.17          $top of graphite plug
229  pz 64.805            $ gap
230  pz 66.075         $top of SS
c
234  pz 80.37            $low SS 6.99+73.38 (= overall rod length w/tri-flutes)
235  pz 81.65            $low graphite
236  pz 90.55            $start of fuel
237  pz 128.65           $end of fuel
238  pz 137.55           $top of graphite
239 pz 138.18S              $gap
240 pz 139.455           $top of SS plug
c
c      fuel storage rack lattice
c
```

Table A-2. Sample MCNP input and output for the new FSR in the corner of the GIF holsters. (continued)

```
251  px 3.175
252  px -3.175
253  py 4.5
254  py -4.5
c
c      GIF pool holster lattice
c
401  px 122              $ pool center line
402  px -149.5           $ thick concrete behind SS pool liner
403  py 2.86              $ pitch
```

```
287-        404  py -2.86
288-        c
289-        411  px 2.86             $ pitch
290-        412  px -2.86
291-        413  py 120              $ pool center line
292-        414  py -60              $ thick concrete behind SS pool liner
293-        c
294-        c
295-
296-        c     ---------
297-        c     materials
298-        c     ---------
299-        c
300-        c     uo2-beo fuel (3.276 g/cc w/o hole, no nb mixed in, correct u-23S)
301-        c
302-        ml    4009.50c -0.282817      8016.50c -0.527675      92235.50c -6.6309e-2
303-              92238.50c -1.22309e-1   92234.50c -4.5482e-4    92236.50c -4.3587e-4
304-        c     no nb mixed in41093.50c -0.01157
305-        c
306-        c     water (1 g/cc)
307-        m2    1001.50c   2        8016.50c   1
308-        c     ss 304 (7.95 g/cc)
309-        m3    14000.50c -0.0059       24000.504c -0.1853      25055.50c -0.017
310-              26000.5Sc -0.688428000.50c -0.1034
311-        c
312-        c     niobium (8.4 g/cc)
313-        m4    41093.50c 1
314-        c
315-        c     b4c poison (2.48 g/cc)
316-        c m5       6000.50c 0.2       5010.50c 0.1592         5011.55c 0.6408
```

Table A-2. Sample MCNP input and output for the new FSR in the corner of the GIF holsters. (continued)

```
317-        c
318-        c     nickel reflector (8.9 g/cc)
319-        c m6       28000.50c 1
320-        c
321-        c     beo (2.8 g/cc)
322-        m7         4009.SOc 0.5       8016.50c 0.5
323-        c
324-        c     al 6061 (2-7 g/cc)
325-        m8         12000.50c-0.01     13027.50c -0.968        14000.50c -0.006
326-                   24000.50c-0.0035   25055.50c -0.0015       26000.55c -0.007
327-                   29000.50c -0.004
328-        c     UZrH-1.625 U=12% 20%enriched
```

```
329-   m9      40000.50c-0.86448      1001.50c -0.01552
330-           92238.50c-0.096        92235.50c -0.024
331-   c    Zr
332-   m10     40000.50c-1.0
333-   c    C
334-   m11     6000.50c-1.0
335-   c    s(a,b) identifiers
336-   c
337-   c    Concrete
338-   m12     8016.50c -1.103        14000.SOc -0.2815      13027.50c -0.033
339-           26000.55c -0.0183      20000.50c -0.7712      6000.50c -0.0761
340-           11023.50c -0.0116      19000.50c -0.0079      1001.50c -0.025
341-           1002.55c -3.75e-6      12000.50c -0.0426
342-   c
343-   mtl     beo.0lt
344-   mt2     lwtr.0lt
345-   mt7     beo.0lt
346-   mt9     h/zr.0lt
347-   mt11    grph.0lt
348-   c
349-   mt12    lwtr.0lt
350-   c
351-   mode    n
352-   kcode   400      0.8      3    300
353-   ksrc      9.2   31.2     50   34.7   22.5    50   53.7   31.2    55   34.7   49.S    50
354-             9.2   85.S     40    9.2  166.5    50   34.7  175.5    60   34.7  148.5    70
355-            53.7  130.5     40   -2.6   65.5    50   -2.6  163.0    60
356-   print   10        60    100    110
```

Table A-2. Sample MCNP input and output for the new FSR in the corner of the GIF holsters. (continued)

```
357-   prdmp   0         0      0      4
 total fission nubar data are being used.

 warning.   2 of the materials had unnormalized fractions.
1cells                                                                        print table 60
```

	cell	mat	atom density	gram density	volume	mass	pieces	neutron importance
1	1	0	0.00000E+00	0.00000E+00	0.00000E+00	0.00000E+00	0	0.000E+00
2	2	0	0.00000E+00	0.00000E+00	6.44270E+06	0.00000E+00	0	1.000E+00
3	3	0	0.00000E+00	0.00000E+00	1.28152E+07	0.00000E+00	0	1.000E+00
4	4	125	8.03142E-02	2.37000E+00	1.27402E+06	3.01943E+06	0	1.000E+00
5	5	125	8.03142E-02	2.37000E+00	2.85601E+06	6.76874E+06	0	1.000E+00

6	14	25	6.01851E-02	6.00000E-01	0.00000E+00	0.00000E+00	0	1.000E+00
7	15	25	6.01851E-02	6.00000E-01	0.00000E+00	0.00000E+00	0	1.000E+00
8	17	25	6.018SlE-02	6.00000E-01	0.00000E+00	0.00000E+00	0	1.000E+00
9	28	25	6.01851E-02	6.00000E-01	0.00000E+00	0.00000E+00	0	1.000E+00
10	29	3	8.60140E-02	7.86000E+00	0.00000E+00	0.00000E+00	0	1.000E+00
11	30	125	8.03142E-02	2.37000E+00	0.00000E+00	0.00000E+00	0	1.000E+00
12	32	25	6.01851E-02	6.00000E-01	0.00000E+00	0.00000E+00	0	1.000E+00
13	33	25	6.01851E-02	6.00000E-01	0.00000E+00	0.00000E+00	0	1.000E+00
14	34	3	8.60140E-02	7.86000E+00	0.00000E+00	0.00000E+00	0	1.000E+00
15	35	125	8.03142E-02	2.37000E+00	0.00000E+00	0.00000E+00	0	1.000E+00
16	36	3	8.60140E-02	7.86000E+00	0.00000E+00	0.00000E+00	0	1.000E+00
17	39	10	4.29091E-02	6.50000E+00	1.20660E+Ol	7.84288E+Ol	1	1.000E+00
18	40	95	9.34205E-02	6.11200E+00	3.66749E+02	2.24157E+03	1	1.000E+00
19	41	115	8.02201E-02	1.60000E+00	8.84895E+Ol	1.41583E+02	1	1.000E+00
20	42	115	8.02201E-02	1.60000E+00	8.84895E+Ol	1.41583E+02	1	1.000E+00
21	43	0	0.00000E+00	0.00000E+00	6.31358E+00	0.00000E+00	1	1.000E+00
22	44	0	0.00000E+00	0.00000E+00	2.75017E+Ol	0.00000E+00	1	1.000E+00
23	45	3	8.60140E-02	7.86000E+00	1.33492E+Ol	1.0492SE+02	1	1.000E+00
24	46	3	8.60140E-02	7.86000E+00	1.32450E+Ol	1.04105E+02	1	1.000E+00
25	47	3	8.60140E-02	7.86000E+00	3.49793E+Ol	2.74938E+02	1	1.000E+00
26	48	3	8.60140E-02	7.86000E+00	2.52614E+Ol	1.98554E+02	1	1.000E+00
27	49	25	6.01851E-02	6.00000E-01	1.32285E+02	7.93713E+Ol	1	1.000E+00
28	50	25	6.018SlE-02	6.00000E-01	7.70376E+Ol	4.62225E+Ol	1	1.000E+00
29	51	25	6.018SlE-02	6.00000E-01	0.00000E+00	0.00000E+00	0	1.000E+00
30	52	8	5.98096E-02	2.70000E+00	0.00000E+00	0.00000E+00	0	1.000E+00
31	53	25	6.018SlE-02	6.00000E-01	0.00000E+00	0.00000E+00	0	1.000E+00

Table A-2. Sample MCNP input and output for the new FSR in the corner of the GIF holsters. (continued)

32	54	3	8.60140E-02	7.86000E+00	0.00000E+00	0.00000E+00	0	1.000E+00
33	55	125	8.03142E-02	2.37000E+00	0.00000E+00	0.00000E+00	0	1.000E+00
34	56	3	8.60140E-02	7.86000E+00	0.00000E+00	0.00000E+00	0	1.000E+00
35	57	125	8.03142E-02	2.37000E+00	0.00000E+00	0.00000E+00	0	1.000E+00
36	60	10	4.29091E-02	6.50000E+00	1.20660E+Ol	7.84288E+Ol	1	1.000E+00
37	61	95	9.3420SE-02	6.11200E+00	3.66749E+02	2.24157E+03	1	1.000E+00
38	62	115	8.02201E-02	1.60000E+00	8.84895E+Ol	1.41583E+02	1	1.000E+00
39	63	115	8.02201E-02	1.60000E+00	8.84895E+Ol	1.41583E+02	1	1.000E+00
40	64	0	0.00000E+00	0.00000E+00	6.31358E+00	0.00000E+00	1	1.000E+00
41	65	0	0.00000E+00	0.00000E+00	2.7SO17E+Ol	0.00000E+00	1	1.000E+00
42	66	3	8.60140E-02	7.86000E+00	1.33492E+Ol	1.0492SE+02	1	1.000E+00
43	67	3	8.60140E-02	7.86000E+00	1.32450E+Ol	1.04105E+02	1	1.000E+00
44	68	3	8.60140E-02	7.86000E+00	3.49793E+Ol	2.74938E+02	1	1.000E+00
45	69	25	6.01851E-02	6.00000E-01	0.00000E+00	0.00000E+00	0	1.000E+00
46	80	25	6.01851E-02	6.00000E-01	0.00000E+00	0.00000E+00	0	1.000E+00
47	81	3	8.60140E-02	7.86000E+00	0.00000E+00	0.00000E+00	0	1.000E+00

48	82	125	8.03142E-02	2.37000E+00	0.00000E+00	0.00000E+00	0	1.000E+00
49	83	3	8.60140E-02	7.86000E+00	0.00000E+00	0.00000E+00	0	1.000E+00
50	84	125	8.03142E-02	2.37000E+00	0.00000E+00	0.00000E+00	0	1.000E+00
51	100	25	6.01851E-02	6.00000E-01	0.00000E+00	0.00000E+00	0	1.000E+00
52	101	25	6.01851E-02	6.00000E-01	0.00000E+00	0.00000E+00	0	1.000E+00
53	102	3	8.60140E-02	7.86000E+00	0.00000E+00	0.00000E+00	0	1.000E+00
54	103	125	8.03142E-02	2.37000E+00	0.00000E+00	0.00000E+00	0	1.000E+00
55	104	3	8.60140E-02	7.86000E+00	0.00000E+00	0.00000E+00	0	1.000E+00
56	110	25	6.01851E-02	6.00000E-01	0.00000E+00	0.00000E+00	0	1.000E+00
57	111	25	6.01851E-02	6.00000E-01	0.00000E+00	0.00000E+00	0	1.000E+00
58	112	3	8.60140E-02	7.86000E+00	0.00000E+00	0.00000E+00	0	1.000E+00
59	113	125	8.03142E-02	2.37000E+00	0.00000E+00	0.00000E+00	0	1.000E+00
60	114	3	8.60140E-02	7.86000E+00	0.00000E+00	0.00000E+00	0	1.000E+00
61	120	25	6.01851E-02	6.00000E-01	0.00000E+00	0.00000E+00	0	1.000E+00
62	121	25	6.01851E-02	6.00000E-01	0.00000E+00	0.00000E+00	0	1.000E+00
63	122	3	8.60140E-02	7.86000E+00	0.00000E+00	0.00000E+00	0	1.000E+00
64	123	125	8.03142E-02	2.37000E+00	0.00000E+00	0.00000E+00	0	1.000E+00
65	124	3	8.60140E-02	7.86000E+00	0.00000E+00	0.00000E+00	0	1.000E+00
66	127	10	4.29091E-02	6.50000E+00	1.20660E+Ol	7.84288E+Ol	1	1.000E+00
67	128	95	9.34205E-02	6.11200E+00	3.66749E+02	2.24157E+03	1	1.000E+00
68	129	115	8.02201E-02	1.60000E+00	8.84895E+Ol	1.41583E+02	1	1.000E+00
69	130	115	8.02201E-02	1.60000E+00	8.84895E+Ol	1.41583E+02	1	1.000E+00
70	131	0	0.00000E+00	0.00000E+00	6.31358E+00	0.00000E+00	1	1.000E+00
71	132	0	0.00000E+00	0.00000E+00	2.75017E+Ol	0.00000E+00	1	1.000E+00

Table A-2. Sample MCNP input and output for the new FSR in the corner of the GIF holsters. (continued)

72	133	3	8.60140E-02	7.86000E+00	1.33492E+Ol	1.04925E+02	1	1.000E+00
73	134	3	8.60140E-02	7.86000E+00	1.324SOE+Ol	1.04105E+02	1	1.000E+00
74	135	3	8.60140E-02	7.86000E+00	3.49793E+Ol	2.74938E+02	1	1.000E+00
75	136	3	8.60140E-02	7.86000E+00	2.52614E+Ol	1.985S4E+02	1	1.000E+00
76	137	25	6.01851E-02	6.00000E-01	1.32285E+02	7.93713E+Ol	1	1.000E+00
77	138	25	6.018SlE-02	6.00000E-01	7.70376E+Ol	4.62225E+Ol	1	1.000E+00
78	139	25	6.01851E-02	6.00000E-01	0.00000E+00	0.00000E+00	0	1.000E+00
79	140	8	S.98096E-02	2.70000E+00	0.00000E+00	0.00000E+00	0	1.000E+00
80	153	25	6.01851E-02	6.00000E-01	0.00000E+00	0.00000E+00	0	1.000E+00
81	154	3	8.60140E-02	7.86000E+00	0.00000E+00	0.00000E+00	0	1.000E+00
82	155	125	8.03142E-02	2.37000E+00	0.00000E+00	0.00000E+00	0	1.000E+00
83	156	3	8.60140E-02	7.86000E+00	0.00000E+00	0.00000E+00	0	1.000E+00
84	157	125	8.03142E-02	2.37000E+00	0.00000E+00	0.00000E+00	0	1.000E+00
85	160	10	4.29091E-02	6.00000E-01	1.20660E+Ol	7.84288E+Ol	1	1.000E+00
86	161	95	9.34205E-02	6.11200E+00	3.66749E+02	2.24157E+03	1	1.000E+00
87	162	115	8.02201E-02	1.60000E+00	8.84895E+Ol	1.41583E+02	1	1.000E+00
88	163	115	8.02201E-02	1.60000E+00	8.84895E+Ol	1.41583E+02	1	1.000E+00
89	164	0	0.00000E+00	0.00000E+00	6.31358E+00	0.00000E+00	1	1.000E+00

90	165	0	0.00000E+00	0.00000E+00	2.75017E+Ol	0.00000E+00	1	1.000E+00
91	166	3	8.60140E-02	7.86000E+00	1.33492E+Ol	1.04925E+02	1	1.000E+00
92	167	3	8.60140E-02	7.86000E+00	1.32450E+Ol	1.04105E+02	1	1.000E+00
93	168	3	8.60140E-02	7.86000E+00	3.49793E+Ol	2.74938E+02	1	1.000E+00
94	169	25	6.01851E-02	6.00000E-01	0.00000E+00	0.00000E+00	0	1.000E+00
95	209	0	0.00000E+00	0.00000E+00	9.55764E+00	0.00000E+00	1	1.000E+00
96	210	15	1.31268E-01	3.34470E+00	4.55943E+02	1.52499E+03	1	1.000E+00
97	211	0	0.00000E+00	0.00000E+00	2.02566E+Ol	0.00000E+00	1	1.000E+00
98	212	4	5.44475E-02	8.40000E+00	2.92293E+Ol	2.4S526E+02	1	1.000E+00
99	213	0	0.00000E+00	0.00000E+00	3.00832E+Ol	0.00000E+00	1	1.000E+00
100	214	75	1.34855E-01	2.80000E+00	1.32333E+Ol	3.70531E+Ol	1	1.000E+00
101	215	75	1.3485SE-01	2.80000E+00	1.32333E+Ol	3.7OS31E+Ol	1	1.000E+00
102	216	3	8.60140E-02	7.86000E+00	5.88Sl6E+Ol	4.62573E+02	1	1.000E+00
103	217	3	8.60140E-02	7.86000E+00	3.87179E+Ol	3.04323E+02	1	1.000E+00
104	218	3	8.60140E-02	7.86000E+00	3.79771E+Ol	2.98500E+02	1	1.000E+00
105	219	25	6.01851E-02	6.00000E-01	0.00000E+00	0.00000E+00	0	1.000E+00
106	220	25	6.01851E-02	6.00000E-01	5.60022E+Ol	3.36013E+Ol	1	1.000E+00
107	221	25	6.01851E-02	6.00000E-01	1.13699E+02	6.82193E+Ol	1	1.000E+00
108	222	8	5.98096E-02	2.70000E+00	0.00000E+00	0.00000E+00	0	1.000E+00
109	223	25	6.01851E-02	6.00000E-01	0.00000E+00	0.00000E+00	0	1.000E+00
110	224	25	6.01851E-02	6.00000E-01	0.00000E+00	0.00000E+00	0	1.000E+00
111	225	25	6.01851E-02	6.00000E-01	0.00000E+00	0.00000E+00	0	1.000E+00

Table A-2. Sample MCNP input and output for the new FSR in the corner of the GIF holsters. (continued)

112	226	3	8.60140E-02	7.86000E+00	0.00000E+00	0.00000E+00	0	1.000E+00
113	227	125	8.03142E-02	2.37000E+00	0.00000E+00	0.00000E+00	0	1.000E+00
total					2.33919E+07	9.80418E+06		

1 warning message so far.

1cross-sectiontables print table 100

table length

tables from file rmccsl

1001.50c	1153	njoy	(1301)	79/07/31.
4009.50c	6717	njoy	(1304)	79/06/07.
6000.50c	16126	njoy	(1306)	79/07/31.
8016.50c	23669	njoy	(1276)	05/14/81
13027.50c	22891	njoy	(1313)	79/09/08.
24000.50c	89104	njoy	(1324)	79/06/21.
26000.55c	84136	njoy	(260)	10/21/82
28000.50c	82267	njoy	(1328)	79/06/21.

```
    29000.50c   22473   njoy                                              ( 1329)      02/05/80
    92235.50c   44188   njoy                               total nu       ( 1395)      79/09/12.
    92238.50c   66440   njoy                               total nu       ( 1398)      79/09/13.

                          tables from file testlibl

     1002.55c    4102   njoy                                              (  120)      04/26/82
      grph.01t  16572   graphite at 300 degrees kelvin              6000    6012      009/08/86
      lwtr.01t  10193   hydrogen in light water at 300 degrees kelvin  1001  0        010/22/85

                          tables from file endfspi

    11023.50c   36270   njoy                                              ( 1311)      79/06/21.
    14000.50c   48275   njoy                                              ( 1314)      79/06/21.
    40000.50c   35842   njoy                                              ( 1340)      79/07/31.
    41093.50c   72673   njoy                                              ( 1189)      79/08/02.

 warning. nubar of     92234.50c may be either prompt or total.
   92234.50c     76999   njoy                                             ( 1394)      79/10/17.
```

Table A-2. Sample MCNP input and output for the new FSR in the corner of the GIF holsters. (continued)

```
 warning.       nubar of     92236.50c may be either prompt or total.
   92236.50c     119238   njoy                                            ( 1396)      79/08/30.

                          tables from file endf5ul

   12000.50c    39283   njoy                                              ( 1312)      79/08/30.
   19000.50c     9766   njoy                                              ( 1150)      79/10/29.
   20000.50c    26104   njoy                                              ( 1320)      79/06/22.
   25055.50c    60097   njoy                                              ( 1325)      79/06/21.

                          tables from file tmccsl

   beo.01t          16262 beryllium oxide at 300 degrees kelvin           4009 8016    009/08/86
   h/zr.01t         11544 hydrogen in zirconium hydride at 300 degrees kelvin  1001  0  010/22/85

 total              1042384

warning. neutron energy cutoff is below some cross-section tables.
1decimal words of dynamically allocated storage

      general                        159662
      tallies                             0
```

bank	12403
cross sections	1042384
total	1214449

****

dump no. 1 on file runtpe nps = 0 coll = 0 ctm = 0.00 nrn = 0

source distribution written to file srctp cycle = 0

4 warning messages so far.

1 starting rncrun. field length = 0 cp0 = 10.50 print table 110

Table A-2. Sample MCNP input and output for the new FSR in the corner of the GIF holsters. (continued)

1neutron activity in each cell   print table 126

	cell	tracks entering	population	collisions	collisions * weight (per history)	number weighted energy	flux weighted energy	average track weight (relative)	average track mfp (cm)
2	2	0	0	0	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
3	3	0	0	0	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
4	4	126	46	6431	2.5898E-02	5.6905E-05	2.3676E-01	5.5251E-01	1.4347E+00
5	5	0	0	0	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
6	14	0	0	0	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
7	15	0	0	0	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
8	17	0	0	0	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
9	28	144627	10571	1858214	7.4992E+00	3.2S91E-05	1.9795E-01	S.3372E-01	1.1602E+00
10	29	1255	407	1223	5.0276E-03	1.0243E-04	4.5129E-01	5.5313E-01	1.7373E+00
11	30	5161	509	48186	1.9184E-01	5.6149E-OS	2.7559E-01	5.Sl43E-01	1.4730E+00
12	32	65050	14236	722048	3.5721E+00	7.1231E-05	3.0472E-01	6.7809E-01	1.5602E+00
13	33	45644	13883	38396	1.8886E-01	1.1557E-04	3.9148E-01	6.9830E-01	1.8568E+00
14	34	702	316	698	3.2325E-03	1.0043E-04	3.0465E-01	6.1745E-01	1.6326E+00
15	35	1952	437	18324	7.6735E-02	5.3299E-05	2.4220E-01	5.7899E-01	1.4194E+00
16	36	45342	13633	24658	1.2727E-01	1.2017E-04	3.9518E-01	6.8541E-01	1.7798E+00
17	39	2626	2060	409	2.9958E-03	4.7777E-04	8.0631E-01	8.5671E-01	4.2639E+00
18	40	25019	9817	85653	5.0406E-01	3.7589E-04	7.1861E-01	8.2763E-01	1.3574E+00
19	41	2919	1107	3023	1.6033E-02	7.1910E-OS	2.8253E-01	6.5952E-01	3.1322E+00
20	42	3411	1272	3711	1.934SE-02	9.2104E-OS	3.8319E-01	6.6296E-01	3.2914E+00
21	43	540	328	0	0.0000E+00	5.4836E-05	2.4329E-01	6.1506E-01	0.0000E+00
22	44	45581	10722	0	0.0000E+00	1.8933E-04	5.4399E-01	7.5632E-01	0.0000E+00
23	45	590	332	837	3.5625E-03	4.4084E-05	1.9385E-01	5.6119E-01	1.3731E+00
24	46	656	398	869	4.27OOE-03	7.1107E-OS	2.4708E-01	6.2533E-01	1.4868E+00
25	47	47729	10885	4101	2.3301E-02	1.7986E-04	5.2745E-01	7.5114E-01	1.9560E+00
26	48	688	387	835	3.7194E-03	7.4277E-OS	2.7198E-01	5.9316E-01	1.5738E+00
27	49	2455	671	8782	3.731SE-02	5.4006E-05	2.4531E-01	5.8857E-01	1.3974E+00
28	50	1143	415	5893	2.4779E-02	4.8634E-05	2.2380E-01	5.7631E-01	1.3088E+00
29	51	57910	11616	28184	1.4465E-01	1.4510E-04	4.7498E-01	7.2902E-01	2.0642E+00
30	52	63764	11721	2588	1.6491E-02	1.35OOE-04	4.5082E-01	7.2478E-01	9.0504E+00
90	165	36	9	0	0.0000E+00	1.6682E-04	4.3247E-01	7.8821E-01	0.0000E+00
91	166	5	5	11	4.7018E-05	3.3268E-04	1.1355E+00	6.OS52E-01	2.9180E+00
92	167	0	0	0	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
93	168	40	12	3	1.8632E-05	3.1658E-04	6.7583E-01	8.0610E-01	1.9123E+00
94	169	0	0	0	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00

Table A-2. Sample MCNP input and output for the new FSR in the corner of the GIF holsters. (continued)

95	209	44210	34051	0	0.0000E+00	8.2947E-04	8.8098E-01	8.8916E-01	0.0000E+00
96	210	468574	119381	648354	4.4416E+00	6.4581E-04	8.320BE-01	8.7736E-01	2.1240E+00
97	211	653523	118462	0	0.0000E+00	4.0126E-04	7.1105E-01	8.4895E-01	0.0000E+00
98	212	668926	118450	24148	1.6850E-01	3.8355E-04	6.9367E-01	8.4619E-01	3.0045E+00
99	213	686682	118406	0	0.0000E+00	3.6633E-04	6.7720E-01	8.4380E-01	0.0000E+00
100	214	8214	5294	8067	4.9817E-02	2.5767E-04	S.4287E-01	7.6933E-01	2.0256E+00
101	215	8305	5297	8033	4.9346E-02	2.4227E-04	5.3796E-01	7.6189E-01	2.0346E+00
102	216	25860	9118	36754	1.8933E-01	1.8416E-04	4.4129E-01	6.9604E-01	1.9756E+00
103	217	23453	8746	28139	1.4361E-01	1.7601E-04	4.643SE-01	6.8898E-01	1.9347E+00
104	218	766181	119482	59095	3.7454E-01	3.3320E-04	6.5022E-01	8.3059E-01	2.2503E+00
105	219	34574	5960	212327	8.8870E-01	3.8362E-05	2.1015E-01	S.6131E-Ol	1.2277E+00
106	220	10584	3953	45572	2.1501E-01	6.8902E-05	2.7805E-01	6.5152E-01	l.Sl4OE+00
107	221	646993	101520	250161	1.4807E+00	2.8172E-04	6.1056E-01	8.2653E-01	2.5181E+00
108	222	1002286	119635	45245	3.1559E-01	2.2117E-04	5.S4S9E-01	7.9825E-01	8.7101E+00
109	223	1309429	103402	6142916	3.5461E+Ol	1.4256E-04	4.43SOE-01	7.9122E-01	2.0143E+00
110	224	550599	43672	275SB72	1.4465E+Ol	1.0967E-04	3.9609E-01	7.2856E-01	1.8479E+00
111	225	267808	40883	123039	6.4229E-01	1.8355E-04	S.227SE-01	7.4766E-01	2.2324E+00
112	226	12052	3368	11274	5.3462E-02	1.213BE-04	3.8029E-01	6.3553E-01	1.7665E+00
113	227	34028	3030	313374	1.3019E+00	6.3953E-05	2.8210E-01	5.8585E-01	1.5443E+00
	total	8252561	12858S2	16709483	8.6862E+0l				

1keff results for: New FSR w/BeO in corner of GIF; Holsters w/ZrH low water density probid = 06/21/96 08:02:57

the initial fission neutron source distribution used the 11 source points that were input on the ksrc card.
the criticality problem was scheduled to skip 3 cycles and run a total of 300 cycles with nominally 400 neutrons per cycle.
this problem has run 3 inactive cycles with 1219 neutron histories and 297 active cycles with 119985 neutron histories.

this calculation has completed the requested number of keff cycles using a total of 121204 fission neutron source histories.
all cells with fissionable material were sampled and had fission neutron source points.

the results of the w test for normality applied to the individual collision, absorption, and track-length keff cycle values are:

the k(collision) cycle values appear normally distributed at the 95 percent confidence level
the k(absorption) cycle values appear normally distributed at the 95 percent confidence level
the k(trk length) cycle values appear normally distributed at the 95 percent confidence level

Table A-2. Sample MCNP input and output for the new FSR in the corner of the GIF holsters. (continued)

---

the final estimated combined collision/absorption/track-length keff = 0.94249 with an estimated standard deviation of 0.00217

the estimated 68, 95, & 99 percent keff confidence intervals are 0.94032 to 0.94466, 0.93818 to 0.94681, and 0.93677 to 0.94821

the estimated collision/absorption neutron removal lifetime = 1.42E-04 seconds with an estimated standard deviation of 5.14E-07

---

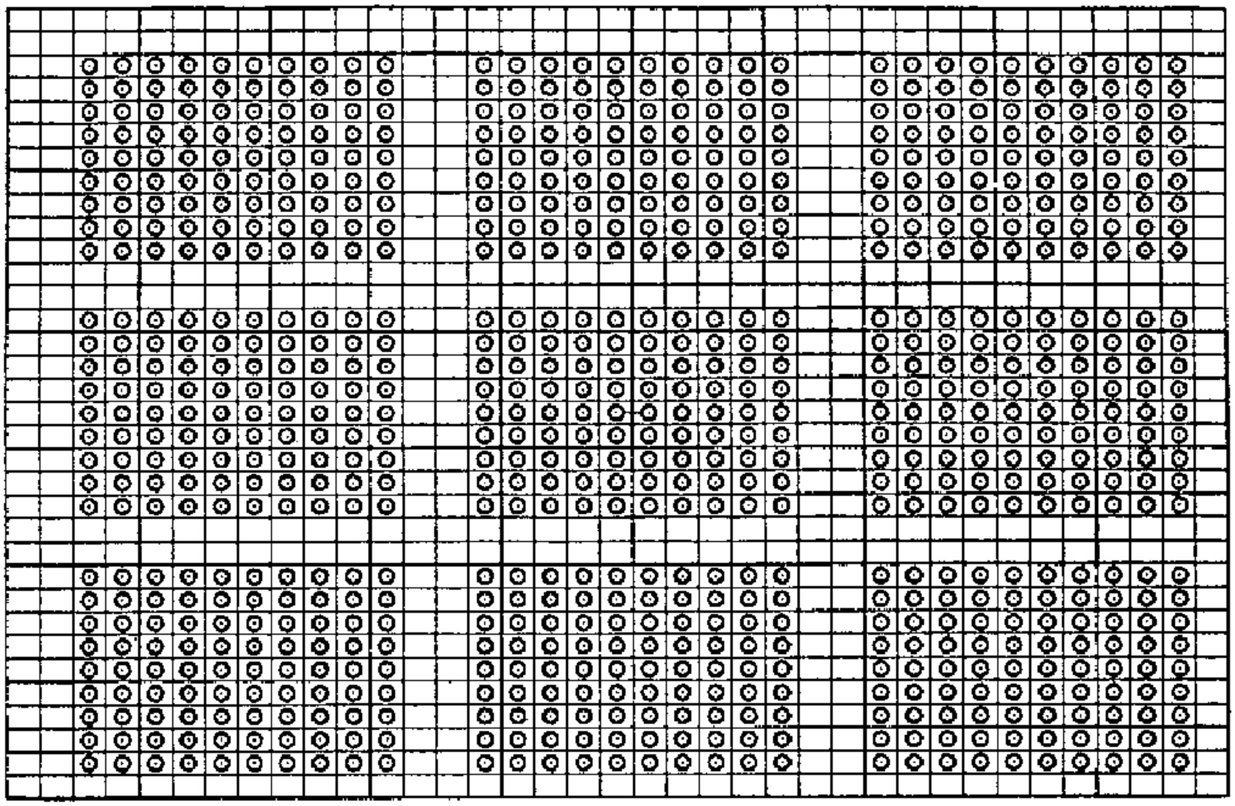
the estimated average keffs, one standard deviations, and 68, 9S. and 99 percent confidence intervals are:

keff estimator	keff	standard deviation	68% confidence	95% confidence	99% confidence	corr

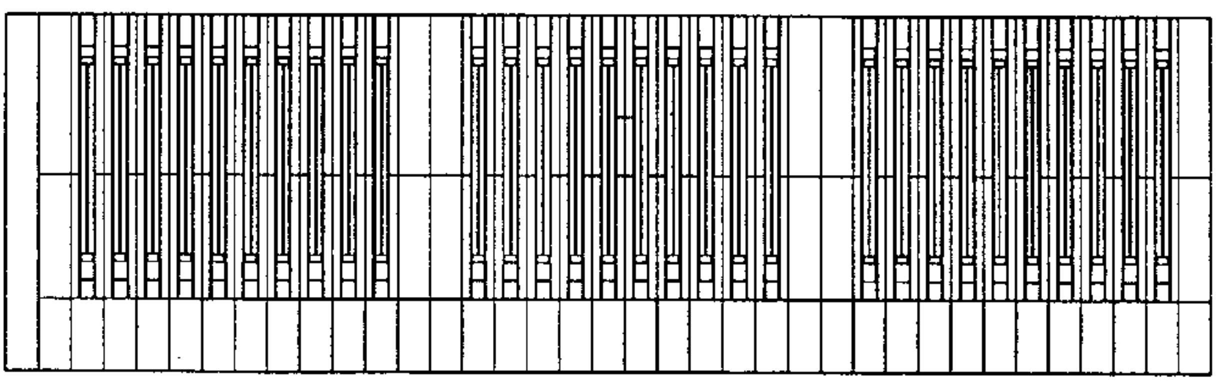
Appendix B

Sample MCNP Models

Figures



Horizontal Cut



Vertical Cut

Figure B-1. MCNP model for a 3 by 3 by 1 array of ACRR fuel storage racks.

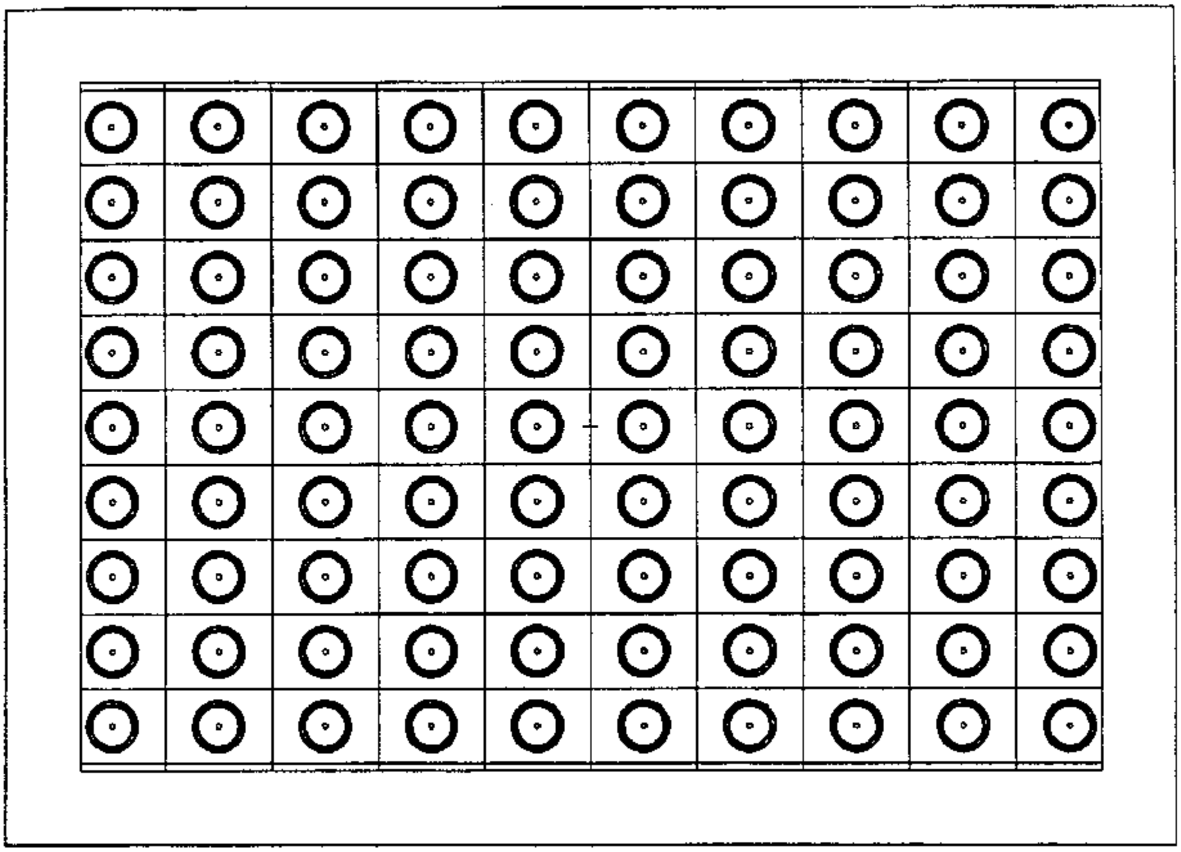


Figure B-2. MCNP model for a single ACRR fuel storage rack, horizontal cut at 50 cm.

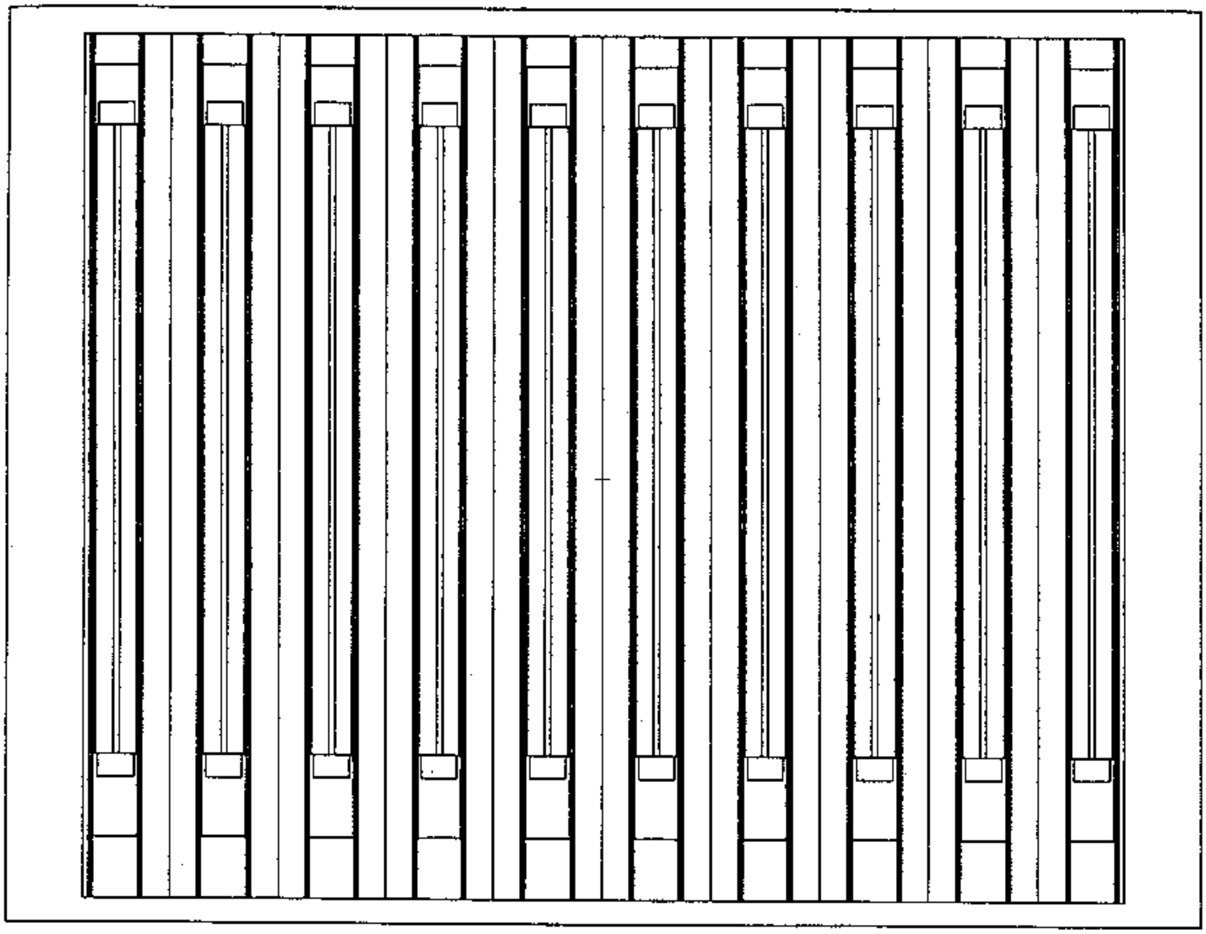


Figure B-3. MCNP model for a single ACRR fuel storage rack, vertical cut through the center of a row of fuel pins.

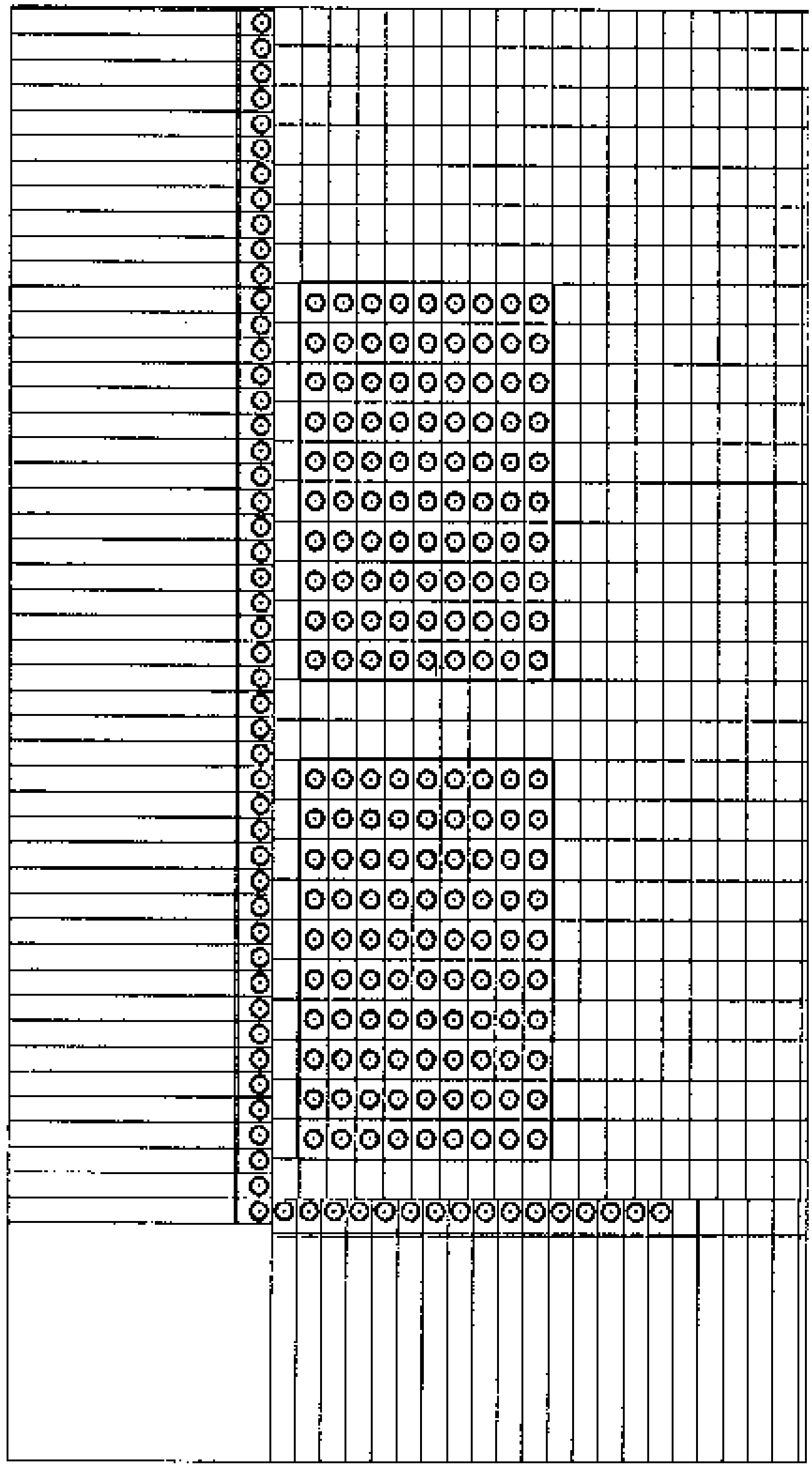


Figure B-4. MCNP model for two ACRR fuel storage racks in a corner of the GIF pool with fuel in GIF holsters, horizontal cut.

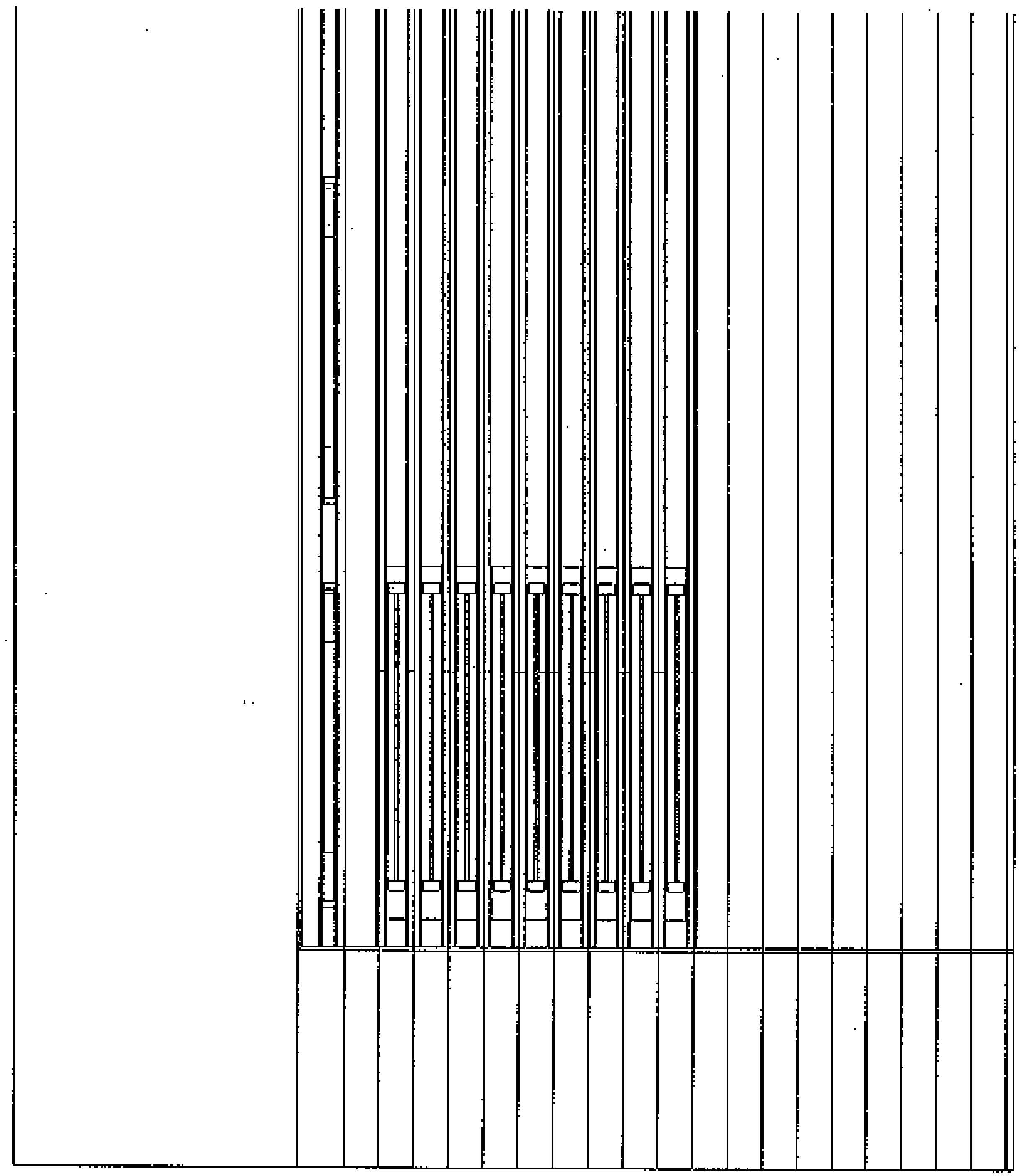


Figure B-5. MCNP model for ACRR fuel storage racks in a corner of the GIF pool with fuel in GIF holsters, vertical cut.

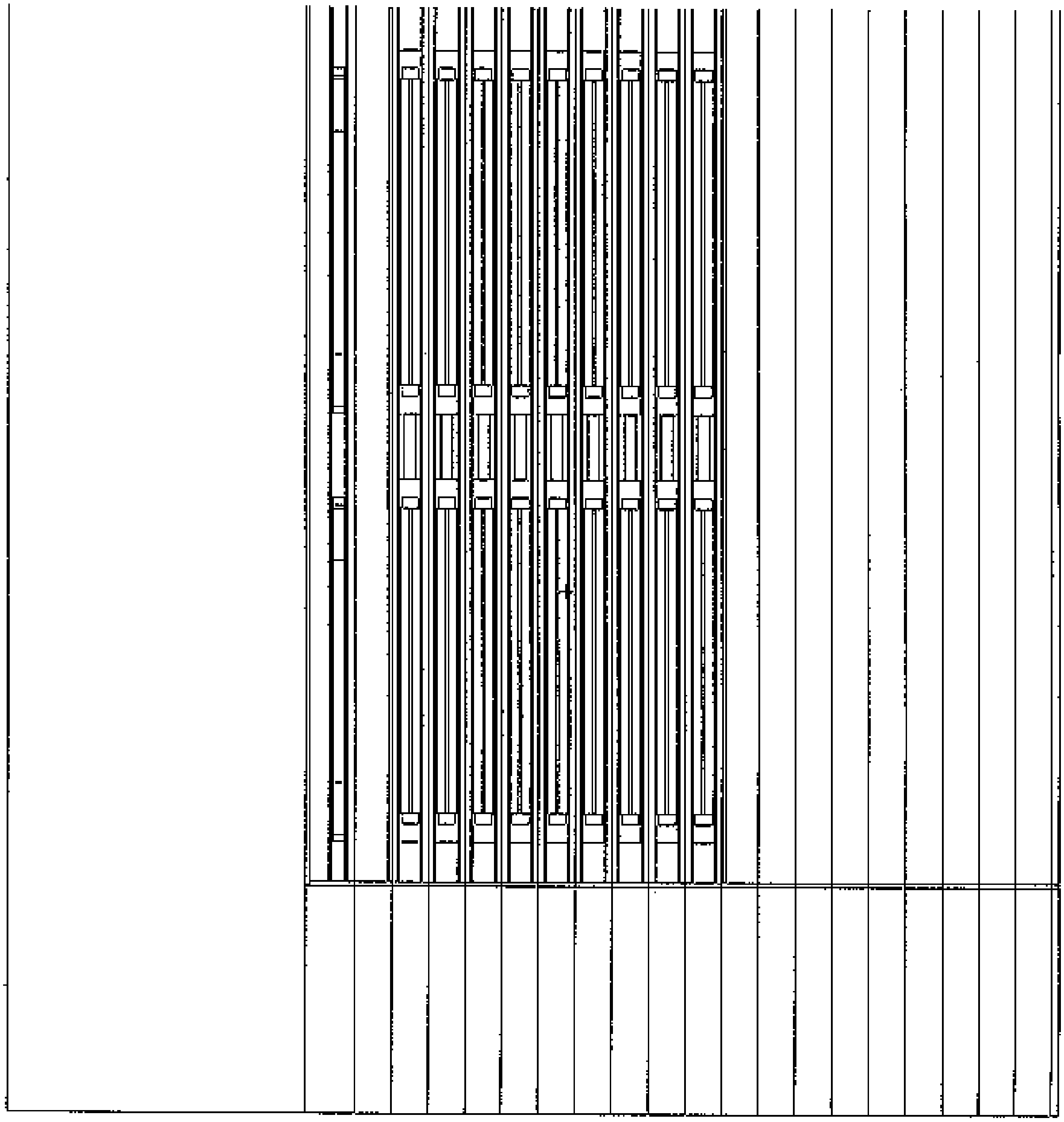


Figure B-6. MCNP model for two stacked ACRR fuel storage racks in the GIF pool with fuel in GIF holsters, vertical cut.

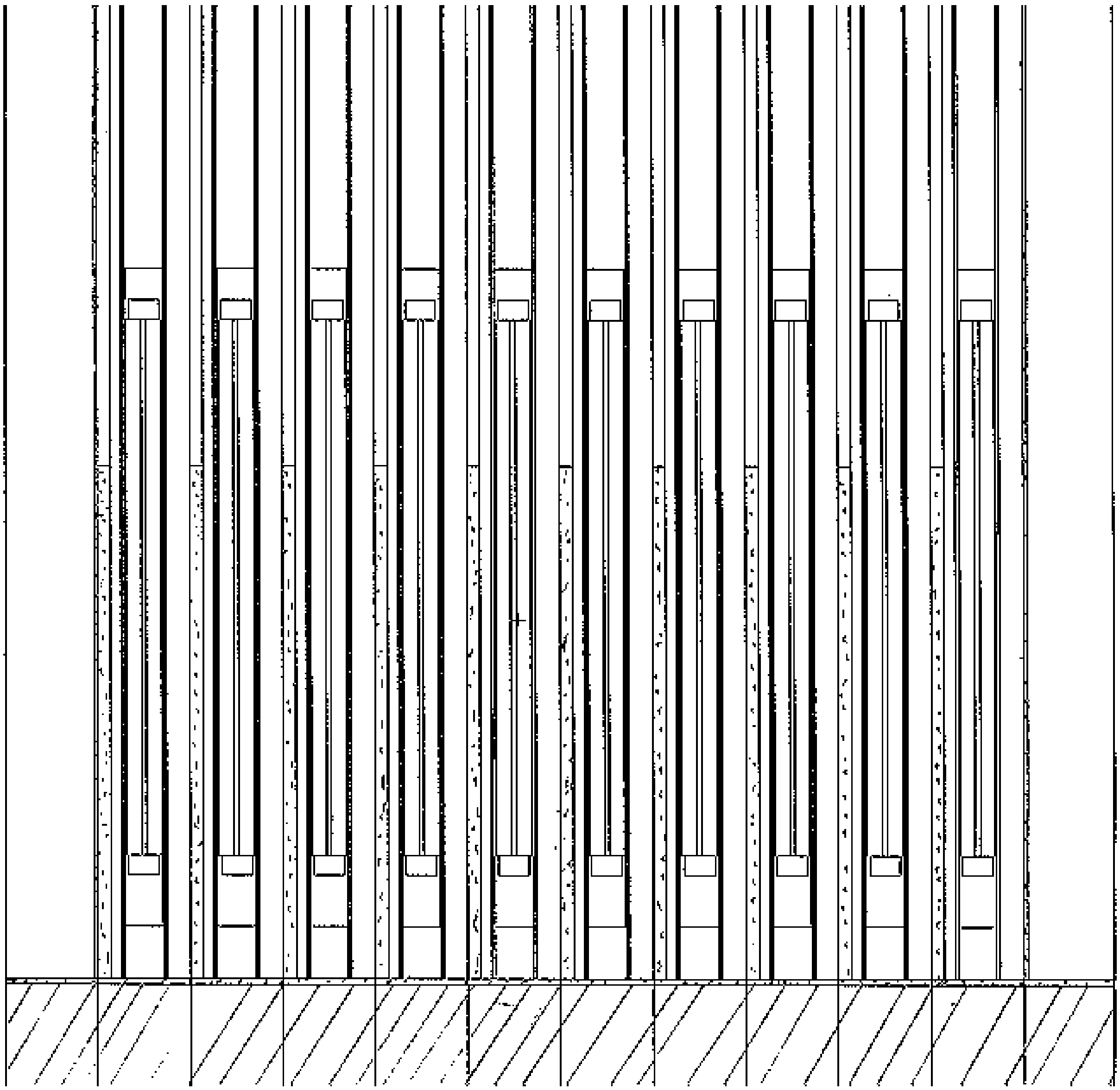


Figure B-7. MCNP model for ACRR fuel storage racks with stainless steel neutron absorber plates, vertical cut.

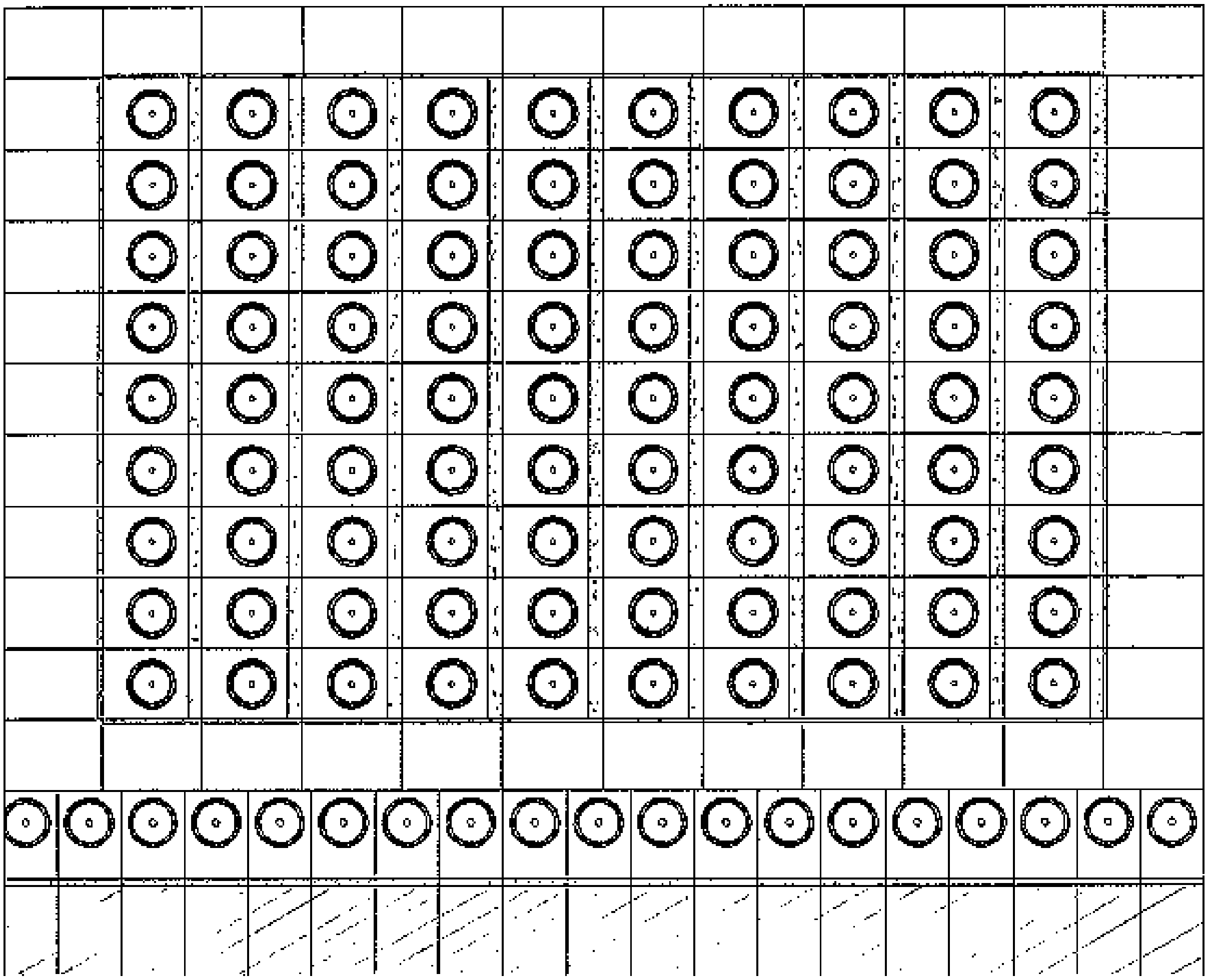
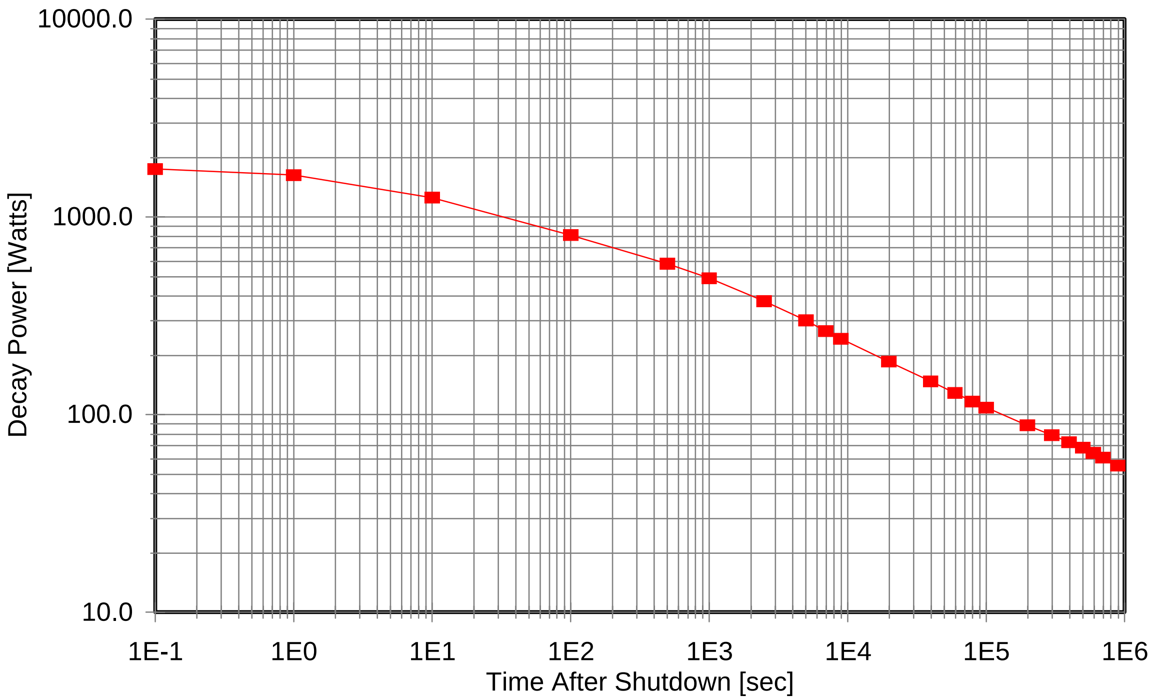


Figure B-8. MCNP model for ACRR fuel storage racks with stainless steel neutron absorber plates, horizontal cut.

Decay Power

27 kW target irradiated for 365 days



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