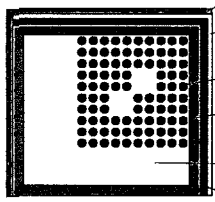
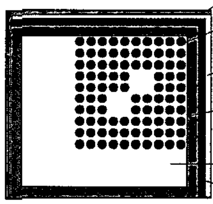
Unit 96 Upper Compartment in SW Quadrant



Unit 97 Lower Compartment in SE Quadrant



Unit 98 Upper Compartment in SE Quadrant

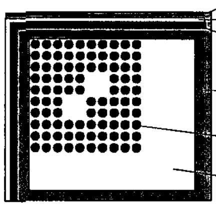


Figure A.6.5.2-3
KENO V.a units and radial cross sections of the model
Part 21 of 23 - (All units 0.635 cm (0.25 inches) high)

DELETED

Figure A.6.5.2-3
KENO V.a units and radial cross sections of the model
Part 22 of 23 - (All units 0.635 cm (0.25 inches) high)

DELETED

Figure A.6.5.2-3
KENO V.a units and radial cross sections of the model
Part 23 of 23 - (All units 0.635 cm (0.25 inches) high)

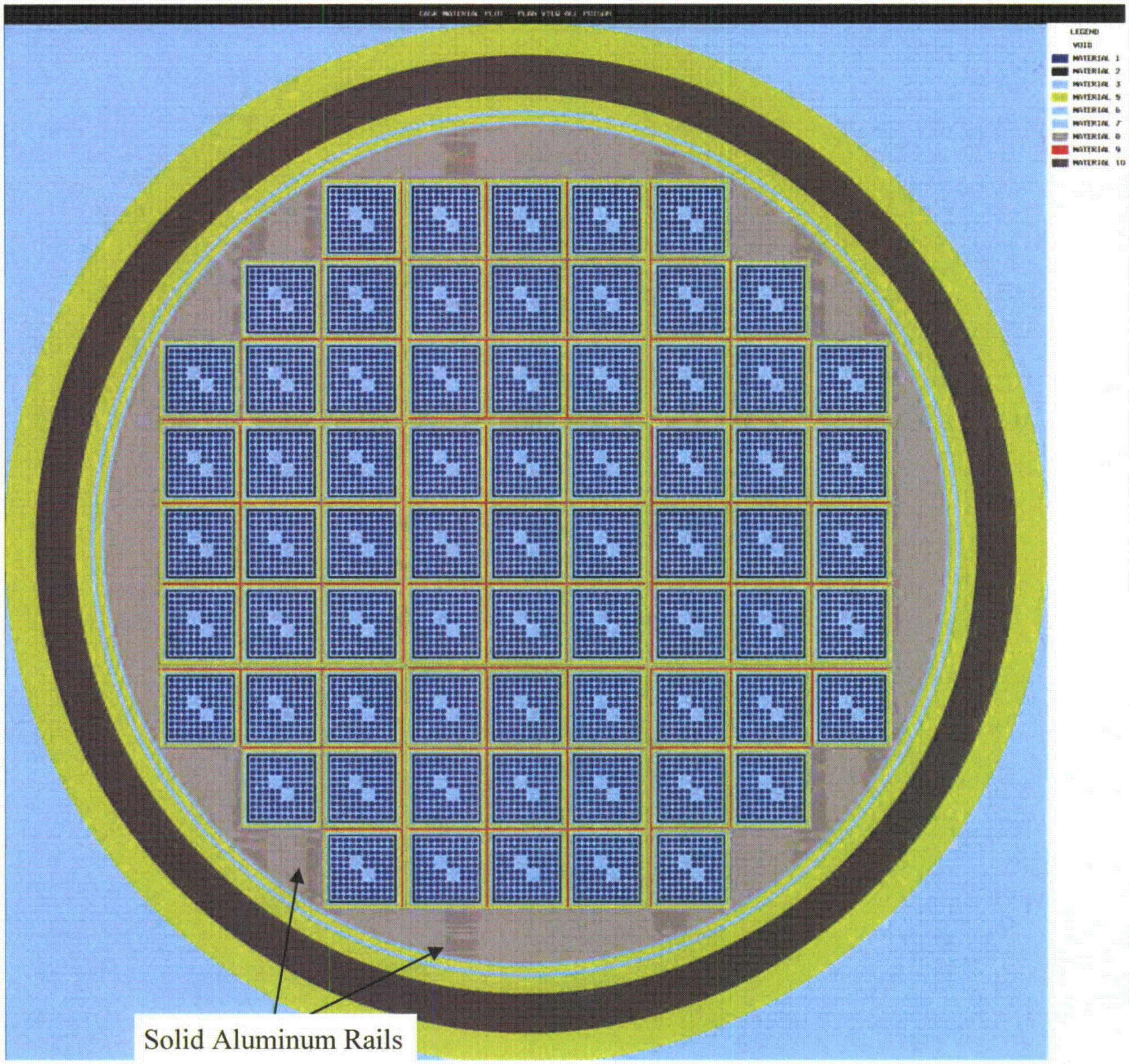


Figure A.6.5.2-4
Criticality Calculational KENO Model for Intact Fuel – UNIT 58
Part 1 of 3–Transversal Cross Section of Unit 58 (All poison; assemblies with channel and centered)

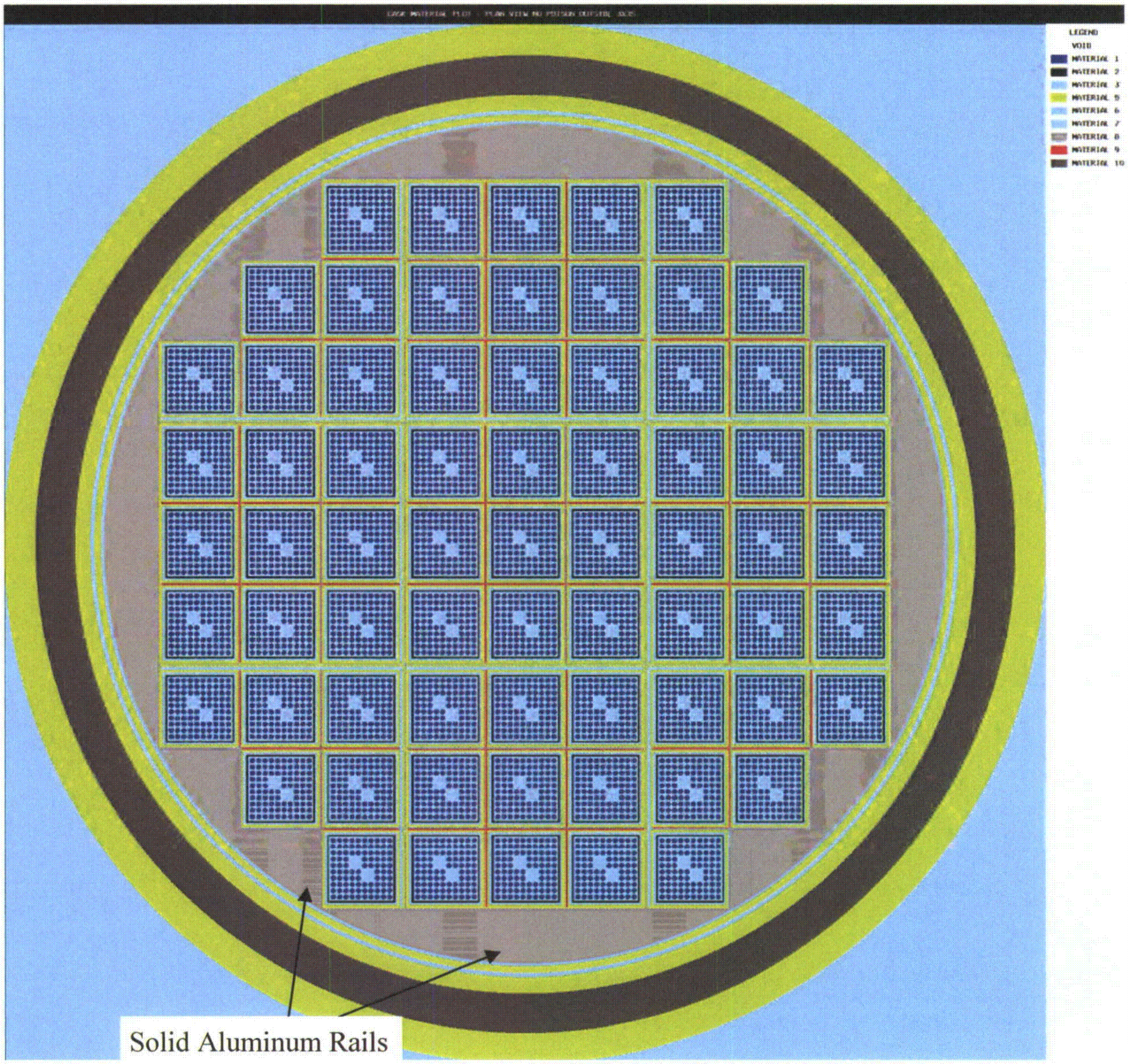


Figure A.6.5.2-5
Criticality Calculational KENO Model for Intact Fuel – UNIT 59
Part 2 of 3–Transversal Cross Section of Unit 59 (poison inside 3x3 and corner assembly arrays only; assemblies with channel and centered)

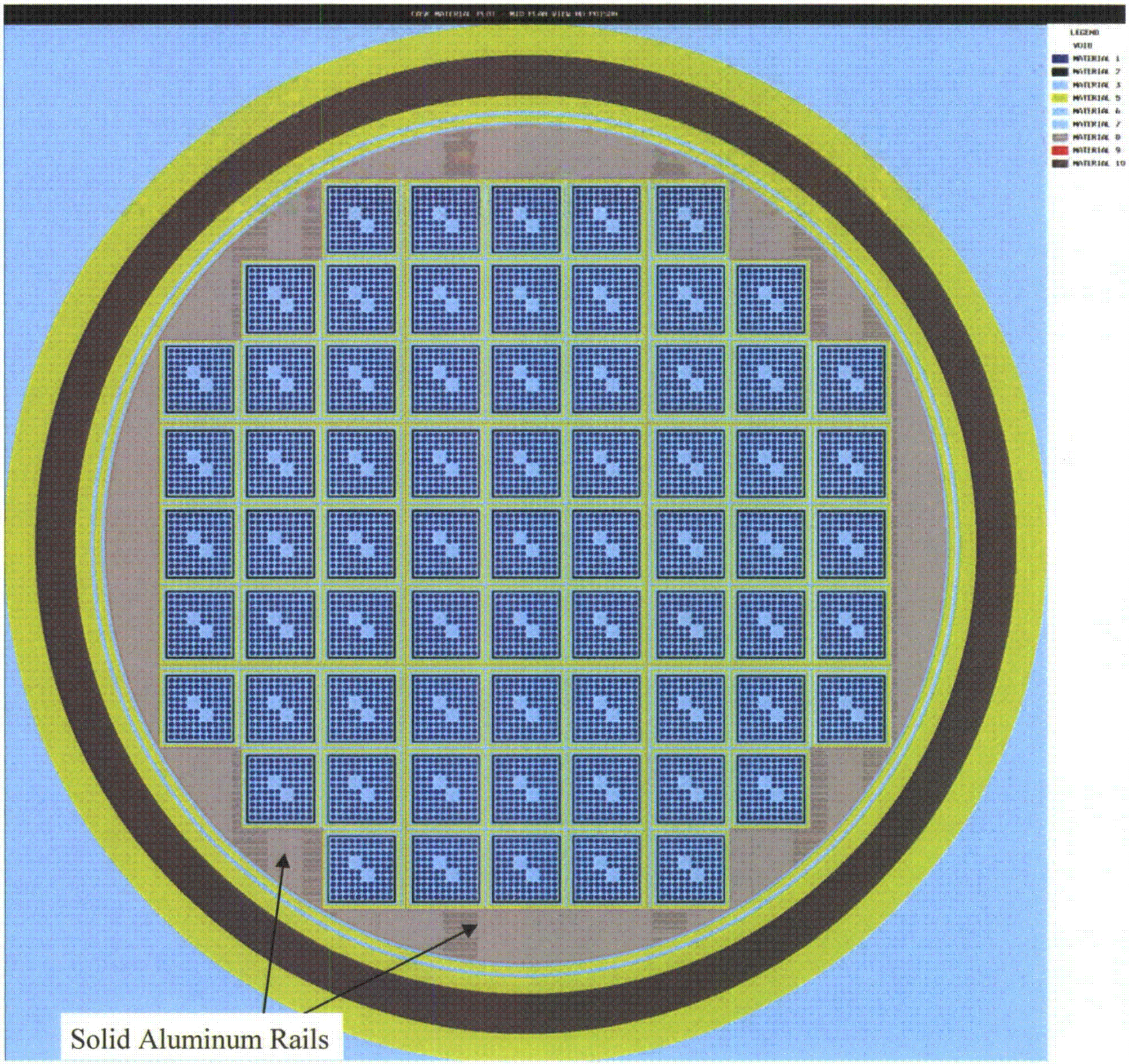
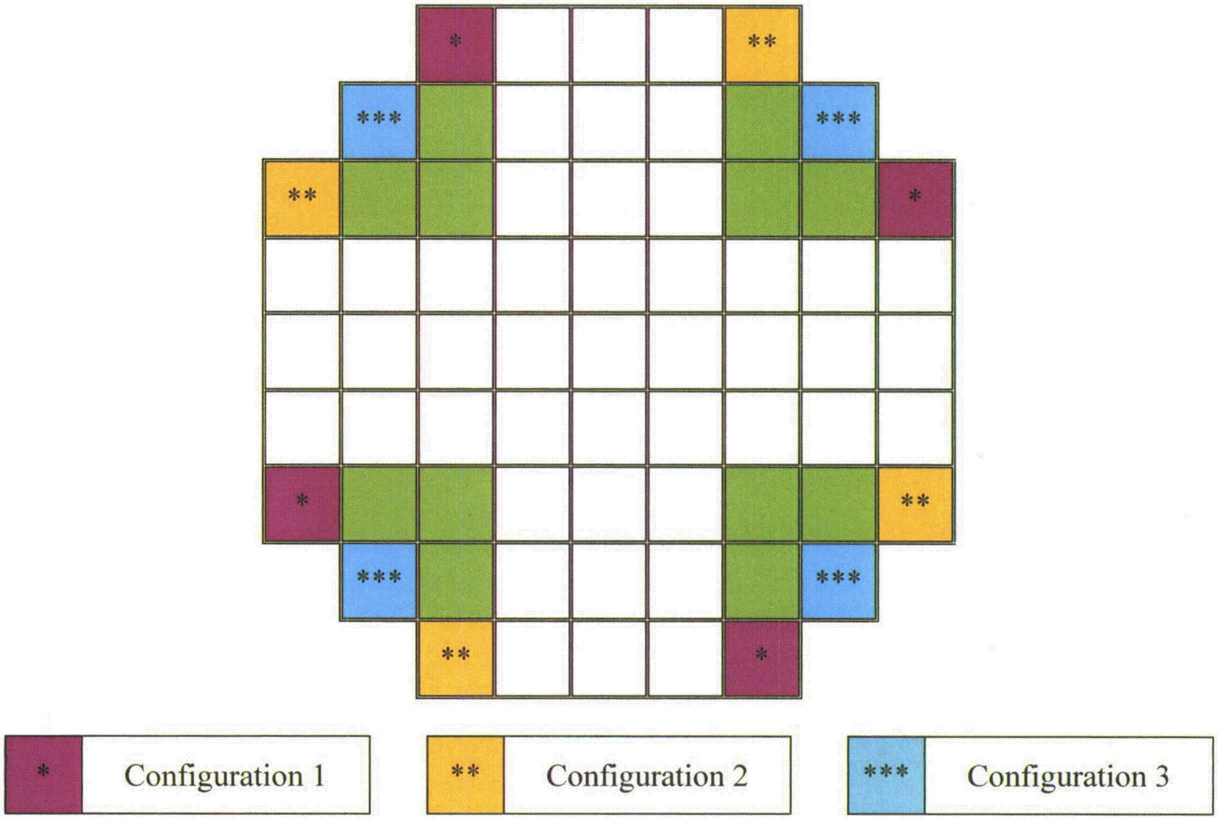


Figure A.6.5.2-6
Criticality Calculational KENO Model for Intact Fuel – UNIT 79
Part 3 of 3–Transversal Cross Section of Unit 79 (basket middle axial poison gap; assemblies with channel and centered)



Either one of these three sets of corner locations shall only be utilized to load up to four damaged assemblies with the remaining intact in a 69BTH Basket. The maximum lattice average initial enrichment of fuel assemblies (damaged or intact stored in either magenta set of cells for configuration 1, gold set of cells for configuration 2, or blue set of cells for configuration 3 is limited to the "up to 4 damaged assemblies" column of Table A.6.5.2-1.
Following the placement of damaged fuel assemblies in either configuration 1 or 2, the remaining gold or magenta locations shall be used to load up to 4 additional damaged assemblies, with the remaining intact in a 69BTH Basket. The maximum lattice average initial enrichment for these fuel assemblies (damaged or intact stored in gold or magenta cells available) is limited to the "5 to 8 damaged assemblies" column of Table A.6.5.2-1.
Following the placement of eight damaged fuel assemblies in the set of corner locations marked with a "*" (shaded in magenta) and a "**" (shaded in gold), the locations shaded in green or blue shall be used to load up to sixteen additional damaged assemblies, with the remaining intact in a 69BTH Basket. The maximum lattice average initial enrichment for these fuel assemblies (damaged or intact stored in the 24 shaded locations) is limited to the "9 to 24 damaged assemblies" column of Table A.6.5.2-1.

Figure A.6.5.2-7
NUHOMS® -69BTH Damaged Assembly Locations

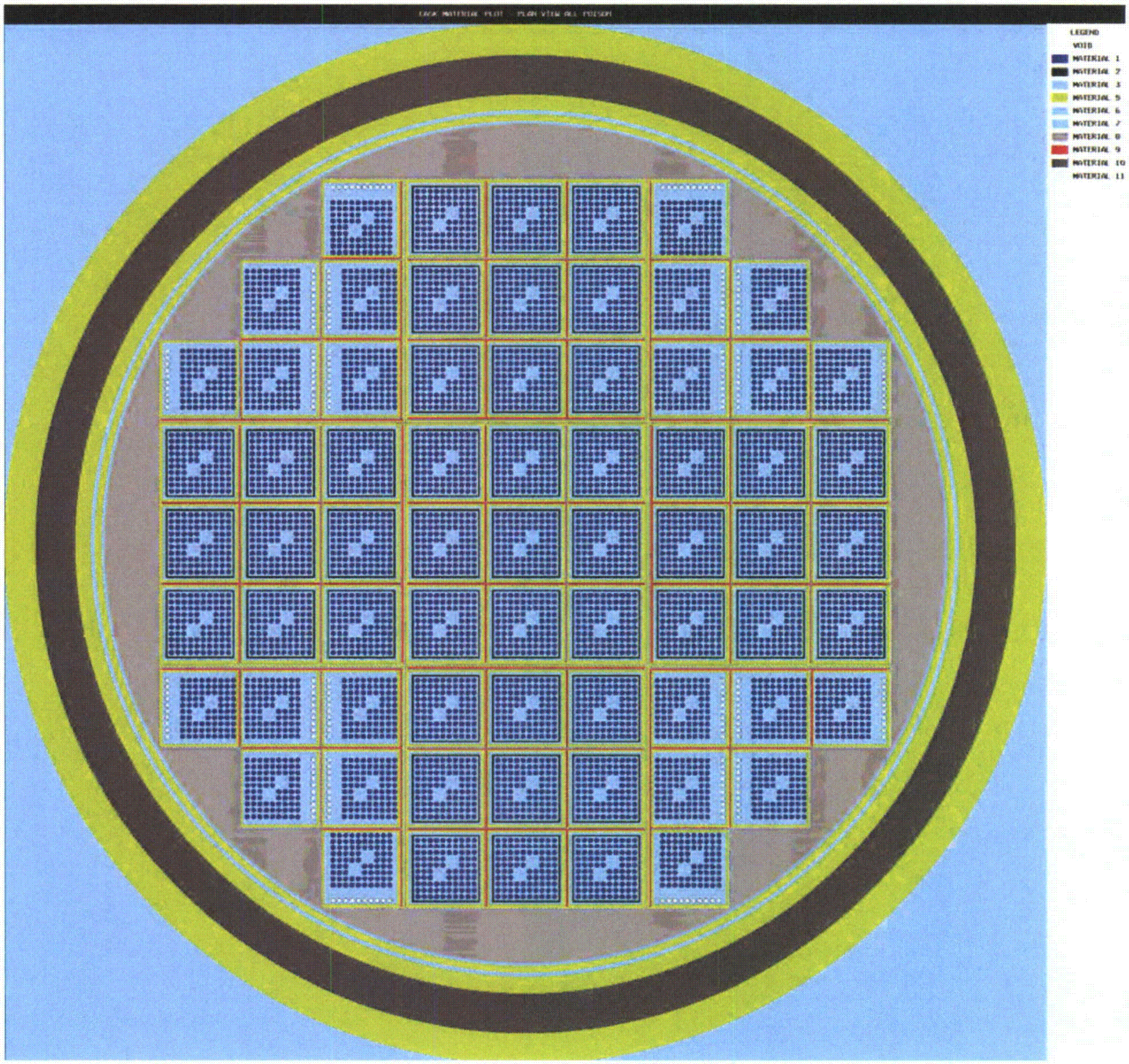


Figure A.6.5.2-8
KENO Model of the Single Break Case–Maximum Separation

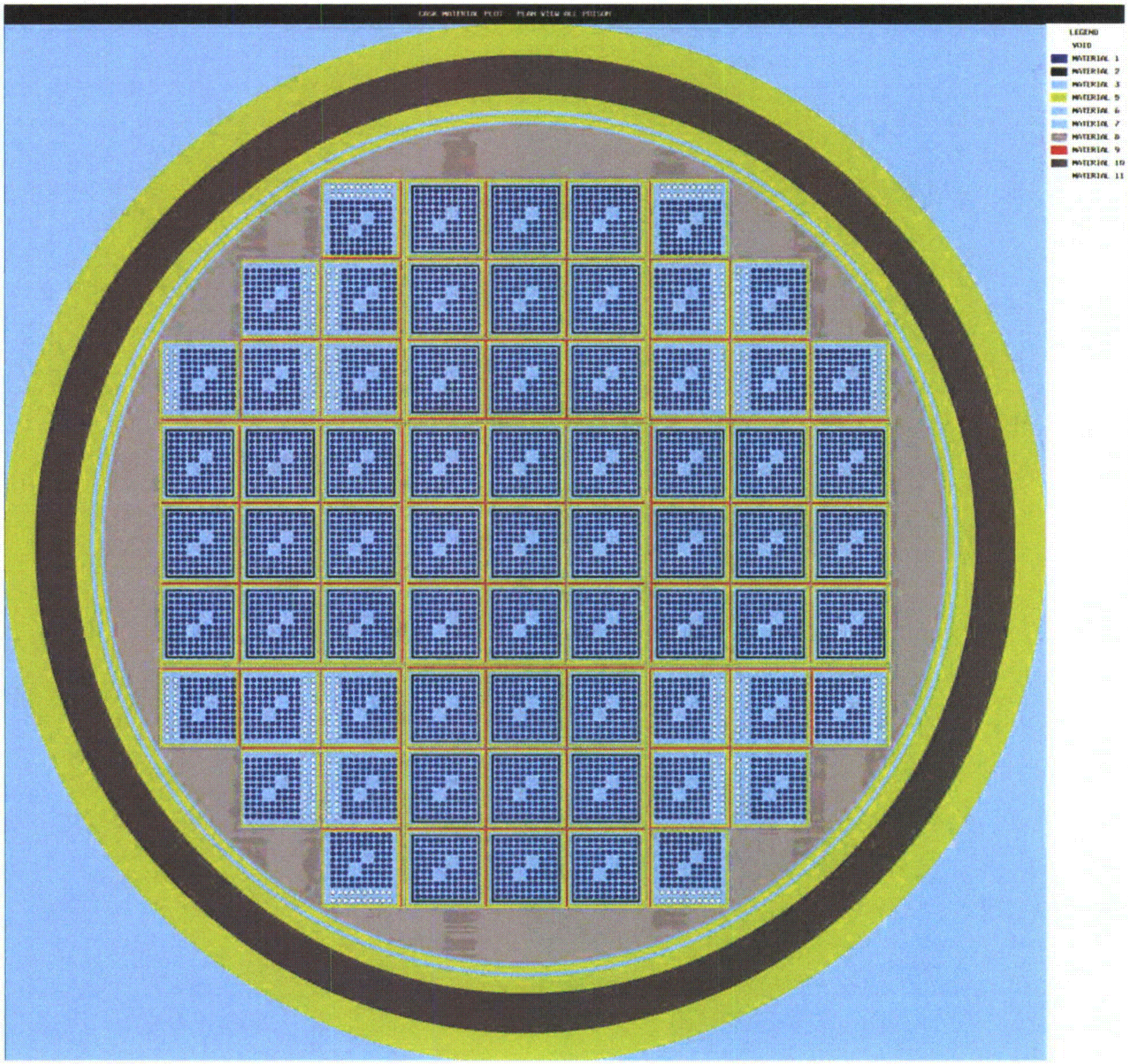


Figure A.6.5.2-9
KENO Model of the Double Break Case

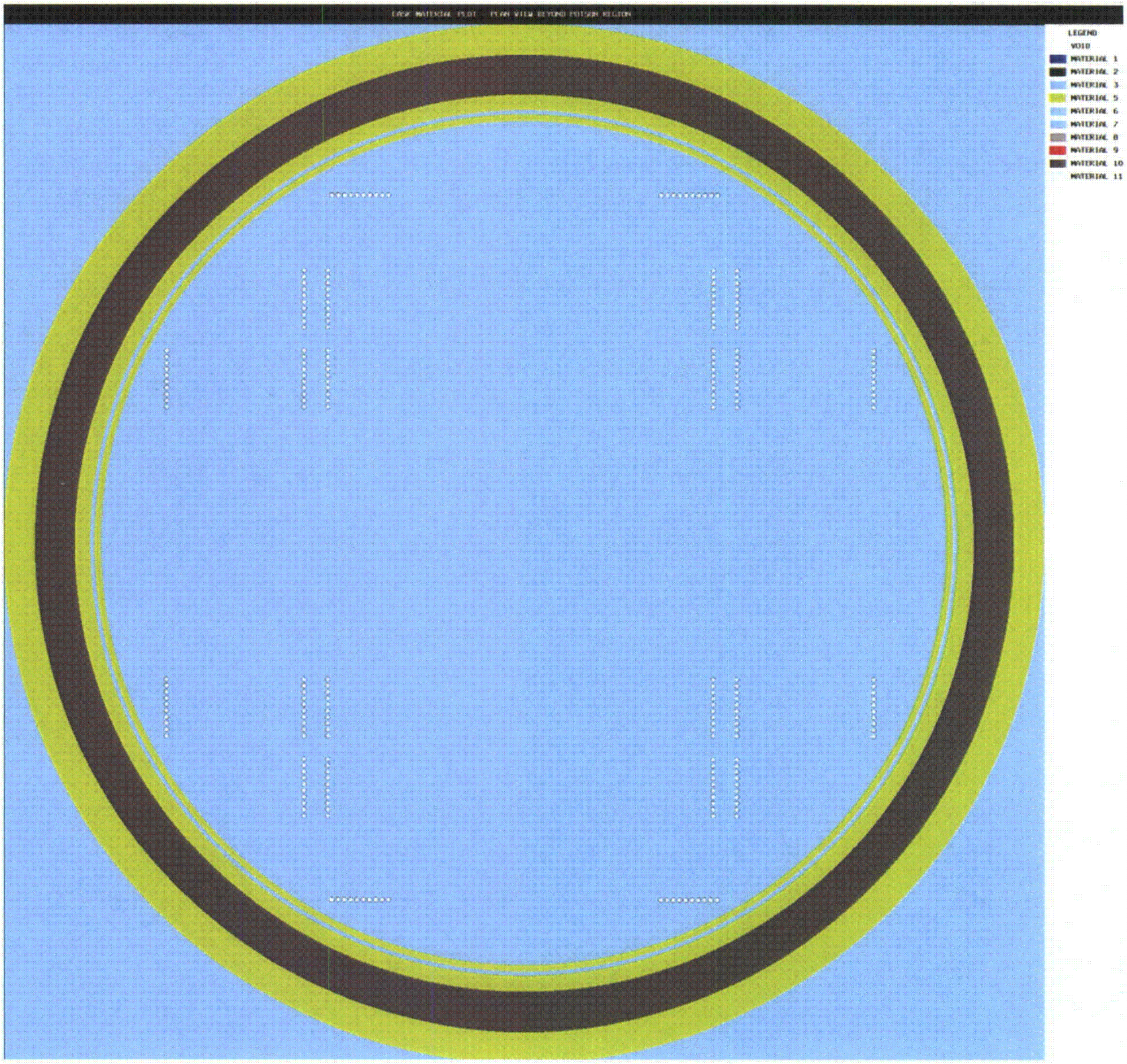


Figure A.6.5.2-10
KENO Model of Single Break Case – Beyond Poison

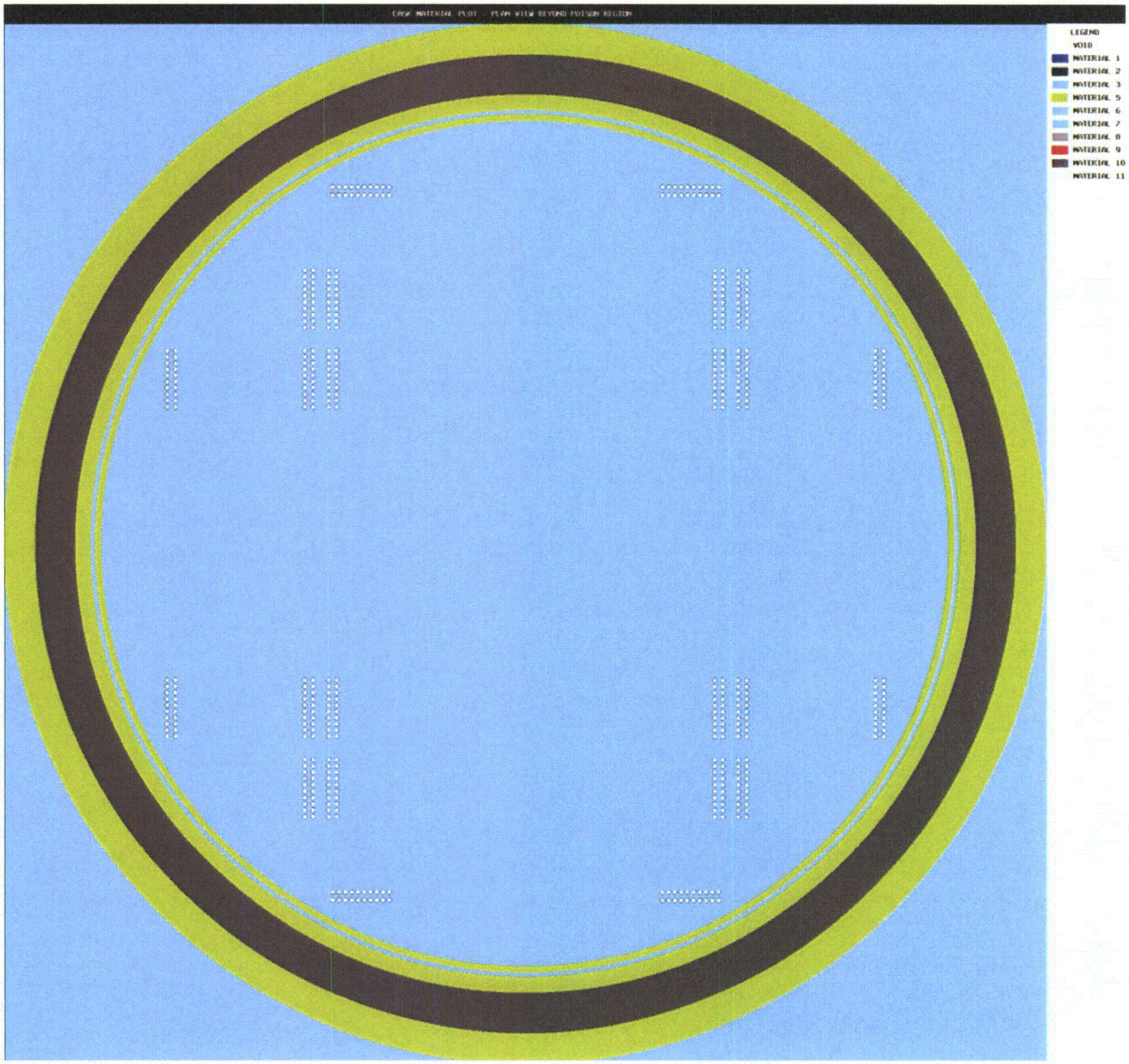


Figure A.6.5.2-11
KENO Model of Double Break Case – Beyond Poison

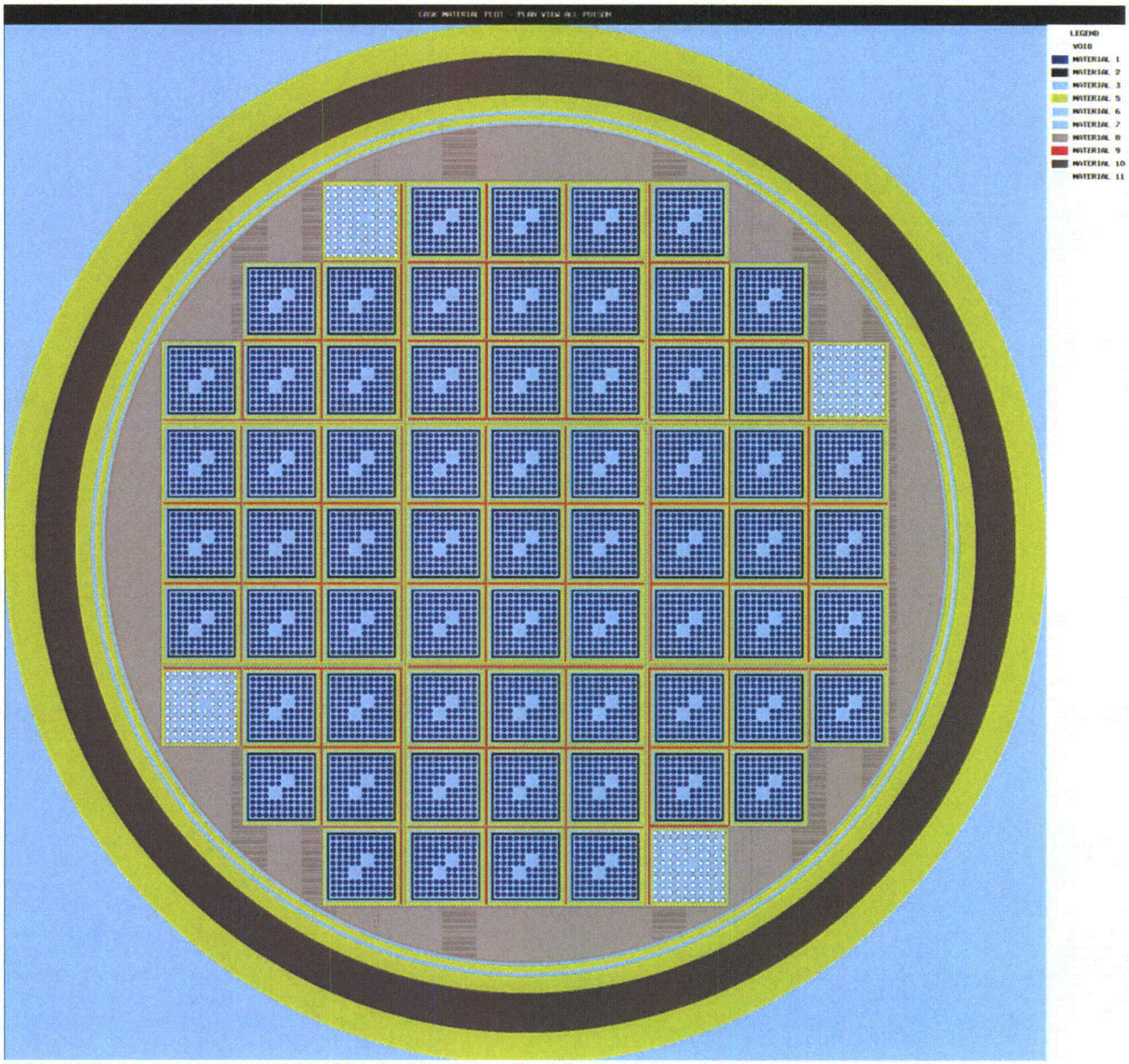


Figure A.6.5.2-12
69BTH DSC Damaged Assembly Loading–4 Assemblies

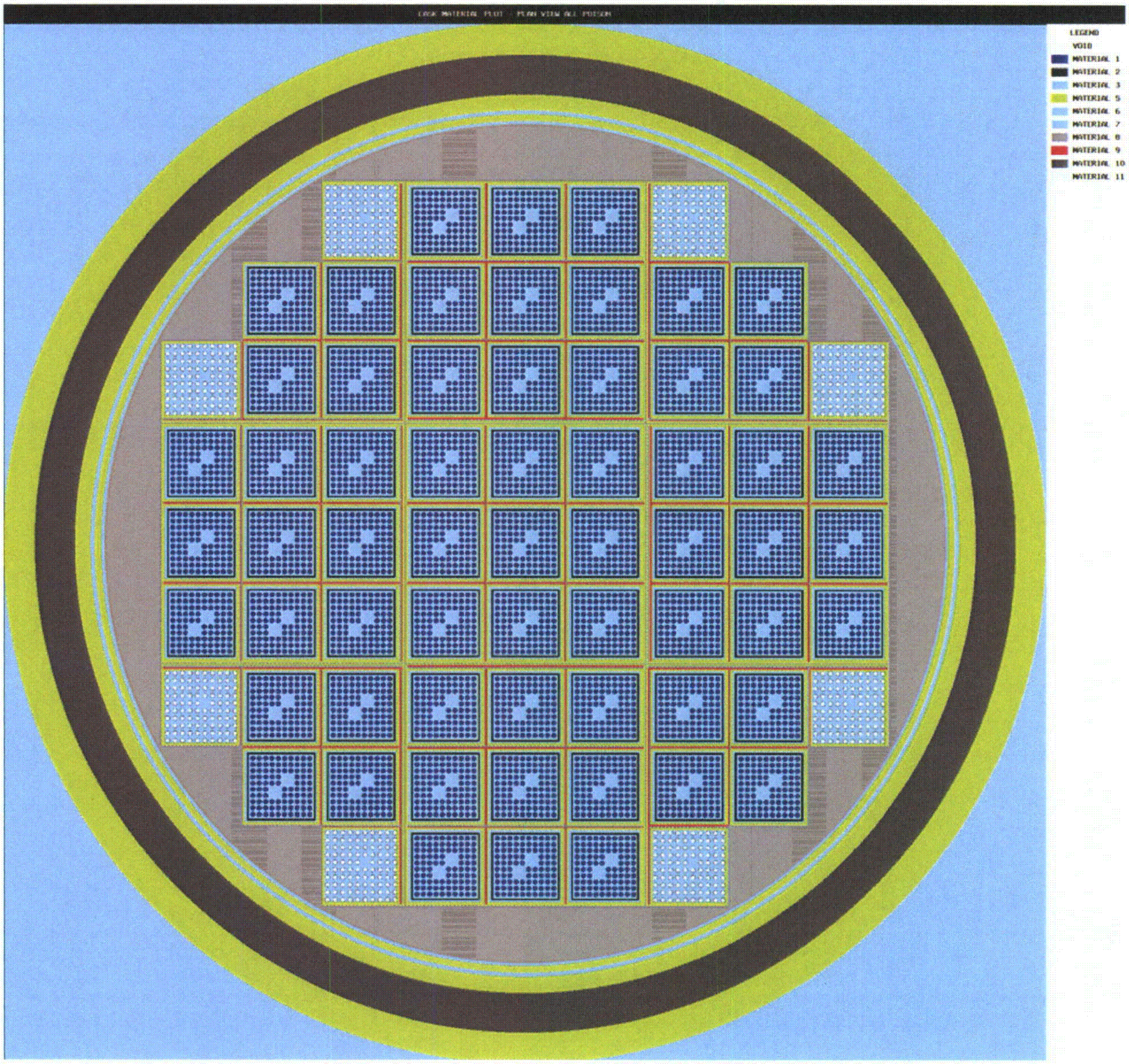


Figure A.6.5.2-13
69BTH DSC Damaged Assembly Loading–8 Assemblies

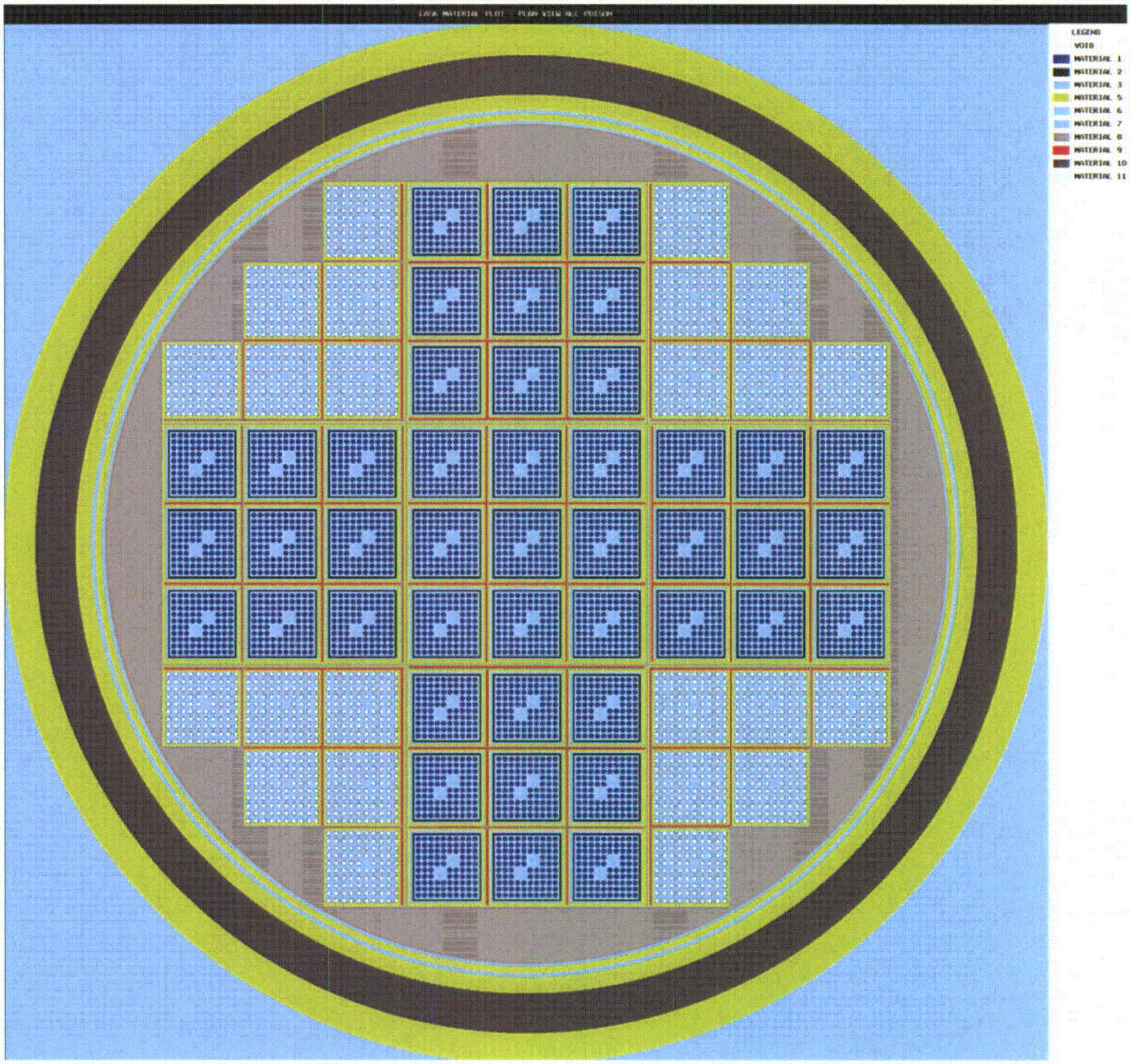


Figure A.6.5.2-14
69BTH DSC Damaged Assembly Loading–24 Assemblies

Appendix A.6.5.3
NUHOMS®-24PT4 DSC Criticality Evaluation

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Appendix A.6.5.3
NUHOMS®-24PT4 DSC Criticality Evaluation

NOTE: References in this Appendix are shown as [1], [2], etc. and refer to the reference list in Section A.6.5.3.7.

This Appendix A.6.5.3 to Chapter A.6 demonstrates that the MP197HB package when transporting the NUHOMS®-24PT4 DSC payloads meets the criticality performance requirements specified in Sections 71.55 and 71.59 of 10 CFR Part 71 [2]. The criticality control design ensures that the effective multiplication factor (k_{eff}) of the contained fuel is no greater than an Upper Subcritical Limit (USL) for the most reactive configuration. The USL includes a confidence band with an administrative safety margin of 0.05. The design has a Criticality Safety Index (CSI, given in 10 CFR 71.59(b) as CSI = 50/"N") of 0 because "N" is infinity (∞). The number "N" is based on all of the following conditions being satisfied, assuming packages are stacked together in any arrangement and with close full reflection on all sides of the stack by water:

1. Five times "N" undamaged packages with nothing between the packages are subcritical;
2. Two times "N" damaged packages, if each package is subjected to the tests specified in 10 CFR Part 71.73 (HAC) is subcritical with optimum interspersed hydrogenous moderation; and
3. The value of "N" cannot be less than 0.5.

A.6.5.3.1 Discussion and Results

Chapter A.6 of the Advanced NUHOMS UFSAR [5] presents the criticality analysis of the CE 16x16 PWR assemblies authorized for storage in the NUHOMS-24PT4 DSC. See Appendix A.1.4.1 for a detailed description of the contents of this DSC.

The criticality analysis documented for the 24PT4 DSC utilizes a transfer cask (TC) that is similar to the MP197HB cask. The TC has a liquid neutron shield and has a slightly (1/2") thicker lead gamma shield.

However, the calculations documented herein assume complete loss of neutron shielding and employ close reflection around the TC structural shell. This is conservative since the MP197HB cask has a solid neutron shield. Therefore, no additional modeling with the MP197HB cask is necessary for the 24PT4 DSC.

The criticality analysis for the NUHOMS®-24PT4 DSC is based on fresh fuel assumption.

Figure A.6.5.3-3 shows the radial cross section of the NUHOMS® -24PT4 DSC. Criticality control in the the NUHOMS® -24PT4 DSC is provided by the basket structural components that maintain the relative position of the spent fuel assemblies under all normal and Hypothetical Accident Conditions (HAC) and by fixed neutron absorbers. The fixed nutron absorbers are present in the form of Boral® poison plates provided around the DSC guidesleeves and poison rodlets which are inserted in the guide tubes of certain assemblies in the basket.

The NUHOMS® -MP197HB Cask containing the NUHOMS® -24PT4 DSC is shown to be subcritical for an infinite array of flooded undamaged casks and for an infinite array of damaged

casks after being subjected to hypothetical accident conditions. “N” is equal to ∞. The cask is shown to be subcritical for five times “N” or an infinite number of undamaged packages with close full reflection between packages and no inleakage of water as required by 10 CFR Part 71.59(a)(1). In addition, as required by 10 CFR Part 71.59(a)(2), two times “N” or an infinite array of packages is shown to be subcritical with the fissile material in its most reactive configuration, optimum water moderation and close full water reflection consistent with its damaged condition. A CSI of 0 (less than 50) ensures that, per 10 CFR Part 71.59 (c)(1), the package may be shipped by a carrier in a nonexclusive conveyance.

The results of the evaluation demonstrate that the maximum k_{eff}, including statistical uncertainty, is less than the USL determined from a statistical analysis of benchmark criticality experiments. The statistical analysis procedure includes a confidence band with an administrative safety margin of 0.05.

A.6.5.3.2 Package Fuel Loading

This section provides a summary of the maximum spent fuel loading and spent fuel parameters for the 24PT4-DSC. The allowable contents are listed in Chapter A.1, Appendix A.1.4.1.

Each 24PT4-DSC is designed to accommodate up to 12 damaged fuel assemblies in lieu of intact assemblies. The required placement of the damaged fuel assemblies is in the twelve outermost fuel assembly locations as specified in Figure A.6.5.3-18 (Zones A and/or B only). Damaged fuel includes assemblies with known or suspected cladding defects greater than hairline cracks or pinhole leaks or an assembly with partial and/or mssing rods (i.e., extra water holes). Damaged fuel assemblies shall be placed in failed fuel cans which will replace basket guidesleeves.

The fuel parameters used in the criticality calculations for CE 16x16 fuel assemblies are listed in Table A.6.5.3-2.

Design parameters for Boral® and poison rodlets are listed in Table A.6.5.3-4.

The KENO V.a model incorporates borated stainless steel (1.75 wt. % Boron) poison rodlets for storage of damaged fuel in specific configurations. An option is allowed to fabricate the poison rodlets from B_4C filled thin wall stainless steel tubing incorporating an equivalent amount of ^{10}B. The equivalent linear B_4C content per rodlet is calculated by:

1. The modeled boron density (1.75 wt. % x 7.60 g/cm^3) of the borated stainless steel is multiplied by the cross sectional area of minimum borated steel rod (0.71875 inches OD) = 0.348 g/cm boron.

2. To convert to the B_4C equivalent linear weight, divide by the boron weight fraction of B_4C (0.7828) = 0.445 g/cm B_4C.

3. Divide this result by 0.64 to account for 64% credit taken for the ^{10}B content in the criticality analysis.

   This results in a minimum required linear B_4C content of 0.70g/cm.

A.6.5.3.3 Model Specification

A.6.5.3.3.1 Description of the Calculational Models

Criticality analyses were performed using the KENO V.a and the 44 neutron group library based on ENDF-B Version 5 cross-section data that are part of the SCALE 4.4 code package [3]. Validation and benchmarking of these codes is discussed in Section A.6.5.3.6.

SCALE 4.4 [3] is an extensive computer code package which has many applications, including cross section processing, criticality studies, and heat transfer analyses. The package is comprised of many functional modules, which can be run independently of each other. Control Modules were created to combine certain functional modules in order to make the input requirements less complex. For the purpose of criticality analysis, only four functional modules and one control module are used. These Modules are CSAS25, which includes the three dimensional criticality code KENO V.a and the preprocessing codes BONAMI-S, NITAWL-II and XSDRNPM-S.

KENO V.a, in conjunction with a suitable working library of nuclear cross section data, is used to calculate the multiplication factor, k_{eff}, of systems of fissile material. It can also compute lifetime and generation time, energy dependent leakages, energy and region-dependent absorptions, fissions, fluxes, and fission densities. KENO V.a utilizes a three-dimensional Monte-Carlo computation scheme. KENO V.a is capable of modeling complex geometries including facilities for handling arrays, arrays of arrays, and holes.

SCALE 4.4 is set up so that any number of cross-section libraries may be used with the preprocessing functional and control modules. For the purpose of this analysis, only the 44-group ENDF/B V library is used.

The preprocessing codes used for this analysis are the functional modules BONAMI-S, NITAWL-II and XSDRNPM-S. They are consolidated into the control module CSAS25. BONAMI-S has the function of performing Bondarenko calculations for resonance self-shielding. The cross sections and Bondarenko factor data are pulled from an AMPX master library. The output is placed into a master library as well. Dancoff approximations allow for different fuel lattice cell geometries. The main function of NITAWL-II is to change the format of the master cross-section libraries to one that the criticality code (KENO V.a) can access. It also provides the Nordheim Integral Treatment for resonance self-shielding. XSDRNPM-S provides cell-weighted cross sections based on the specified unit cell.

The criticality analysis, using the above computer codes, is performed in compliance with 10CFR 71 [2] and bounds the 10CFR 72 [1] requirements. Transportation regulations (10CFR 71) distinguish between "damaged" and "undamaged" packages. The undamaged condition is denoted "NOC" for Normal Operating Condition and the damaged condition is denoted "HAC" for Hypothetical Accident Condition. The conditions of a damaged package are established by tests that simulate the effects of a cask drop during handling, fire, extremes of summer heat, winter cold and rain. Specifically for criticality analysis, the HAC case eliminates the neutron shield and neutron shield panels and fills the space with moderator.

The KENO V.a model consists of 304 axial layers stacked into an array. The layers consist of partial spacer disk or partial moderator regions of various lengths along the active fuel region as shown in Figure A.6.5.3-1 and Figure A.6.5.3-2. The length of the active fuel is modeled as 150.12 inches but with specular boundary conditions applied it is considered as infinitely long.

The 24PT4-DSC model contains 28 spacer disk regions, each 1.25 inches thick, surrounded by a total of 29 non-disk regions. The center to center spacing of the spacer disk intervals varies over a range from 4 inches to 5.63 inches. An infinite array of casks is created by specifying specular reflection on the ± x and ± y axis and is used for all cases.

Figure A.6.5.3-2 shows the KENO V.a model in an exploded view. UNIT 33 is a 0.25 inch slice through the cask at the 24PT4-DSC spacer disk level. UNIT 34 is a 0.25 inch slice through the moderator region between spacer disks. Units 35 and 36 are the same as UNIT 34 except the length of the slice is increased from 0.25 inches to 4.43 inches and 5.63 inches, respectively.

Figure A.6.5.3-3 shows the structure of the cask at the 24PT4-DSC spacer disk level (UNIT 33), while Figure A.6.5.3-4 highlights the structure of the cask at the moderator region between spacer disks (UNIT 34). Note that the difference between the two is that UNIT 33 has a spacer disk (steel surrounding fuel assemblies) and UNIT 34 has steel support rods in addition to water surrounding fuel assemblies. The fuel assemblies are identified in Figure A.6.5.3-3 and Figure A.6.5.3-4 by the position numbers (1-24) which are used to refer to their unique locations. UNIT numbers 1-8, 101-108, and 201-208 are used to represent the active fuel assemblies in both the spacer disk region and in the moderator region differing only in the UNIT heights. The fuel assemblies are inserted into the model using KENO's HOLE capability.

A detail of the guidesleeve and fuel assembly is shown in Figure A.6.5.3-5. The KENO V.a cases model the square tube, Boral® sheets (4 per tube for the inner fuel assembly locations and 2 per tube for the outer fuel assembly locations), and a stainless steel oversleeve wrapper, not shown, which holds the Boral® sheets in place. Note that the absorber sheets on the outer periphery of the basket (12 sheets total) are not needed due to neutron leakage through the cask walls.

The analytical results reported in Appendix A.2.13.1 demonstrate that the cask containment boundary and canister basket structure do not experience any significant distortion under hypothetical accident conditions. The maximum local plastic deformation calculated in Appendix A.2.13.8 is less than 0.1 inch and is well below the precision of the KENO V.a models.

The fuel assembly drop analyses documented in Appendix A.2.13.11 also demonstrate that the fuel rods do not experience any deformation significant to cause a change in the fuel geometry that increases the fuel assembly reactivity. The fuel assembly drop analyses results for HAC demonstrate that the fuel rods experience small permanent plastic deformation that results in a statistically insignificant change in the fuel assembly pitch.

The analyses performed are based on a completely flooded 24PT4-DSC. Slots are provided at the bottom of the guidesleeves and openings are provided at the bottom and sides (near the bottom) of the failed fuel cans to ensure uniform draining and filling of all areas of the 24PT4-DSC. The failed fuel can openings are screened to contain potentially loose pellets or debris.

The models developed are conservative. Major conservatisms in the models are:

- No cases have been made to model fission products, absorber materials (^{10}B, Gadolinia or Erbia, etc.) in the burnable poison rods, or axial and radial variations in initial fuel enrichment. Instead, fuel assemblies have been modeled as if they were composed of only a single enrichment unirradiated fuel. This results in a very large margin of conservatism in the calculated keff.

- Only 75% credit for the boron in the Boral® panels is taken in the criticality evaluation.
- Poison rodlets are placed only in the guide tubes of the intact assemblies located in Zone C of Figure A.6.5.3-18.

The major assumptions made in the analyses are:

- No credit is taken for soluble boron in the spent fuel pool. All moderation is assumed to be from pure water. No credit is taken for neutron absorption in water impurities.
- Omission of spacer grids, spacers, and hardware in the fuel assembly. This is conservative because this material results in parasitic neutron absorption and displaces moderating material reducing the fuel assembly k_{eff}.
- The maximum fuel pin enrichment is modeled as uniform everywhere throughout the assembly. Natural Uranium blankets, Erbia Rods, and axial or radial enrichment zones are modeled as fully enriched uranium. It is assumed that the fuel assemblies are of uniform enrichment everywhere. All fuel rods are assumed to be filled with 100% moderator in the fuel/cladding gap to account for the possibility of water being entrained in the fuel pin and because it has a slight positive effect on reactivity.
- The fuel assemblies are conservatively modeled as infinitely long.
- The fuel pellet stack density was conservatively modeled at 97% of theoretical density with no allowance for dishing and chamfer, although this assumption conservatively increases the total fuel content in the model.
- The burnable absorber rod material is modeled as pure (11B) 4C only. Modeling the poison as (11B) 4C is appropriate since the net effect is to substitute material with a very small thermal absorption cross section for the material, which in reality would contain 10B for a fresh fuel assembly. (11B = 1.10000E-01 atms/bn-cm and C = 2.75000E-02 atms/bn-cm)
- The worst case position tolerance was assumed for all spacer disk cutout locations. This is achieved by utilizing the maximum tolerance on the spacer disk hole dimensions and minimum possible tolerance on the ligament widths. The ligament represents the steel region between spacer disk cutouts. This arrangement effectively moves all the guidesleeve assembly units further inwards thereby minimizing the inter-assembly separation distance. Further, the values utilized in the criticality models for fuel assembly placement are slightly lower than the actual positions bringing the fuel assemblies even closer together. This is the worst case condition for criticality since inter-assembly moderation is minimized, thereby reducing the effectiveness of the neutron absorber plates.
- The fuel is assumed to be intact with no gross damage or missing rods for the intact fuel analyses. Damaged and missing rods are addressed in the damaged fuel analyses.
- Reconstituted fuel assemblies are considered intact unless otherwise specified as damaged fuel assemblies.
- It is assumed for the criticality analyses for all Hypothetical Accident Condition (HAC) cases, the TC neutron shield and stainless steel neutron shield panels are stripped away and replaced with moderator.

- The least material condition (LMC) was assumed for the guidesleeves and wrappers. This minimizes neutron absorption in the steel sheets and poison plates. The "least material condition" means use of those feature dimensions that minimize the amount of material in the part.
- Both the bottom of the bottom spacer disk and the bottom of the guidesleeve and Boral® panel start at the same axial level. The fuel assembly is completely covered by the Boral® panels over the entire active fuel length for the intact fuel analyses.
- The Boral® material is modeled as Al/10B material sandwiched between two thin sheets of pure Al. The Aluminum in the poison material is assumed to have a theoretical density of 70%. This assumption is conservative, as less material leads to less neutron absorption, although aluminum is such a weak absorber that this assumption is within the uncertainty of the Monte Carlo method itself.

Damaged Fuel Assemblies Model

The following additional assumptions were made for the damaged fuel analyses:

- The worst case gross damage resulting from a cask-drop accident is assumed to be either a single-ended or double-ended rod shear with fresh water intrusion.
- The rod pitch is allowed to vary from its nominal fuel rod pitch.
- The single-ended fuel rod shear cases assume that sixteen fuel rods (one assembly face) shear in one place and are displaced to new locations. The fuel pellets are conservatively assumed to remain in the fuel rods. The possibility of fuel rods and/or rod fragments being lodged above or below the Boral® panel height is addressed in the damaged fuel analyses. This was addressed by considering a 16x16 array of bare fuel rods 5.25" long above the active fuel. Additional analyses of one row and two rows of rods displaced 6" above the Boral® panels were performed to address possible repositioning of the fuel during a drop. These results were bounded by the results of the optional pitch study with one row of rods missing.
- The double-ended fuel rod shear cases assume that sixteen fuel rods (one assembly face) shear in two places and the intact fuel rod pieces are separated from the parent fuel rods. The fuel pellets are conservatively assumed to remain in the fuel rods.
- The bounding case crediting poison rodlets was analyzed for a rodlet 2" shorter than the active fuel. This analysis resulted in a change in k_{eff} that was within the statistical uncertainty of the base case.

Table A.6.5.3-3 and Table A.6.5.3-4 summarize the 24PT4-DSC materials and dimensions that were assumed in these analyses.

The fuel parameters used in the criticality calculations for CE 16x16 Fuel Assemblies are listed in Table A.6.5.3-2. The assembly fuel pin loading pattern is given in Figure A.6.5.3-5. The analysis methodology and modeling provide an accurate representation of actual cask configurations with the exception of conservatisms employed and the use of conservative simplifying assumptions.

A.6.5.3.3.2 Neutron Absorber Material Efficacy

The absorber panel material used in the 24PT4-DSC was chosen due to its desirable neutron attenuation, low density, and minimal thickness. It has been used for applications and in environments comparable to those found in spent fuel storage and transportation since the early 1950s (the U.S. Atomic Energy Commission's AE-6 Water-Boiler Reactor). In the 1960s, it was used as a poison material to ship irradiated fuel rods from Canada's Chalk River laboratories to Savannah River. More than 12,000 British Nuclear Fuels, Ltd. (BNFL) flasks containing the material have been used to transport fuel to BNFL's reprocessing plant in Sellafield.

The neutron absorber panels are composed of boron carbide and 1100 alloy aluminum. Boron carbide provides the necessary content of the neutron absorbing ^{10}B isotope in a chemically inert, heat resistant, highly crystalline and extremely hard form. Boron carbide contained in the panels does not react under these conditions. The boron carbide core is tightly held within an 1100 aluminum alloy matrix and further protected by solid 1100 aluminum alloy cladding plates. Although 1100 alloy aluminum is a chemically reactive material; it behaves much like an inert material when properly applied. Proper application includes due consideration to the formation of a highly protective aluminum oxide layer and allowance for creation of the reaction by-product hydrogen.

Aluminum reacts with water to produce hydrogen (H_2) and an impervious tightly adhering layer of hydrated aluminum oxide ($Al_2O_3 \bullet 3H_2O$) called bayerite which protects the surface from further attack.

When the 24PT4-DSC basket is initially submerged in the spent fuel pool, aluminum in the panels will react with water to form a small amount of hydrogen gas and a stable bayerite layer on all surfaces of the panel. The bayerite layer formed on the panel during pool immersion persists through 24PT4-DSC drying, sealing, storage, and eventual shipping, preventing further corrosion or hydrogen production.

Leaching of the boron carbide along the unsealed edges of the panels is expected to occur to an insignificant degree. There are three reasons why this is anticipated to be insignificant. First, the panel core is a sintered Al/B_4C material. Only the boron carbide particles exposed by saw cut are available for leaching. Second, the immersion environment is relatively benign and the time is brief (a few hours or days). The material has been commonly used in the United States spent fuel racks for many years and, in fact, has gained a reputation for not leaching. And third, direct experimental observations of accelerated aging tests performed at the University of Michigan [10] showed no indications of boron degradation. The test specimens were exposed to high neutron and gamma irradiation in a reactor pool environment for over nine years. Subsequent neutron radiography showed no signs of reduced neutron attenuation anywhere on the test specimens.

Depletion of the ^{10}B in the neutron poison plates is evaluated below. Although the license period of the cask is 20 years, actual storage time could be much longer. Using an estimated scalar flux of 5.0×10^5 n/cm^2-s at the center of the basket, and the thermal neutron cross section for ^{10}B of 3837 barn [9], the fraction of the original ^{10}B depleted after 1000 years would be:

$$5 \times 10^5 \text{n/cm}^2\text{-s} \times (3837 \times 10^{-24} \text{ cm}^2) \times 3.156 \times 10^7 \text{ s/year} \times (1000 \text{ year}) = 1.1 \times 10^{-6}$$

which is negligible. Therefore, the continued efficacy of the neutron poison is assured.

A.6.5.3.4 Criticality Calculations

This section contains descriptions of the calculational methods used to determine the nuclear reactivity for the maximum fuel loading intended to be stored in the 24PT4-DSC.

A.6.5.3.4.1 Calculational Method

The effective neutron multiplication factor (k_{eff}) was calculated using the CSAS25 module of the SCALE 4.4 Code with the 44-group ENDF/B-V cross-section library [3]. The control module CSAS25 includes the three dimensional criticality code KENO V.a and the preprocessing codes BONAMI-S, NITAWL-II and XSDRNPM-S.

All the input decks were run with 500 generations with 1000 neutrons per generation. Five neutron generations were omitted before collecting the results. These values provided for a well converged solution.

Section A.6.*5.3.8* contains a listing of select KENO V.a input files.

A.6.5.3.4.2 Fuel Loading Optimization

A Determination of the Most Reactive Intact Fuel Configuration

The following parametric studies were performed for a Boral® sheet with 0.025 g/cm^2 ^{10}B areal density at a maximum fuel enrichment of 4.2 wt. % ^{235}U (except as noted) to determine the worst case geometry. This fuel to poison plate combination is designed to be similar in reactivity to the combination of 0.068 g/cm^2 ^{10}B areal density at a maximum fuel enrichment of 4.85 wt. % ^{235}U and therefore, the results from the parametric studies are applicable to all the fuel to poison plate combinations discussed in this chapter.

1. Most Reactive Fuel Pellet OD assuming 236 fuel rods in the fuel assembly.
2. Most Reactive Fuel Clad Thickness using the worst case model from Step 1.
3. Most Reactive Fuel Rod OD using the worst case model from Step 2.
4. Most Reactive Fuel Assembly using the worst case model from Step 3 and varying the absorber rod configurations for an enrichment of 4.1 wt. % ^{235}U.
5. Boral® Sheet Thickness using the worst case model from Step 4.

The following studies were performed for both a Boral® sheet with 0.025 g/cm^2 ^{10}B areal density at a maximum fuel enrichment of 4.1 wt. % ^{235}U and 0.068 g/cm^2 ^{10}B areal density at a maximum fuel enrichment of 4.85 wt. % ^{235}U using the worst case geometry as determined in Step 6:

6. Most Reactive Fuel Assembly Position using the worst case model from Step 5 (both the fuel/poison design are investigated).
7. Internal Moderator Density Varying.
8. External Moderator Density Varying.

A parametric study on the reactivity effect of the tolerance on the spacer grid was not performed because it is unlikely that biases at a specific location on all 11 spacer grids would be the same magnitude and in the same direction. Therefore only the nominal pitch was used in the criticality calculations.

Fuel Pellet OD Study

The first series of analyses determined the most reactive fuel pellet outer diameter (OD). The maximum fuel enrichment of 4.2 wt. % ^{235}U and a poison plate ^{10}B loading of 0.01875 g/cm^2 are used in the model. (Note that the 0.01875 g/cm^2 used in the model is 75% of the 0.025 g/cm^2 for a maximum lattice average enrichment of 4.2 wt. % ^{235}U). All models use nominal rod pitch, 100% internal and external moderator density, 100% moderator flooded fuel-cladding gap and specular boundary conditions. The most reactive configuration is the nominal pellet diameter (see Table A.6.5.3-5).

Fuel Cladding Thickness Study

The second set of analysis evaluates the effect of fuel clad thickness on the system reactivity. The model starts with the nominal fuel pellet OD case from above and the poison plate thickness is modeled with nominal dimensions. All models assume nominal rod pitch, 100% internal and external moderator density, 100% moderator flooded fuel-cladding gap and specular boundary conditions. The most reactive configuration is the minimum cladding thickness (see Table A.6.5.3-5).

Fuel Cladding OD Study

The third set of analyses evaluates the sensitivity of the system reactivity on fuel cladding OD. The model starts with the nominal fuel pellet OD and the minimum fuel cladding thickness input file from above. All models assume nominal rod pitch, 100% internal and external moderator density, 100% moderator flooded fuel-cladding gap and specular boundary conditions. The most reactive configuration is the minimum clad diameter (see Table A.6.5.3-5).

Burnable Absorber Rod Study

The fourth set of analyses evaluates the sensitivity of the system reactivity to burnable absorber rods included in the fuel assemblies. Note that the ^{10}B in the poison rods is modeled as ^{11}B. The poison rod loading patterns are provided in Figure A.6.5.3-6. The model starts with the nominal fuel pellet OD, the minimum fuel cladding thickness and the minimum clad OD input deck from above except that the fuel enrichment is based on the design basis value of 4.10 wt. % ^{235}U. All models assume nominal rod pitch, 100% internal and external moderator density, 100% moderator flooded fuel-cladding and poison-cladding gap and specular boundary conditions. The most reactive configuration is the zero poison rod configuration (see Table A.6.5.3-5).

Boral® Sheet Thickness Study

The fifth set of analyses evaluates the effect of poison plate thickness on the system reactivity. The model starts with the most reactive dimensions determined above and the poison plate thickness is varied from 0.224 to 0.236 inches. In order to maintain the minimum ^{10}B areal density the gram density of the poison plate material is adjusted in the model. All models assume nominal rod pitch, 100% internal and external moderator density, 100% moderator flooded fuel-cladding gap and specular boundary conditions. The most reactive configuration is the minimum Boral® plate thickness (see Table A.6.5.3-5).

Assembly Position Study

The sixth series of analyses evaluates the effect of the assembly to assembly pitch on the system reactivity. These models represent the most reactive intact fuel models determined above with the assembly-to-assembly pitch varied.

There are four assembly position model types which study how fuel assembly positions within the guidesleeves may affect the system's k_{eff}. Type 1 models the system with all fuel assemblies shifted radially inwards toward the center of the canister. All the fuel assemblies in the middle of the guidesleeves (Type 2) are the same as the worst case model determined in the previous step. Type 3 models all fuel assemblies shifted radially outwards, and Type 4 models all fuel assemblies shifted to the upper left corner of the guidesleeves. Examples of the assembly positions within the guidesleeve are presented in Figure A.6.5.3-7 through Figure A.6.5.3-9. All models use the nominal rod pitch, 100% internal and external moderator density, 100% moderator flooded fuel-cladding gap and specular boundary conditions. This study is performed on both the fuel enrichment / poison loading combination designs of 4.10 wt. % ^{235}U / 0.025 g $^{10}B/cm^2$ and 4.85 wt. % ^{235}U / 0.068 g $^{10}B/cm^2$ to ensure that the relative reactivities are about the same. The results showed that the most reactive assembly position is with the assemblies shifted inwards toward the center of the canister.

Moderator Varying Studies

The seventh set of analyses evaluates the effect of internal and external moderator density on reactivity. The model starts with the most reactive models from above. The internal moderator is varied from 100 to 0 percent full density. The results confirm that the most reactive condition occurs at full internal moderator density.

A second set of runs are also performed which increase the ^{10}B loading from 0.025 g/cm^2 to 0.068 g/cm^2 (less 25%) and an initial fuel enrichment of 4.85 wt. % ^{235}U.

The external moderator density uses the most reactive case with internal moderator (full density) density and the external internal moderator is varied from 100 to 0 percent full density. The results show that the system reactivity is not affected by external moderator density. The variation in the results is due entirely to the statistical uncertainties in KENO V.a.

The HAC models duplicate the NOC moderator variation models outlined above. The only difference between the models is the elimination of the neutron shield and neutron shield panel around the cask. Therefore, in the KENO V.a model, external water replaces both the neutron shield and the stainless steel cylinder around the neutron shield (neutron shield panel).

B Determination of the Most Reactive Damaged Fuel Configuration

There are several mechanisms by which a fuel rod may be breached. These mechanisms may occur while the fuel is loaded in the reactor core, in the spent fuel pool and during transport. In addition, the type and extent of fuel rod breach can be broken down into several categories. For this calculation the method by which the fuel rod is breached is not as important as the extent of the resultant damage. The worst case gross damage resulting from a cask-drop accident is assumed to be either a single-ended or double-ended rod shear with fresh water intrusion. It is possible that the fuel rod pitch may vary. Therefore, this will be evaluated by varying the fuel rod pitch from a minimum pitch of 0.380" to a maximum of 0.551" (limited to the inner guidesleeve opening). All pitch variations assume a uniform rod pitch throughout the entire fuel matrix.

The single-ended fuel rod shear cases assume that a fuel rod shears in one place and is displaced to a new location. The fuel pellets are assumed to remain in the fuel rod. This case will be evaluated by displacing one row of rods (16 rods) from the base fuel assembly matrix at small increments towards the side of the guidesleeves. The base fuel assembly matrix will be at nominal pitch and positioned in the upper left corner of the 24PT4-DSC fuel assembly sleeve to maximize the separation distance between the fuel array and the sheared row of fuel rods. A smaller rod pitch for the base fuel assembly matrix was not chosen because it has been shown from the pitch cases that decreasing the rod pitch decreases reactivity. Increasing the base fuel assembly rod pitch will increase reactivity, however, the resulting model is similar to and is bounded by the rod pitch varying cases presented above and therefore will not be duplicated here.

The double-ended fuel rod shear cases assume that the fuel rod shears in two places and the intact fuel rod piece is separated from the parent fuel rod. Three resulting conditions are exhibited by the occurrence of a double-ended rod shear. These are, the fuel rod piece can remain in place, it can be displaced in the same plane, or it can be displaced to a different plane. The "remain in place" situation results in no deviation from the base fuel assembly matrix, and is therefore considered trivial and will not be evaluated separately. The fuel rod piece displaced in the same plane is equivalent to the single-ended rod shear case discussed above and will not be reevaluated in these cases. The fuel rod piece displaced in a different plane results in two possibilities: an added rod or a removed rod. As in the single-ended shear cases, the base fuel assembly matrix will be positioned in the upper left corner of the 24PT4-DSC guidesleeve to allow room for a row of displaced fuel rods. One row of 16 fuel rods of different lengths will be removed from a section of the assembly and added to another to determine if the system exhibits any trends. The nominal rod pitch of 0.506" is used for the base fuel matrix just as in the single-ended shear rod cases.

It is postulated that during a cask drop accident the neutron shield and its neutron shield panel may be torn away from the cask and replaced with moderator. After all of the previous results are tabulated, an analysis is performed to determine to what degree the multiplication factor, k_{eff}, is affected by the removal of the cask neutron shield panel and subsequent replacement with moderator.

The first step is to determine the most reactive damaged fuel assembly geometry. This was completed using the 0.068 g/cm^2 ^{10}B areal density with 4.85% enriched fuel. All 24 assembly locations were filled with damaged fuel assemblies. The intent of these calculations was to determine the most reactive geometry, not meet the USL. The following is a breakdown of runs made in this analysis:

- Optimum Rod Pitch Study including enough missing fuel rods in an assembly to demonstrate that the worst case fuel geometry has been determined.
- Single-ended Shear Study.
- Double-ended Shear Study.
- Worst Configuration External Moderator Density Varying.
- Worst Single-ended and Double-ended Shear Configuration modeled with Bare Damaged Rods and External Moderator Density Varying.

- Rows of bare rods added to a fuel assembly to bound any possible relocation of fuel pellets.
- Addition of sheared rods below the poison sheet height.

With the selection of the most reactive damaged fuel assembly geometry, the next set of analyses determined the maximum k_{eff} for various damaged fuel assembly loading configurations in the 24PT4-DSC. Cases are run for both Boral® sheets with areal densities of 0.025 g/cm^2 and 0.068 g/cm^2. For both sets of cases, the maximum acceptable ^{235}U enrichment are determined for 12 damaged fuel assemblies loaded around the outside assembly locations and for only 4 damaged fuel assemblies loaded in the assembly locations on the diagonal using the most reactive damaged fuel assembly geometry. The following sets of analyses are performed:

- Maximum enrichment for the 0.068 g/cm^2 ^{10}B areal density, 4 damaged fuel assemblies loaded in the diagonal assembly positions, undamaged fuel in the remaining locations.
- Maximum enrichment for 0.068 g/cm^2 ^{10}B areal density, 12 damaged fuel assemblies loaded around the outside of the 24PT4-DSC, undamaged fuel in the remaining locations.
- Maximum enrichment for 0.025 g/cm^2 ^{10}B areal density, 4 damaged fuel assemblies loaded in the diagonal assembly positions, undamaged fuel in the remaining locations.
- Maximum enrichment for 0.025 g/cm^2 ^{10}B areal density, 12 damaged fuel assemblies loaded around the outside of the 24PT4-DSC, undamaged fuel in the remaining locations.

Rod Pitch Study

The first set of damaged fuel analyses involved a study on the effect of the fuel rod pitch on system reactivity. KENO V.a models with rod pitches ranging from 0.380 inches to 0.551 inches are created. All models assume 100% internal and external moderator density, 100% moderator flooded fuel-cladding gap and specular boundary conditions. Results of this analysis (shown in Table A.6.5.3-10) show that the maximum pitch of 0.551" (limited by the inner diameter of the guidesleeve) was the most reactive fuel rod pitch.

Once the most reactive pitch was determined, a series of calculations were performed that added or subtracted fuel rods from the base assembly to determine the limiting fuel assembly geometry. The removal of fuel rods was restricted to those in the interior locations of the 16x16 lattice. The selection of the rod loading patterns is aimed at maximizing the reactivity and those that are investigated are representative. All combinations of fuel rod positions are not investigated here. It is expected that the reactivities of other cases (not investigated) with the same number of rods but with different loading patterns are within statistical uncertainty. All models assume a rod pitch of 0.551 inches. These results are shown in Table A.6.5.3-11.

In addition to the postulated damaged assembly mechanisms, a damaged fuel assembly arrangement in the form of a rod storage basket is also analyzed. Rod storage baskets are typically used to store damaged fuel rods. A representative and conservative 9x9 arrangement of fuel in this basket is analyzed with two different rod pitches - 0.551 inches and 1.033 inches (corresponding to a grid-sleeve ID of 8.65 inches). All models assume 100% internal and external moderator density, 100% moderator flooded fuel-cladding gap and specular boundary conditions. These results are also shown in Table A.6.5.3-11.

Single-ended Rod Shear Study

The next set of analyses performed is the single-end rod shear study. The Single-ended Rod Shear Study depicts a 16x16 fuel assembly with its last row of rods torn away from the rest of the assembly. The displacement of the dislocated row of torn rods varies radially from fuel assembly up to 0.4738 inches (next to the side of the guidesleeve).

To model this in KENO, a 15x16 fuel assembly array is created along with a 1x16 row of fuel rods. The 15x16 array is pushed up against the upper left hand corner of the guidesleeve to allow for the most room for the displacement of the dislocated 1x16 row of fuel rods. The displaced row of rods is then shifted toward the side of the guidesleeve by varying increments. The amount of fuel remains the same, i.e. no new fuel is added to the system. Nominal rod pitch of 0.506 inches is used for the base 15x16 fuel assembly. The rod pitch studies outlined above show that a decrease in the fuel rod pitch results in a decrease in system reactivity, therefore for the single-ended rod shear study runs, rod pitch is modeled at nominal value. Results of this study (shown in Table A.6.5.3-12) show that the most reactive Single-ended shear case occurs with the sheared row of fuel rods moved 0.55" away from the rest of the fuel assembly.

A graphical representation of the single-ended shear models is provided in Figure A.6.5.3-10. The Δ shown is used to show the separation of the sheared rows distance from the base assembly. All models assume 100% internal and external moderator density, 100% moderator flooded fuel-cladding gap and specular boundary conditions.

Double-ended Rod Shear Study

The three Double-ended Rod Shear cases model a row (1x16 array) of dislocated rods severed at different sections axially and then displacing to other sections of the 24PT4-DSC in order to define a conservative bounding condition for fuel rod location subsequent to a double-ended rod shear. The first run models an outer row of fuel breaking off at the top third of an assembly and then displacing itself to the second third of the assembly, creating a 15x16 assembly at the top third, a 16x16 assembly with an additional 1x16 row of fuel rods at the middle third and a standard 16x16 assembly at the bottom third of the canister. Similar scenarios except with the movement of one exterior row of 1/4 and 1/2 of the fuel assembly length are also modeled. Results of the double-ended rod shear study (shown in Table A.6.5.3-13) show that the movement of one exterior row of 1/2 of the fuel assembly length is the most reactive.

The same rod pitch assumptions made for the Single-ended Shear runs also apply here. The base 16x16 fuel rod matrices are shifted to the top left hand corner. All models assume nominal rod pitch, 100% internal and external moderator density, 100% moderator flooded fuel-cladding gap and specular boundary conditions. A graphical representation of the model including the sheared views along the length of the fuel assembly is shown in Figure A.6.5.3-11.

Most Reactive Configurations

Out of all the damaged fuel runs completed above, the rod pitch of 0.551" with 16 missing rods has the highest reactivity of 0.9847± 0.0012. A set of external moderator varying runs are made with this same configuration.

Additionally, a series of bare rod (replacement of cladding with moderator) external moderator varying runs are performed using the most reactive single-ended shear case and double-ended

shear case. These two cases are modified to reflect the desired external moderator density as well as replacing the sheared row's cladding with internal moderator.

External Moderator Varying for Rod Pitch Case

Mixture 9, which is the mixture ID number for the system's external moderator, is changed for each external moderator case being modeled to cover densities from 0.0001 to 1.0000 g/cm^3. These results are shown in Table A.6.5.3-14.

External Moderator for Single-ended Shear Case

The effect of bare sheared rod is investigated to determine the most reactive single sheared configuration. UNIT 31, UNIT 131, and UNIT 231 are created to model the bare damaged rods . It is similar to UNIT 29 with the exception of the cladding material being replaced with internal moderator. The single row of damaged fuel pins are also modified and linked to the appropriate bare fuel cards. The most reactive single shear case is based on a separation distance of 0.55" with cladded damaged rods. Mixture 9, which is the mixture ID for the system's external moderator, is changed for each external moderator case being modeled. These cases cover moderator densities from 0.0001 to 1.0000 g/cm^3. These results are shown in Table A.6.5.3-15.

External Moderator for Double-ended Shear Case

The effect of bare sheared rod is investigated to determine the most reactive double sheared configuration. UNIT 329 is created to model the bare damaged rods. It is similar to UNIT 29 with the exception of the cladding material being replaced with internal moderator. The most reactive double shear case is based on "1/2 shear" with bare damaged rods. Mixture 9, which is the mixture ID for the system's external moderator, is changed for each external moderator case being modeled. These cases cover moderator densities from 0.0001 to 1.0000 g/cm^3. These results are shown in Table A.6.5.3-16.

Bare Rods and Loose Fuel Pellets Added to a Fuel Assembly

In order to ensure that the worst case geometry is identified by the above cases, two further cases are run. Rows of bare fuel rods were added to intact fuel assemblies to bound the possible movement of loose fuel pellets. To model this in KENO, a 16x16 fuel assembly array is created along with a 1x17 and a 16x1 row of fuel rods. The 16x16 array is pushed up against the lower left hand corner of the guidesleeve to allow for the most amount of room for the placement of the dislocated 1x17 row and 16x1 row of bare fuel rods to create a 17x17 array, as shown in Figure A.6.5.3-12.

Another scenario that was modeled was the accumulation of fuel pellets in the 5.25-inch space between the top of the poison sheet and the bottom of the 24PT4-DSC lid. It is assumed that the fuel pellets stay stacked on top of each other and also retain the 16x16 lattice configuration. To achieve this, a 16x16 array of bare fuel rods was added in the 5.25 inches of uncovered space to the most reactive normal fuel geometry (fuel assembly in the inward most position). These results are shown in Table A.6.5.3-17.

This analysis bounds a loading configuration where loose pellets, from any on-site source (e.g., other reactor fuel sharing the same fuel pool), may be stored in a failed fuel can as long as the fuel pellet enrichment are within the parameters specified in Table A.6.5.3-2 and the total UO_2 in the failed fuel can does not exceed that associated with a CE 16x16 fuel assembly.

Worst Case Damaged Reactivity

The most reactive damaged fuel assembly geometry is determined to be the fuel rod pitch of 0.551" with 16 missing rods, 100% internal and external moderator density, 100% moderator flooded fuel-cladding gap and specular boundary conditions. The next set of analyses is performed to determine the maximum k_{eff} for various damaged fuel assembly loading patterns. Cases are run for both Boral® sheets with areal densities of 0.025 g/cm^2 and 0.068 g/cm^2. For both sets of cases, the maximum acceptable ^{235}U enrichment is determined for 12 damaged fuel assemblies loaded around the outside assembly locations and for only 4 damaged fuel assemblies loaded in the assembly locations on the diagonal. The following set of analyses was performed:

- Maximum enrichment for the 0.068 g/cm^2 ^{10}B areal density and 4 damaged fuel assemblies loaded in the diagonal assembly positions.
- Maximum enrichment for 0.068 g/cm^2 ^{10}B areal density and 12 damaged fuel assemblies loaded around the outside of the 24PT4-DSC.
- Maximum enrichment for 0.025 g/cm^2 ^{10}B areal density and 4 damaged fuel assemblies loaded in the diagonal assembly positions.
- Maximum enrichment for 0.025 g/cm^2 ^{10}B areal density and 12 damaged fuel assemblies loaded around the outside of the 24PT4-DSC.

The normal fuel assembly geometry represents the most reactive intact fuel models with the assemblies shifted radially inwards toward the center of the 24PT4-DSC assuming 100% internal and external moderator density, 100% moderator flooded fuel-cladding gap and specular boundary conditions. For the configurations with both intact and damaged fuel assemblies loaded in a single 24PT4-DSC, modifications in the KENO V.a input files are necessary to represent both the fuel lattices accurately. The fuel lattice data for the damaged fuel assemblies are provided through the "more data" card while those for the intact fuel assemblies are provided through the usual "squarepitch card". This is due to the limitation of KENO V.a to handle only one "squarepitch card." The resonance absorption details in the damaged fuel lattice is input to the model via the Dancoff factor. Since, this is an input value, it is necessary that the value utilized should be correct if not conservative. The Dancoff factor for damaged fuel assemblies is obtained from previous KENO V.a output files for fuel that matches the geometry of the damaged fuel. The maximum enrichment models are then generated by loading the appropriate damaged fuel assembly into the location necessary for the cases being investigated.

Examples of a slice through the 24PT4-DSC are presented in Figure A.6.5.3-13 and Figure A.6.5.3-14. All normal fuel assembly models assume nominal rod pitch and all models assume 100% internal and external moderator density, 100% moderator flooded fuel-cladding gap and specular boundary conditions for the normal assemblies.

For the 12 damaged assembly model, the maximum enrichments determined above will be less than the desired values of 4.85 and 4.10 wt. % ^{235}U for the boron-10 areal densities of 0.068 and 0.025 g/cm^2, respectively. For these cases, poison rodlets, composed of either Borated Stainless Steel or B_4C encased in a thin walled stainless steel tube, are added to each undamaged fuel assembly in order to increase the allowable damaged fuel enrichment for both 0.025 (4.1 ^{235}U wt. %) and 0.068 ^{10}B areal density (4.85 ^{235}U wt. %) The worst case damaged fuel model was modified to include the 5 guide tubes per assembly. The poison rodlets are then inserted into the guide tubes to provide enough negative reactivity to reach the desired enrichment levels, as

shown in Figure A.6.5.3-15. The required number of poison rodlets for each undamaged fuel assembly for the two poison plate designs is determined in this study

The worst case damaged reactivity models described above are for a cask with NOC geometry, i.e., the neutron shield and stainless steel skin are present. To examine the effects on k_{eff} of removing the neutron shield and pushing the casks closer together, the cases with the poison rodlet are also run for this condition.

C Fuel Assembly Replacement

An analysis is conducted to demonstrate that the removal of the four center fuel assembly locations in the 24PT4-DSC is bounded by the USL. The worst case normal geometry was modified to remove the four center fuel assemblies. The models generated have the same geometry as presented previously except that up to four of the center fuel assembly locations are empty, as shown in Figure A.6.5.3-16.

D Assembly Reconstitution

Reconstituted fuel assemblies are those in which the damaged fuel pins are replaced with solid stainless steel pins or fuel pins with the same or lower enrichment and are considered as intact fuel assemblies. There are five models to study the effects of fuel rod reconstitution on the k_{eff} of the system on the worst case normal (intact) fuel geometry. KENO V.a models with rod pitches ranging 2 to 10 replacement stainless steel rods were created. An example of 10 reconstituted rods included in a fuel assembly is shown in Figure A.6.5.3-17. All models use 100% internal and 100% external moderator densities.

A.6.5.3.4.3 Criticality Results

The results for each case are presented in the following sections. These results are compared to the upper subcritical limit (USL=0.9411) to determine the limiting k_{eff} for the 24PT4-DSC for normal and accident conditions and determine the acceptability of the criticality analysis.

The worst case geometry is selected based on a series of parametric studies (see Section A.6.5.3.4.2). The results for the effect of fuel pellet OD show that there was no significant statistical variation between the results for different fuel pellet diameters analyzed and therefore the nominal fuel pellet OD was selected as the worst case. Based on the results of the clad thickness evaluation, the balance of the calculations used the minimum fuel clad thickness because it represented the more reactive condition. The fuel clad OD analysis showed that there was no significant statistical variation between the results. Therefore, the fuel clad was modeled with the minimum fuel clad OD. Results of the analysis to determine the effect of the burnable poison rods on the fuel assembly reactivity showed that it is conservative to model fuel assemblies as consisting completely of fuel rods with no integral burnable poison rods. The analysis of the effect of the Boral® plate thickness showed that there was no significant statistical variation between the results. Therefore, since the minimal thickness was slightly more reactive, it was selected as the worst case. The results of the assembly position study showed that the most reactive assembly position is with the assemblies shifted radially inwards toward the center of the canister. The worst case model was then the combination of the results of the above studies.

The maximum k_{eff} for NUHOMS® 24PT4-DSC system loaded with 24 CE 16x16 Fuel Assemblies using the 0.068 g/cm^2 ^{10}B areal density was determined to be 0.9365±0.0012 (0.9389

w/2 σ) with a ^{235}U maximum enrichment of 4.85 wt. %, an internal moderation at 1.0 g/cm^3, 0.3 g/cm^3 external moderation, and pure water in the fuel-cladding gap. The maximum k_{eff} for NUHOMS® 24PT4-DSC system loaded with 24 CE 16x16 Fuel Assemblies using the 0.025 g/cm^2 ^{10}B areal density was determined to be 0.9361±0.0011 (0.9383 w/2 σ) with a ^{235}U maximum enrichment of 4.1 wt. %, an internal moderation at 1.0 g/cm^3, 1.0 g/cm^3 external moderation, and pure water in the fuel-cladding gap.

The most reactive damaged fuel assembly configuration was determined based on the results of the pitch variation calculations. These results indicate that the most reactive damaged fuel assembly configuration consisted of a 16X16 fuel lattice arranged with a pitch of 0.551" and 16 rods missing. A few other damaged configurations are also investigated including the single and double shear configurations and the rod storage basket with a 9x9 lattice at maximum pitch. An examination of the damaged configuration study indicates that the difference in reactivity between the most reactive configuration and all the other configuration is at least 0.02 in delta-k_{eff} units. Even though, missing rod configurations greater than 20 were not investigated, it is expected that the k_{eff} will be lower for these arrangements. Therefore, the fuel assembly represented by a 16x16 arrangement of CE fuel pins with 16 missing rods forms the design basis fuel assembly to represent the damaged fuel.

Results of worst case damaged fuel analyses show that for the loading of 4 damaged fuel assemblies on the diagonal, the maximum enrichment for both the 0.025 g/cm^2 ^{10}B areal density and for 0.068 g/cm^2 ^{10}B areal density is the same as the normal fuel assembly; 4.1 wt. % ^{235}U and 4.85 wt. % ^{235}U, respectively. The loading of 12 damaged fuel assemblies around the outer perimeter of the 24PT4-DSC shows that the maximum fuel pin enrichment in the damaged fuel assemblies must be limited to 3.7 wt. % ^{235}U for the 0.025 g/cm^2 ^{10}B areal density and 4.1 wt. % ^{235}U for 0.068 g/cm^2 ^{10}B areal density.

The maximum k_{eff} for NUHOMS® 24PT4-DSC system loaded with 4 CE 16x16 Damaged Fuel Assemblies using the 0.068 g/cm^2 ^{10}B areal density was determined to be 0.9360±0.0011 (0.9382 w/2σ) with a ^{235}U maximum enrichment of 4.85 wt. %, an internal moderation at 1.0 g/cm^3, 1.0 g/cm^3 external moderation, and pure water in the fuel-cladding gap. The maximum k_{eff} for NUHOMS® 24PT4-DSC system loaded with 4 CE 16x16 Damaged Fuel Assemblies using the 0.025 g/cm^2 ^{10}B areal density was determined to be 0.9337±0.0012 (0.9361 w/2 σ) with an ^{235}U maximum enrichment of 4.1 wt. %, an internal moderation at 1.0 g/cm^3, 1.0 g/cm^3 external moderation, and pure water in the fuel-cladding gap.

The maximum k_{eff} for NUHOMS® 24PT4-DSC system loaded with 12 CE 16x16 Damaged Fuel Assemblies using the 0.068 g/cm^2 ^{10}B areal density was determined to be 0.9367±0.0012 (0.9391 w/2σ) with a ^{235}U maximum enrichment of 4.1 wt. %, an internal moderation at 1.0 g/cm^3, 1.0 g/cm^3 external moderation, and pure water in the fuel-cladding gap. The maximum k_{eff} for NUHOMS® 24PT4-DSC system loaded with 12 CE 16x16 Damaged Fuel Assemblies using the 0.025 g/cm^2 ^{10}B areal density was determined to be 0.9369±0.0012 (0.9393 w/2 σ) with an ^{235}U maximum enrichment of 3.7 wt. %, an internal moderation at 1.0 g/cm^3, 1.0 g/cm^3 external moderation, and pure water in the fuel-cladding gap.

The discussion in the preceding paragraph did not include the use of poison rodlets in the assembly guide tubes. In order to load fuel at the highest enrichment (of 4.10 wt. % ^{235}U) for the 0.025 g/cm^2 Boral® poison cases, a single poison rodlet in the center guide tube of the fuel assemblies was determined to be sufficient. Similarly, to load fuel at the highest enrichment (of

4.85 wt. % ^{235}U) for the 0.068 g/cm^2 Boral® poison cases, five poison rodlets in each intact fuel assembly (maximum rodlets per assembly) was determined to be sufficient. These poison rodlet cases were run with both NOC and HAC cask geometry. The values obtained for k_{eff} demonstrate that replacing the neutron shield skin with moderator has relatively minimal effect on the system reactivity.

These calculations show that the system k_{eff} remains about the same if one fuel assembly is removed from the above configuration (11 intact fuel assemblies with five poison rodlets each and 12 damaged fuel assemblies). This is due to the fact that the removal of the highly absorbing poison rodlets from the system approximately compensates for the effect of removing fissile material (an intact fuel assembly). However, all these were carried out at full moderator density conditions. Several calculations involving dry damaged fuel assemblies were also performed. The results indicate that the most reactive "dry" fuel is the one with 4 damaged fuel assemblies, with an enrichment of 4.10 wt. % ^{235}U, a Boral® poison loading of 0.025 g/cm^2 and the k_{eff} for this case is 0.4356±0.0005 (0.4366 w/2σ).

The calculations also show that the system k_{eff} decreases as the separation between adjacent assemblies increases. Thus, removing an assembly from the 24PT4-DSC results in an effective increase in the assembly separation decreasing the system eigenvalue. Also, since the assemblies are inside the guidesleeve and the Boral® plates, when an assembly is replaced by water, there will be a flux trap where fast neutrons enter the tube. The neutrons thermalize, but on average, do not escape because of the highly preferential thermal neutron flux trap made by the guidesleeve and the 1/v Boral® plate absorbers. Thus, the system k_{eff} decreases with the removal of fuel assemblies. In addition, the reconstitution of fuel rods with up to 10 stainless steel rods reduces the amount of reactive material in the fuel assembly thereby reducing the system k_{eff}. Fuel assemblies with reconstituted rods are considered intact fuel assemblies and are bounded by the results of the intact fuel calculations since they are shown to be less reactive. Results of all the cases run are presented in Table A.6.5.3-21.

A.6.5.3.5 Summary and Conclusions

In summary, the criticality analysis for the Advanced NUHOMS® -24PT4 DSC system demonstrates that the maximum k_{eff} value is below the USL of 0.9411 for a variety of loading configurations under normal and hypothetical accident conditions. The criticality of the system is analyzed utilizing two types of Boral® loadings in the basket, a normal loading of 0.025 g $^{10}B/cm^2$ and a high loading of 0.068 g $^{10}B/cm^2$. The allowable storage configurations for both ^{10}B loadings for the various fuel assembly types are summarized below and in Table A.6.5.3-21:

A.6.5.3.5.1 Summary of 24PT4-DSC Limits with Normal ^{10}B Loading of 0.025 g/cm^2

Limits for Intact Fuel (no damaged fuel assemblies)

- Intact fuel assemblies (including reconstituted fuel assemblies) can be stored in all 24 fuel assembly locations. Empty locations are allowed.
- The maximum permissible initial fuel enrichment of the fuel assemblies is 4.10 wt. % ^{235}U.

General Limits for Damaged Fuel

- There is no limit on the number of damaged rods in a single fuel assembly. Also, there is no limit on the number of missing rods that constitute a damaged fuel assembly.
- Damaged fuel assemblies can only be stored in the Type A spacer hole positions. These are the fuel assembly positions along the outer periphery of the 24PT4-DSC basket. A maximum of 12 damaged fuel assemblies can be stored per 24PT4-DSC.

Limits for Damaged Fuel without Poison Rodlets

- A maximum of four damaged fuel assemblies at an initial enrichment of 4.10 wt. % ^{235}U can be stored in the four corner locations (positions #5, #11, #17 and #23, see Figure A.6.5.3-7) along with intact fuel assemblies. The remaining intact fuel assemblies are also limited to an initial enrichment of 4.10 wt. % ^{235}U.
- For the case of 5 to 12 damaged fuel assemblies, the initial enrichment of the damaged fuel assemblies is limited to 3.70 wt. % ^{235}U. The remaining intact fuel assemblies are limited to an initial enrichment of 4.10 wt. % ^{235}U.

Limits for Damaged Fuel with Poison Rodlets (5 to 12 damaged fuel assemblies)

- For the case of 5 to 12 damaged fuel assemblies, if a poison rodlet is inserted into the center position of each intact fuel assembly, the maximum permissible fuel enrichment of each damaged fuel assembly is 4.10 wt. % ^{235}U. The maximum enrichment of the intact fuel assemblies is also 4.10 wt. % ^{235}U. Empty intact fuel assembly locations are permissible. Poison rodlets are not required for intact assemblies in Zone A or B positions (see Figure A.6.5.3-18), if present.

A.6.5.3.5.2 Summary of 24PT4-DSC Limits with High ^{10}B Loading of 0.068 g/cm^2

Limits for Intact Fuel (no damaged fuel assemblies)

- Intact fuel assemblies (including reconstituted fuel assemblies) can be stored in all 24 fuel assembly locations. Empty locations are allowed.
- The maximum permissible initial fuel enrichment of the fuel assemblies is 4.85 wt. % ^{235}U.

General Limits for Damaged Fuel

- There is no limit on the number of damaged rods in a single fuel assembly. Also, there is no limit on the number of missing rods that constitute a damaged fuel assembly.
- Damaged fuel assemblies can only be stored in the Type A spacer hole positions. These are the fuel assembly positions along the outer periphery of the 24PT4-DSC basket. A maximum of 12 damaged fuel assemblies can be stored per 24PT4-DSC.

Limits for Damaged Fuel without Poison Rodlets

- A maximum of four damaged fuel assemblies at an initial enrichment of 4.85 wt. % ^{235}U can be stored in the peripheral locations (positions #5, #11, #17 and #23, see Figure A.6.5.3-4) along with intact fuel assemblies. The remaining intact fuel assemblies are also limited to an initial enrichment of 4.85 wt. % ^{235}U.
- For the case of 5 to 12 damaged fuel assemblies, the initial enrichment of the damaged fuel assemblies is limited to 4.10 wt. % ^{235}U. The remaining intact fuel assemblies are limited to an initial enrichment of 4.85 wt. % ^{235}U.

Limits for Damaged Fuel with Poison Rodlets (5 to 12 damaged fuel assemblies)

- For the case of 5 to 12 damaged fuel assemblies, if 5 poison rodlets are inserted into each intact inner fuel assembly, the maximum permissible fuel enrichment of each damaged fuel assembly is 4.85 wt. % ^{235}U. The maximum enrichment of the intact fuel assemblies is also 4.85 wt. % ^{235}U. Empty intact fuel assembly locations are permissible. Poison rodlets are not required for intact assemblies in Zone A or B positions (see Figure A.6.5.3-18), if present.

A.6.5.3.6 Critical Benchmark Experiments

Section A.6.5 of [5] provide the details of the methodology and the results for the benchmark verification for the NUHOMS-24PT4 DSC. The USL is calculated in accordance with NUREG-6361 [6] and the basis for the administrative margin is from [7]. Results from the USL evaluation are from Table A.6.5-2 of [5] which is reproduced here as Table A.6.5.3-22.

The minimum value of the USL was determined to be 0.9411 in Table A.6.5-3 of [5] which is reproduced here as Table A.6.5.3-23.

A.6.5.3.7 References

1. Code of Federal Regulations, Title 10, Part 72, "Licensing Requirements for the Independent Storage of Spent Nuclear Fuel and High-Level Radioactive Waste."
2. Code of Federal Regulations, Title 10, Part 71, "Packaging and Transportation of Radioactive Material."
3. "SCALE, A Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluation," NUREG/CR-0200, Rev. 6 (ORNL/NUREG/CSD-2/R6), Vol. I-III, September 1998.
4. Deleted.
5. ANUH-01.0150, Updated Final Safety Analysis Report for the Standardized Advanced NUHOMS® Horizontal Modular Storage System for the Irradiated Nuclear Fuel (UFSAR), Revision 3.
6. U.S. Nuclear Regulatory Commission, "Criticality Benchmark Guide for Light-Water-Reactor fuel in Transportation and Storage Packages," NUREG/CR-6361, ORNL-TM-13211, March 1997.
7. U.S. Nuclear Regulatory Commission, "Recommendations for Preparing the Criticality Safety Evaluation of Transportation Packages," NUREG/CR-5661, ORNL/TM-11936, April 1997.
8. Deleted.
9. J. J. Duderstadt and L. J. Hamilton, "Nuclear Reactor Analysis," John Wiley and Sons, 1976.
10. Burn, Reed R., "Boral™ Accelerated Radiation Aging Tests," Nuclear Reactor Laboratory, University of Michigan, Ann Arbor, Michigan, May 9, 1990.

Proprietary information on pages A.6.5.3-24 to A.6.5.3-24ll withheld pursuant to 10 CFR 2.390

Table A.6.5.3-1
Summary of Limiting Criticality Evaluations[1] for the CE 16x16 Fuel Assembly

.025 g/cm^2 ^{10}B Configuration	Maximum Initial Enrichment ^{235}U	K_{KENO}	σ	K_{eff}	USL
0.025 g/cm^2 ^{10}B, 24 intact assemblies	4.10 wt. %	0.9361	0.0011	0.9383	0.9411
0.025 g/cm^2 ^{10}B, 4 damaged assemblies + 20 intact assemblies, no poison rodlets	4.10 wt. %	0.9337	0.0012	0.9361	0.9411
0.025 g/cm^2 ^{10}B, 12 damaged assemblies + 12 intact assemblies, no poison rodlets	3.70 wt. % damaged assys; 4.1 wt. % intact assys	0.9369	0.0012	0.9393	0.9411
0.025 g/cm^2 ^{10}B, 12 damaged assemblies + 12 intact assemblies, 1 poison rodlet per undamaged fuel assembly	4.10 wt. %	0.9315	0.0013	0.9341	0.9411

0.068 g/cm^2 ^{10}B Configuration	Maximum Initial Enrichment ^{235}U	K_{KENO}	σ	K_{eff}	USL
0.068 g/cm^2 ^{10}B, 24 intact assemblies	4.85 wt. %	0.9365	0.0012	0.9389	0.9411
0.068 g/cm^2 ^{10}B, 4 damaged assemblies + 20 intact assemblies, no poison rodlets	4.85 wt. %	0.9360	0.0011	0.9382	0.9411
0.068 g/cm^2 ^{10}B, 12 damaged assemblies + 12 intact assemblies, no poison rodlets	4.10 wt. % damaged assys; 4.85 wt. % intact assys	0.9367	0.0012	0.9391	0.9411
0.068 g/cm^2 ^{10}B, 12 damaged assemblies + 12 intact assemblies, 5 poison rodlets per undamaged fuel assembly	4.85 wt. %	0.9354	0.0012	0.9378	0.9411

(1) See Figure A.6.5.3-18 for location of damaged fuel assemblies and poison rodlets within the 24PT4-DSC.

Table A.6.5.3-2
Fuel Parameters for Criticality Analysis of the CE 16x16 Fuel Assemblies

Maximum Initial Enrichment	4.85 weight % ^{235}U
Number of Rods	236 fuel rods
Number of Guide Tubes	5 guide tubes
Fuel Rod Material (sintered pellet)	UO_2
Pellet Diameter (nominal, inches)	0.3255
Pellet Density (% theoretical)	97
Clad Material	Zircaloy-4
Clad OD (nominal, inches)	0.382
Clad Thickness (nominal, inches)	0.025
Active Fuel Length (inches)	150
Rod Pitch (inches)	0.506
Guide Tube ID (in)	0.90
Guide Tube OD (in)	0.98

Table A.6.5.3-3
Geometric Parameters Used in the Criticality Analysis

DSC Shell		SS-304*	
Transfer Cask Inner Shell		Stainless Steel	
Transfer Cask Structural Shell		Stainless Steel	
Transfer Cask N-Shield Panel		Stainless Steel	
Transfer Cask N-Shield		Water	
Guidesleeve		Stainless Steel	
Boral® Wrapper		Stainless Steel	
Absorber Material		Boral®	
Spacer Disk		Carbon Steel	
Top & Bottom Outer Cover Plates		Stainless Steel	
Shield Plugs		Lead	
Support Rods		Stainless Steel	
Transfer Cask Gamma Shield		Lead	
Assembly 1	(Centerline with respect to the center of support plate – cm)	13.4048	13.4048
Assembly 2		39.7637	13.4048
Assembly 3		65.6590	13.5255
Assembly 4		13.4048	39.7637
Assembly 5		41.7957	41.7957
Assembly 6		13.5255	65.6590
Assembly 7		-13.4048	13.4048
Assembly 8		-39.7637	13.4048
Assembly 9		-65.6590	13.5255
Assembly 10		-13.4048	39.7637
Assembly 11		-41.7957	41.7957
Assembly 12		-13.5255	65.6590
Assembly 13		-13.4048	-13.4048
Assembly 14		-39.7637	-13.4048
Assembly 15		-65.6590	-13.5255
Assembly 16		-13.4048	-39.7637
Assembly 17		-41.7957	-41.7957
Assembly 18		-13.5255	-65.6590
Assembly 19		13.4048	-13.4048
Assembly 20		39.7637	-13.4048
Assembly 21		65.6590	-13.5255
Assembly 22		13.4048	-39.7637
Assembly 23		41.7957	-41.7957
Assembly 24		13.5255	-65.6590

* DSC shell material SS-316 or SS-316L are also acceptable with no effect on k_{eff}.

Table A.6.5.3-3
Geometric Parameters Used in the Criticality Analysis

(continued)

Support Rod 1 (centerline)	60.96	34.7218
Support Rod 2 (centerline)	-60.96	-34.7218
Support Rod 3 (centerline)	60.96	-34.7218
Support Rod 4 (centerline)	-60.96	34.7218
Support Rod Radius (cm)	1.5875	
DSC Shell Radius (cm)	83.26 to 85.3313	
H_2O Gap Radius	85.3313 to 86.36	
Transfer Cask Inner Shell Radius	86.36 to 87.63	
Transfer Cask Gamma Shield Radius	87.63 to 96.67	
Transfer Cask Structural Shell Radius	96.67 to 100.48	
Transfer Cask Neutron Shield Radius	100.48 to 108.10	
Transfer Cask Neutron Shield Panel	108.10 to 108.58	
Boral® Sheet		
Total Thickness (maximum–inches)	0.236	
Total Thickness (minimum–inches)	0.224	
Al Cover Thickness (nominal–inches)	0.01	
Width (Minimum–inches)	8.16	
Wrapper Thickness (minimum–inches)	0.0148	
Guidesleeve/FF Can (nominal opening size)		
Inner (cm)	21.9710	
Outer (cm)	22.5552	
Spacer Disc Thickness (cm)	3.175	
Inner Spacer Disc Opening Type B	24.2951 x 24.2951	
Outer Spacer Disc Opening Type A (centimeters)	23.5585 x 23.5585	
DSC Height (inches)	196.5	
Top Lid Thickness (inches)	7.24	
Bottom Lid Thickness (inches)	6.88	
Guidesleeve/Boral® Sheet Height (inches)	150.12	

Table A.6.5.3-3
Geometric Parameters Used in the Criticality Analysis

(concluded)

Spacer Disc #	Centerline Location from Bottom of 24PT4-DSC Cavity (cm)
1	12.840
2	26.175
3	39.510
4	52.845
5	68.720
6	84.595
7	101.105
8	118.580
9	136.055
10	153.530
11	171.005
12	188.480
13	205.955
14	223.430
15	240.905
16	258.380
17	275.855
18	293.330
19	310.805
20	328.280
21	344.790
22	361.300
23	377.810
24	392.415
25	407.020
26	419.720
27	432.420
28	445.120

Table A.6.5.3-4
Design Parameters for Poison Material

Boral® (75% ^{10}B) Material Density		
Aluminum		70% theoretical density
^{10}B (0.068 g/cm^2)		0.092957 g/cm^3 (max)
		0.098425 g/cm^3 (min)
		0.095613 g/cm^3 (nom)
^{10}B (0.025 g/cm^2)		0.034175 g/cm^3 (max)
		0.036186 g/cm^3 (min)
		0.0352152 g/cm^3 (nom)
Poison Rodlet Design Parameters		
Borated Stainless Steel Rod		
Material density		7.60 g/cm^3
Composition (by weight)		SS304 (98.25%)
		Boron (1.75%)
Rodlet outer diameter		0.78125 inches (max)
		0.71875 inches (min)
		0.75000 inches (nom)
Rodlet length		171 inches
B_4C Filled Stainless Steel Tube		
Tube	OD	0.750 ± .005
	Wall thickness	0.035 ± .002
Material density	Tube	7.60 g/cm^3
	B_4C	0.70 g/cm
Rodlet length		171 inches

Table A.6.5.3-5
Parametric Study Results – ^{10}B Areal density of 0.025 g/cm^2

Fuel Pellet OD			
k_{KENO}	1 σ	k_{eff}	Description
0.9323	**0.0012**	**0.9347**	**nominal pellet OD**
0.9297	0.0011	0.9319	maximum pellet OD
0.9317	0.0012	0.9341	minimum pellet OD
Cladding Thickness			
k_{KENO}	1 σ	k_{eff}	Description
0.9323	0.0012	0.9347	nominal clad thickness
0.9360	**0.0012**	**0.9384**	**minimum clad thickness**
0.9281	0.0011	0.9303	maximum clad thickness
Cladding OD			
k_{KENO}	1 σ	k_{eff}	Description
0.9360	0.0012	0.9384	nominal clad OD
0.9351	0.0011	0.9373	maximum clad OD
0.9362	**0.0012**	**0.9386**	**minimum clad OD**
Burnable Absorber Rods			
k_{KENO}	1 σ	k_{eff}	Description
0.9290	0.0012	0.9314	16 Poison Rods with water in the gap
0.9273	0.0013	0.9299	16 Poison Rods without water in the gap
0.9265	0.0013	0.9291	12 Poison Rods with water in the gap
0.9286	0.0013	0.9312	8 Poison Rods with water in the gap
0.9323	0.0012	0.9347	4 Poison Rods with water in the gap
0.9331	**0.0013**	**0.9357**	**0 Poison Rods with water in the gap**
Boral Plate Thickness			
k_{KENO}	1 σ	k_{eff}	Description
0.9297	0.0011	0.9319	nominal Boral® plate thickness
0.9328	0.0012	0.9352	maximum Boral® plate thickness
0.9331	**0.0013**	**0.9357**	**minimum Boral® plate thickness**
Assembly Position			
k_{KENO}	1 σ	k_{eff}	Description
0.9361	**0.0011**	**0.9383**	**radially inward (minimum Boral®)**
0.9331	0.0013	0.9357	centered (minimum Boral®)
0.9227	0.0011	0.9249	radially outward (nominal Boral®)
0.9258	0.0012	0.9282	upper left corner (nominal Boral®)

Note: Bold type identifies bounding analysis.

Table A.6.5.3-6
NOC Moderator Varying Results – ^{10}B Areal density of 0.068 g/cm^2

Internal Moderator Varying			
k_{KENO}	1 σ	k_{eff}	Description
0.4219	0.0005	0.4229	H_20: 0.0001 g/cc
0.5078	0.0007	0.5092	H_20: 0.1 g/cc
0.5692	0.0009	0.5710	H_20: 0.2 g/cc
0.6258	0.0009	0.6276	H_20: 0.3 g/cc
0.6855	0.0011	0.6877	H_20: 0.4 g/cc
0.7351	0.0011	0.7373	H_20: 0.5 g/cc
0.7857	0.0012	0.7881	H_20: 0.6 g/cc
0.8264	0.0013	0.8290	H_20: 0.7 g/cc
0.8687	0.0013	0.8713	H_20: 0.8 g/cc
0.9032	0.0011	0.9054	H_20: 0.9 g/cc
0.9359	**0.0013**	**0.9385**	**H_20: 1.0 g/cc**
External Moderator Varying			
k_{KENO}	1 σ	k_{eff}	Description
0.9325	0.0013	0.9351	H_20: 0.0001 g/cc
0.9337	0.0013	0.9363	H_20: 0.05 g/cc
0.9351	0.0011	0.9373	H_20: 0.1 g/cc
0.9345	0.0013	0.9371	H_20: 0.2 g/cc
0.9348	0.0013	0.9374	H_20: 0.3 g/cc
0.9348	0.0011	0.9370	H_20: 0.4 g/cc
0.9357	0.0014	0.9385	H_20: 0.5 g/cc
0.9361	**0.0012**	**0.9385**	**H_20: 0.6 g/cc**
0.9342	0.0013	0.9368	H_20: 0.7 g/cc
0.9336	0.0014	0.9364	H_20: 0.8 g/cc
0.9355	0.0011	0.9377	H_20: 0.9 g/cc
0.9359	0.0013	0.9385	H_20: 1.0 g/cc

Table A.6.5.3-7
NOC Moderator Varying Results - ^{10}B Areal density of 0.025 g/cm^2

Internal Moderator Varying			
k_{KENO}	1 σ	k_{eff}	Description
0.4437	0.0005	0.4447	H_20: 0.0001 g/cc
0.5477	0.0007	0.5491	H_20: 0.1 g/cc
0.6099	0.0008	0.6115	H_20: 0.2 g/cc
0.6667	0.0010	0.6687	H_20: 0.3 g/cc
0.7179	0.0010	0.7199	H_20: 0.4 g/cc
0.7645	0.0012	0.7669	H_20: 0.5 g/cc
0.8056	0.0013	0.8082	H_20: 0.6 g/cc
0.8446	0.0012	0.8470	H_20: 0.7 g/cc
0.8763	0.0011	0.8785	H_20: 0.8 g/cc
0.9082	0.0013	0.9108	H_20: 0.9 g/cc
0.9361	**0.0011**	**0.9383**	**H_20: 1.0 g/cc**
External Moderator Varying			
k_{KENO}	1 σ	k_{eff}	Description
0.9346	0.0014	0.9374	H_20: 0.0001 g/cc
0.9339	0.0011	0.9361	H_20: 0.05 g/cc
0.9341	0.0011	0.9363	H_20: 0.1 g/cc
0.9351	0.0012	0.9375	H_20: 0.2 g/cc
0.9351	0.0012	0.9375	H_20: 0.3 g/cc
0.9340	0.0012	0.9364	H_20: 0.4 g/cc
0.9341	0.0011	0.9363	H_20: 0.5 g/cc
0.9333	0.0013	0.9359	H_20: 0.6 g/cc
0.9341	0.0011	0.9363	H_20: 0.7 g/cc
0.9337	0.0012	0.9361	H_20: 0.8 g/cc
0.9351	0.0012	0.9375	H_20: 0.9 g/cc
0.9361	**0.0011**	**0.9383**	**H_20: 1.0 g/cc**

Table A.6.5.3-8
HAC Moderator Varying Results - ^{10}B Areal density of 0.068 g/cm^2

Internal Moderator Varying			
k_{KENO}	1 σ	k_{eff}	Description
0.4228	0.0005	0.4238	H_20: 0.0001 g/cc
0.5069	0.0007	0.5083	H_20: 0.1 g/cc
0.5689	0.0009	0.5707	H_20: 0.2 g/cc
0.6288	0.0011	0.6310	H_20: 0.3 g/cc
0.6824	0.0010	0.6844	H_20: 0.4 g/cc
0.7391	0.0012	0.7415	H_20: 0.5 g/cc
0.7860	0.0014	0.7888	H_20: 0.6 g/cc
0.8310	0.0013	0.8336	H_20: 0.7 g/cc
0.8689	0.0012	0.8713	H_20: 0.8 g/cc
0.9031	0.0013	0.9057	H_20: 0.9 g/cc
0.9361	**0.0012**	**0.9385**	**H_20: 1.0 g/cc**

External Moderator Varying			
k_{KENO}	1 σ	k_{eff}	Description
0.9341	0.0013	0.9367	H_20: 0.0001 g/cc
0.9345	0.0013	0.9371	H_20: 0.05 g/cc
0.9343	0.0012	0.9367	H_20: 0.1 g/cc
0.9321	0.0012	0.9345	H_20: 0.2 g/cc
0.9365	**0.0012**	**0.9389**	**H_20: 0.3 g/cc**
0.9352	0.0013	0.9378	H_20: 0.4 g/cc
0.9323	0.0014	0.9351	H_20: 0.5 g/cc
0.9322	0.0015	0.9352	H_20: 0.6 g/cc
0.9353	0.0012	0.9377	H_20: 0.7 g/cc
0.9353	0.0011	0.9375	H_20: 0.8 g/cc
0.9353	0.0013	0.9379	H_20: 0.9 g/cc
0.9361	0.0012	0.9385	H_20: 1.0 g/cc

Table A.6.5.3-9
HAC Moderator Varying Results - ^{10}B Areal density of 0.025 g/cm^2

Internal Moderator Varying			
k_{KENO}	1 σ	k_{eff}	Description
0.4440	0.0005	0.4450	H_20: 0.0001 g/cc
0.5474	0.0008	0.5490	H_20: 0.1 g/cc
0.6097	0.0008	0.6113	H_20: 0.2 g/cc
0.6677	0.0009	0.6695	H_20: 0.3 g/cc
0.7205	0.0011	0.7227	H_20: 0.4 g/cc
0.7653	0.0011	0.7675	H_20: 0.5 g/cc
0.8066	0.0012	0.8090	H_20: 0.6 g/cc
0.8445	0.0013	0.8471	H_20: 0.7 g/cc
0.8811	0.0014	0.8839	H_20: 0.8 g/cc
0.9075	0.0015	0.9105	H_20: 0.9 g/cc
0.9320	**0.0013**	**0.9346**	**H_20: 1.0 g/cc**
External Moderator Varying			
k_{KENO}	1 σ	k_{eff}	Description
0.9355	0.0011	0.9377	H_20: 0.0001 g/cc
0.9332	0.0013	0.9358	H_20: 0.05 g/cc
0.9341	0.0012	0.9365	H_20: 0.1 g/cc
0.9351	0.0014	0.9379	H_20: 0.2 g/cc
0.9353	**0.0013**	**0.9379**	**H_20: 0.3 g/cc**
0.9338	0.0013	0.9364	H_20: 0.4 g/cc
0.9327	0.0012	0.9351	H_20: 0.5 g/cc
0.9322	0.0013	0.9348	H_20: 0.6 g/cc
0.9350	0.0012	0.9374	H_20: 0.7 g/cc
0.9332	0.0013	0.9358	H_20: 0.8 g/cc
0.9347	0.0013	0.9373	H_20: 0.9 g/cc
0.9320	0.0013	0.9346	H_20: 1.0 g/cc

Table A.6.5.3-10
Damaged Fuel, Rod Pitch Varying Results - ^{10}B Areal density of 0.068 g/cm^2

k_{KENO}	1 σ	k_{eff}	Pitch (inches)
0.7002	0.0011	0.7024	0.380
0.7900	0.0012	0.7924	0.4200
0.8671	0.0011	0.8693	0.4600
0.9268	0.0012	0.9292	0.5000
0.9471	0.0013	0.9497	0.5160
0.9550	0.0014	0.9578	0.5260
0.9663	0.0013	0.9689	0.5360
0.9741	0.0013	0.9767	0.5460
0.9774	**0.0012**	**0.9798**	**0.5510**

Table A.6.5.3-11
Damaged Fuel, Rod Pitch Varying Results with Rod Addition or Subtraction

k_{KENO}	1 σ	k_{eff}	Pitch (inches)	Rods Added or Subtracted
0.9751	0.0011	0.9773	0.5510	20
0.9759	0.0014	0.9787	0.5510	15
0.9790	0.0013	0.9816	0.5510	14
0.9796	0.0011	0.9818	0.5510	10
0.9783	0.0011	0.9805	0.5510	5
0.9785	0.0013	0.9811	0.5510	4
0.9774	0.0012	0.9798	0.5510	0
0.9773	0.0012	0.9797	0.5510	-2
0.9769	0.0012	0.9793	0.5510	-4
0.9771	0.0012	0.9795	0.5510	-6
0.9777	0.0013	0.9803	0.5510	-8
0.9774	0.0013	0.9800	0.5510	-10
0.9802	0.0012	0.9826	0.5510	-12
0.9804	0.0013	0.9830	0.5510	-14
0.9847	**0.0012**	**0.9871**	**0.5510**	**-16**
0.9798	0.0011	0.9820	0.5510	-18
0.9806	0.0011	0.9828	0.5510	-20
Cases for the 9x9 Rod Storage Basket				
0.7061	0.0013	0.7087	0.5510	0
0.7930	0.0013	0.7956	1.0330	0

Table A.6.5.3-12
Damaged Fuel, Single-ended Shear

k_{KENO}	1 σ	k_{eff}	Delta, in
0.9271	0.0013	0.9297	0.0000
0.9396	0.0013	0.9422	0.3000 (bare)
0.9379	0.0011	0.9401	0.3000
0.9413	0.0012	0.9437	0.3500 (bare)
0.9390	0.0013	0.9416	0.3500
0.9422	0.0013	0.9448	0.4000 (bare)
0.9395	0.0011	0.9417	0.4000
0.9421	0.0011	0.9443	0.4500 (bare)
0.9421	0.0014	0.9449	0.4500
0.9415	0.0012	0.9439	0.5000 (bare)
0.9403	0.0013	0.9429	0.5000
0.9414	0.0013	0.9440	0.5500 (bare)
0.9429	**0.0013**	**0.9455**	**0.5500**

Table A.6.5.3-13
Damaged Fuel, Double-ended Shear

k_{KENO}	1 σ	k_{eff}	Description
0.9423	**0.0014**	**0.9451**	**1/2 sheared bare fuel**
0.9367	0.0013	0.9393	1/2 rod sheared
0.9352	0.0014	0.9380	1/3 sheared bare fuel
0.9368	0.0013	0.9394	1/3 rod sheared
0.9349	0.0011	0.9371	1/4 rod sheared bare fuel
0.9324	0.0012	0.9348	1/4 sheared

Table A.6.5.3-14
Damaged Fuel, Rod Pitch Cases – External Moderator Density Varying

k_{KENO}	1 σ	k_{eff}	Description
0.9807	0.0012	0.9831	$H_2$0: 0.0001 g/cc
0.9805	0.0012	0.9829	$H_2$0: 0.05 g/cc
0.9829	0.0013	0.9855	$H_2$0: 0.1 g/cc
0.9800	0.0014	0.9828	$H_2$0: 0.2 g/cc
0.9808	0.0011	0.9830	$H_2$0: 0.3 g/cc
0.9823	0.0013	0.9849	$H_2$0: 0.4 g/cc
0.9836	0.0013	0.9862	$H_2$0: 0.5 g/cc
0.9808	0.0013	0.9834	$H_2$0: 0.6 g/cc
0.9816	0.0012	0.9840	$H_2$0: 0.7 g/cc
0.9813	0.0012	0.9837	$H_2$0: 0.8 g/cc
0.9800	0.0013	0.9826	$H_2$0: 0.9 g/cc
0.9847	**0.0012**	**0.9871**	**$H_2$0: 1.0 g/cc**

Table A.6.5.3-15
Damaged Fuel, Single Shear Cases – External Moderator Density Varying

k_{KENO}	1 σ	k_{eff}	Description
0.9415	0.0012	0.9439	$H_2$0: 0.0001 g/cc
0.9431	0.0012	0.9455	$H_2$0: 0.05 g/cc
0.9410	0.0011	0.9432	$H_2$0: 0.1 g/cc
0.9408	0.0011	0.9430	$H_2$0: 0.2 g/cc
0.9409	0.0013	0.9435	$H_2$0: 0.3 g/cc
0.9395	0.0013	0.9421	**$H_2$0: 0.4 g/cc**
0.9394	0.0011	0.9416	$H_2$0: 0.5 g/cc
0.9408	0.0015	0.9438	$H_2$0: 0.6 g/cc
0.9412	0.0011	0.9434	$H_2$0: 0.7 g/cc
0.9426	**0.0015**	**0.9456**	$H_2$0: 0.8 g/cc
0.9426	0.0014	0.9454	$H_2$0: 0.9 g/cc
0.9429	0.0013	0.9455	$H_2$0: 1.0 g/cc

Table A.6.5.3-16
Damaged Fuel, Double Shear Cases – External Moderator Density Varying

k_{KENO}	1 σ	k_{eff}	Description
0.9390	0.0012	0.9414	H_20: 0.0001 g/cc
0.9394	0.0012	0.9418	H_20: 0.05 g/cc
0.9411	0.0016	0.9443	H_20: 0.1 g/cc
0.9387	0.0014	0.9415	H_20: 0.2 g/cc
0.9405	0.0013	0.9431	H_20: 0.3 g/cc
0.9420	0.0013	0.9446	H_20: 0.4 g/cc
0.9389	0.0013	0.9415	H_20: 0.5 g/cc
0.9384	0.0012	0.9408	H_20: 0.6 g/cc
0.9390	0.0013	0.9416	H_20: 0.7 g/cc
0.9410	0.0014	0.9438	**H_20: 0.8 g/cc**
0.9397	0.0011	0.9419	H_20: 0.9 g/cc
0.9423	**0.0014**	**0.9451**	H_20: 1.0 g/cc

Table A.6.5.3-17
Damaged Fuel, Bare Fuel Added

k_{KENO}	1 σ	k_{eff}	Description
0.9564	**0.0014**	**0.9592**	**extra bare rods added**
0.9353	0.0013	0.9379	bare pellets added above the boral sheet height, 0.025 g/cm^2 ^{10}B
0.9333	0.0015	0.9363	bare pellets added above the boral sheet height, 0.068 g/cm^2 ^{10}B

Table A.6.5.3-18
Summary of Maximum Enrichment for the Damaged Fuel Assemblies

k_{KENO}	1 σ	k_{eff}	Description	Enrich
0.9360	0.0011	0.9382	4 damaged assemblies, NOC cask	4.85 (Intact) 4.85 (Dam)
0.9337	0.0012	0.9361	4 damaged assemblies, NOC cask	4.10 (Intact) 4.10 (Dam)
0.9367	0.0012	0.9391	12 damaged assemblies, NOC cask	4.85 (Intact) 4.10 (Dam)
0.9369	0.0012	0.9393	12 damaged assemblies, NOC cask	4.10 (Intact) 3.70 (Dam)
0.9340	0.0014	0.9368	12 damaged assemblies w/ 5 poison rodlet, NOC cask	4.85 (Intact) 4.85 (Dam)
0.9315	0.0013	0.9341	12 damaged assemblies w/ 1 poison rodlet, NOC cask	4.10 (Intact) 4.10 (Dam)
0.9354	0.0012	0.9378	12 damaged assemblies w/ 5 poison rodlet, HAC cask	4.85 (Intact) 4.85 (Dam)
0.9279	0.0013	0.9305	12 damaged assemblies w/ 1 poison rodlet, HAC cask	4.10 (Intact) 4.10 (Dam)
0.9353	0.0016	0.9385	12 damaged, HAC, Assy # 1 missing, 5 poison rodlets	4.85 (Intact) 4.85 (dam)
0.9339	0.0016	0.9371	12 damaged, HAC, Assy # 2 missing, 5 poison rodlets	4.85 (Intact) 4.85 (dam)
0.9341	0.0014	0.9369	12 damaged, HAC, Assy # 3 missing, 5 poison rodlets	4.85 (Intact) 4.85 (dam)
0.4356	0.0005	0.4366	4 damaged, NOC, dry case	4.10 (Intact) 4.10 (dam)
0.4177	0.0006	0.4189	12 damaged, NOC dry case	4.10 (Intact) 3.70 (dam)
0.4203	0.0005	0.4213	12 damaged, NOC, 1 poison rodlet, dry case	4.10 (Intact) 4.10 (dam)
0.4157	0.0005	0.4167	4 damaged, NOC, dry case	4.85 (Intact) 4.85 (dam)
0.3954	0.0005	0.3964	12 damaged, NOC dry case	4.85 (Intact) 4.10 (dam)
0.3961	0.0005	0.3971	12 damaged, NOC, 5 poison rodlets at min OD, dry case	4.85 (Intact) 4.85 (dam)

Table A.6.5.3-19
Empty Fuel Assembly Locations

k_{KENO}	1 σ	k_{eff}	Description
0.9359	**0.0013**	**0.9385**	**0 empty assembly positions**
0.9228	0.0013	0.9254	1 empty assembly positions
0.9140	0.0012	0.9164	2 empty assembly positions
0.9045	0.0013	0.9071	3 empty assembly positions
0.9010	0.0011	0.9032	4 empty assembly positions

Table A.6.5.3-20
Reconstituted Fuel Assemblies

k_{KENO}	1 σ	k_{eff}	Description
0.9359	**0.0013**	**0.9385**	**0 reconstituted rods**
0.9255	0.0011	0.9277	2 reconstituted rods
0.9226	0.0013	0.9252	4 reconstituted rods
0.9151	0.0013	0.9177	6 reconstituted rods
0.9092	0.0014	0.9120	8 reconstituted rods
0.9039	0.0012	0.9063	10 reconstituted rods

Table A.6.5.3-21
Maximum Fuel Enrichment v/s Neutron Poison Requirements for 24PT4-DSC

Storage Configuration	Maximum No. of Damaged Fuel Assemblies[1]	Maximum ^{235}U Fuel Enrichment (wt %)	DSC Basket, Minimum BORAL® Areal Density (gm/cm^2)	Minimum No. of Poison Rodlets Required[2]
All Intact Fuel Assemblies	0	4.1	.025 (Type A Basket)	0
	0	4.85	.068 (Type B Basket)	0
Combination of Damaged and Intact Fuel Assemblies	4	4.1	.025 (Type A Basket)	0
	4	4.85	.068 (Type B Basket)	0
	12	3.7 (damaged) 4.1 (intact)	.025 (Type A Basket)	0
	12	4.1 (damaged) 4.85 (intact)	.068 (Type B Basket)	0
	12	4.1	.025 (Type A Basket)	1[2] (Located in center guide tube of each intact assembly)
	12	4.85	.068 (Type B Basket)	5[2] (Located in all five guide tubes of each intact assembly)

Notes:
(1) See Figure A.6.5.3-18 for location of damaged fuel assemblies within the 24PT4-DSC (Zones A and/or B only).
(2) Poison rodlets are only required for a specific DSC configuration with a payload of 5-12 damaged assemblies in combination with maximum fuel enrichment levels as shown. The poison rodlets are to be located within the guide tubes of the Zone C intact assemblies as shown in Figure A.6.5.3-18.

Table A.6.5.3-22
USL-1 Results

Parameter	Range of Applicability	USL-1
U Enrichment (wt. % ^{235}U)	2.4	0.9423
	2.8	0.9429
	3.3	0.9434
	3.8–5.7	0.9437
Fuel Rod Pitch (cm)	0.89	0.9396
	1.1	0.9407
	1.2	0.9411
	1.4	0.9418
	1.6	0.9429
	1.8–2.6	0.9438
Water/Fuel Volume Ratio	0.38	0.9420
	1.1	0.9425
	1.7	0.9429
	2.4–5.1	0.9433
Assembly Separation (cm)	1.4	0.9412
	1.6	0.9413
	4.4	0.9428
	7.1–21	0.9442
Average Energy Group Causing Fission (AEG)	30–32	0.9434
	33	0.9433
	34	0.9432
	35	0.9431
	36	0.9430
	37	0.9430

Table A.6.5.3-23
USL Determination for Criticality Analysis

Parameter	Value from Limiting Analysis	Bounding USL-1
U Enrichment (wt. % ^{235}U)	4.2	0.9437
Fuel Rod Pitch (cm)	1.28524	**0.9411**
Water/Fuel Ratio	1.663	0.9425
Assembly Separation (cm)	1.80 – 3.07 (value of 1.60 used)	0.9413
Average Energy Group Causing Fission (AEG)	33.6	0.9433

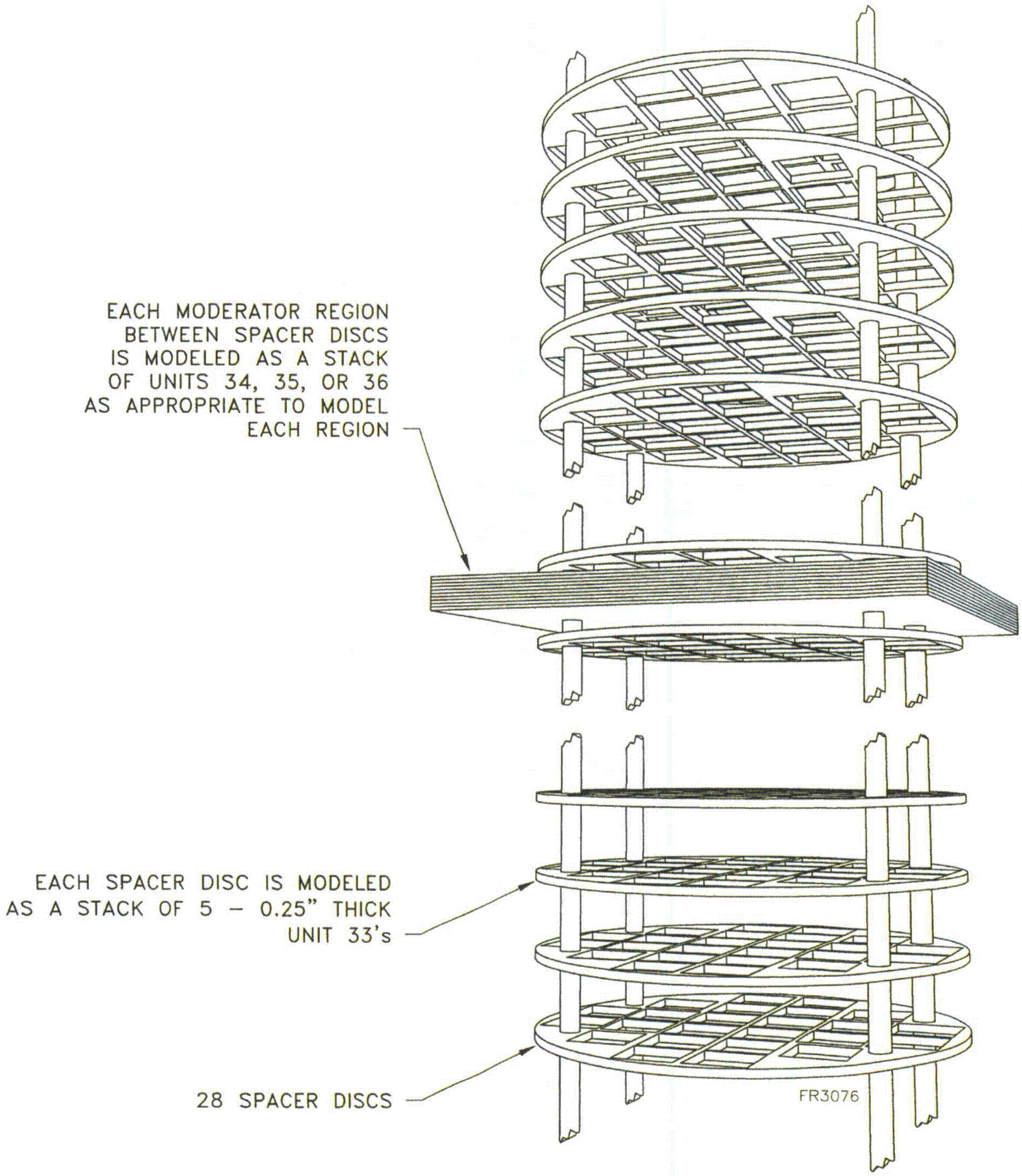


Figure A.6.5.3-1
KENO V.a Model of the 24PT4-DSC Basket

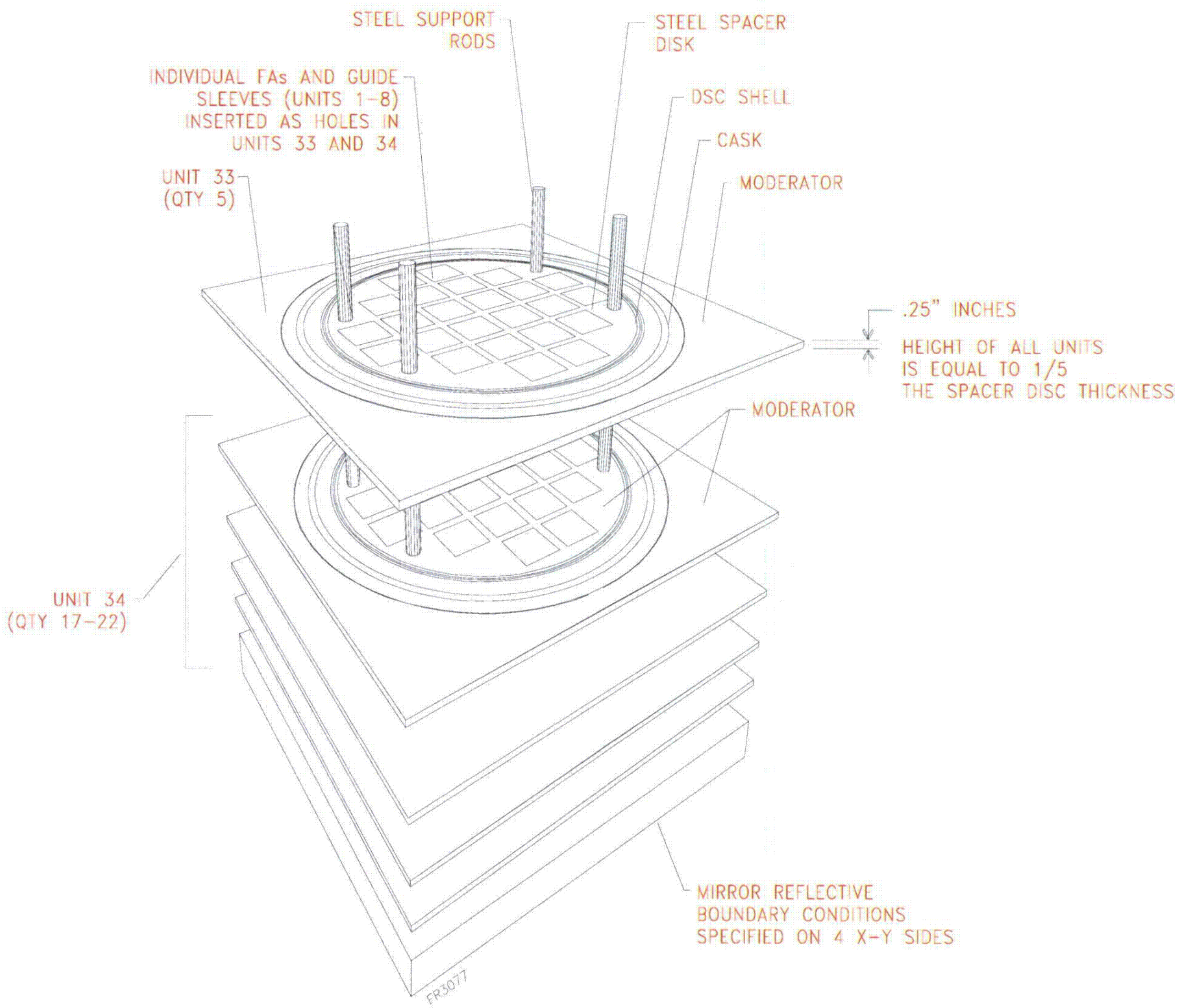


Figure A.6.5.3-2
Exploded View of KENO V.a Model

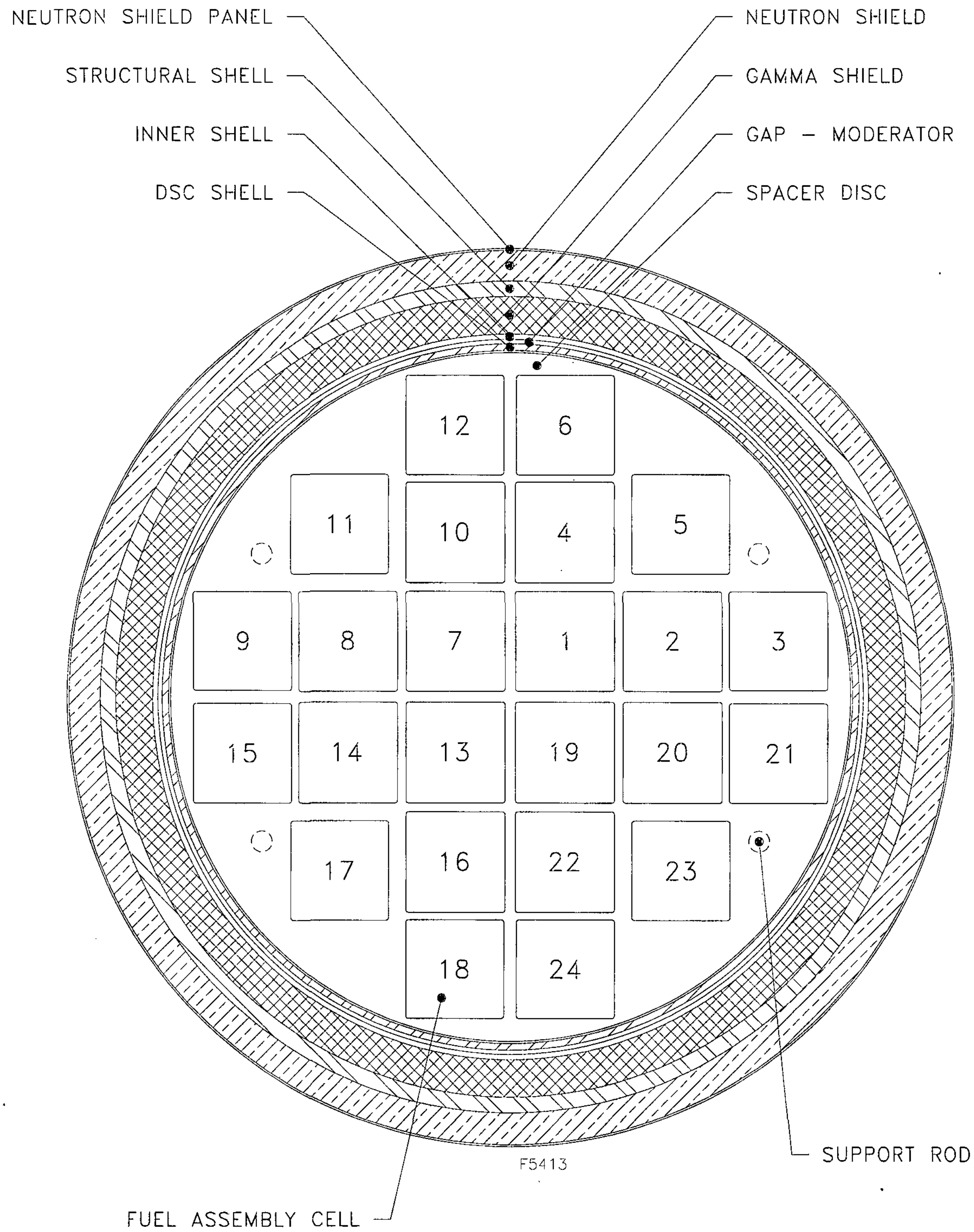


Figure A.6.5.3-3
Structure of KENO V.a Model – UNIT 33

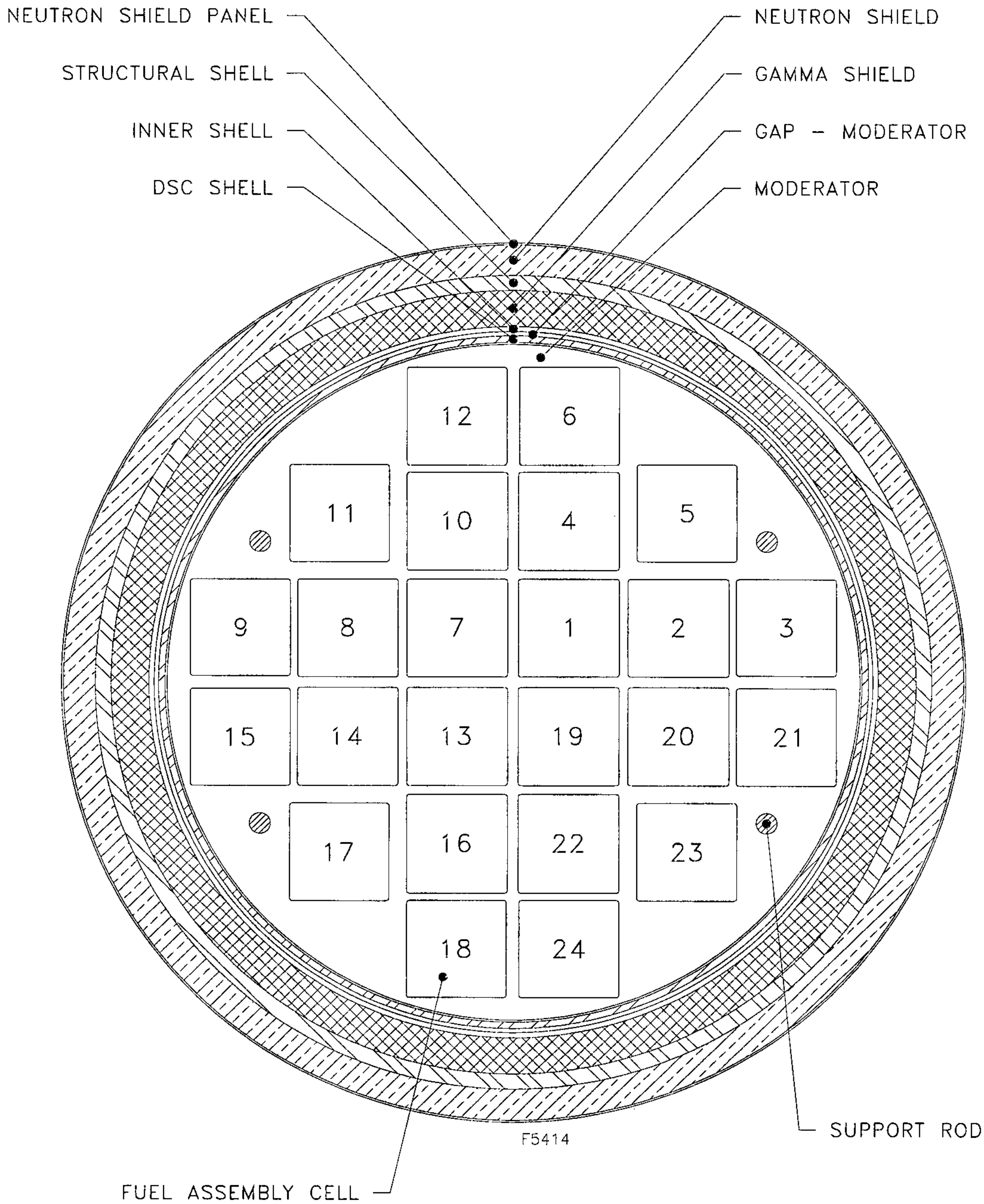


Figure A.6.5.3-4
Structure of KENO V.a Model – UNIT 34

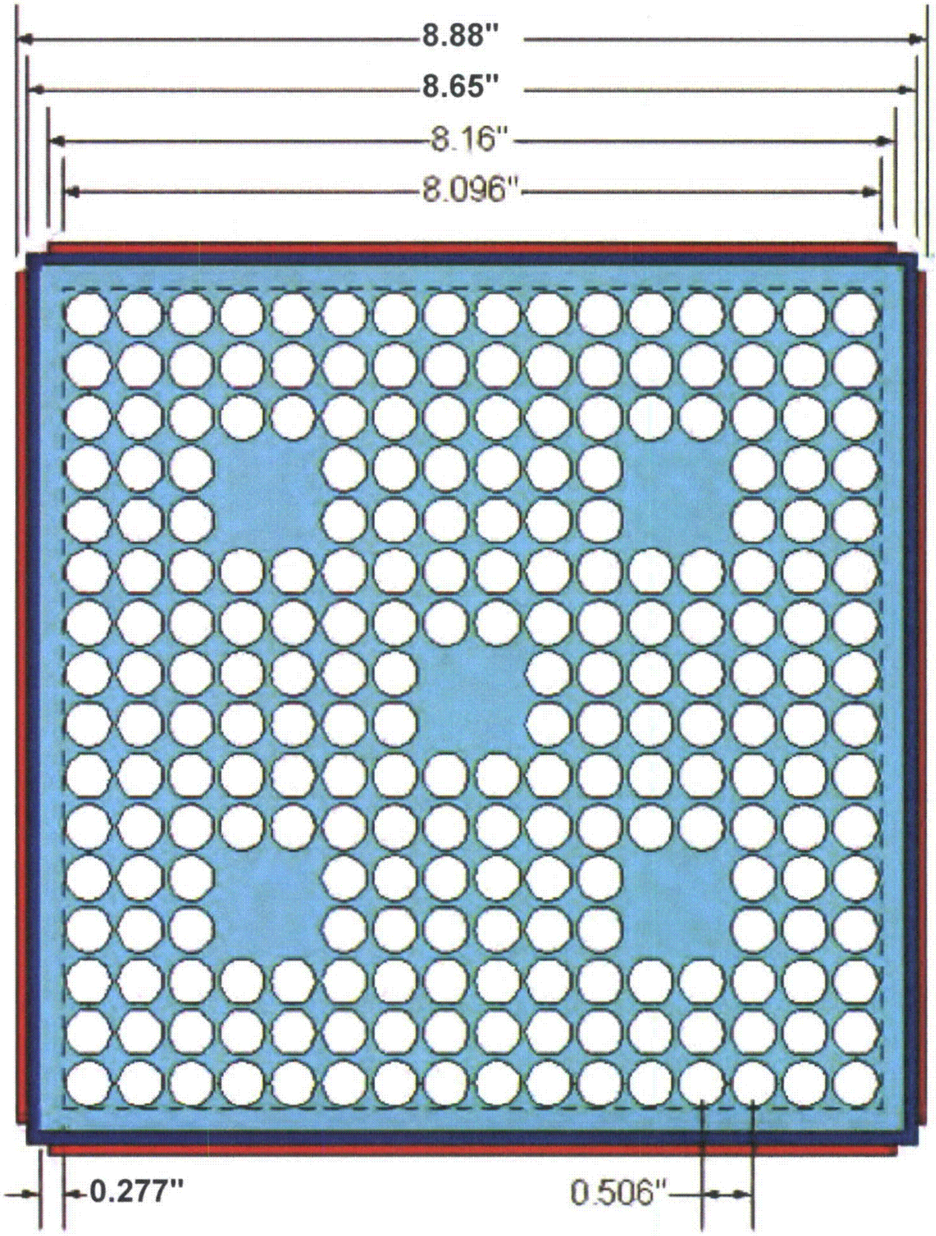
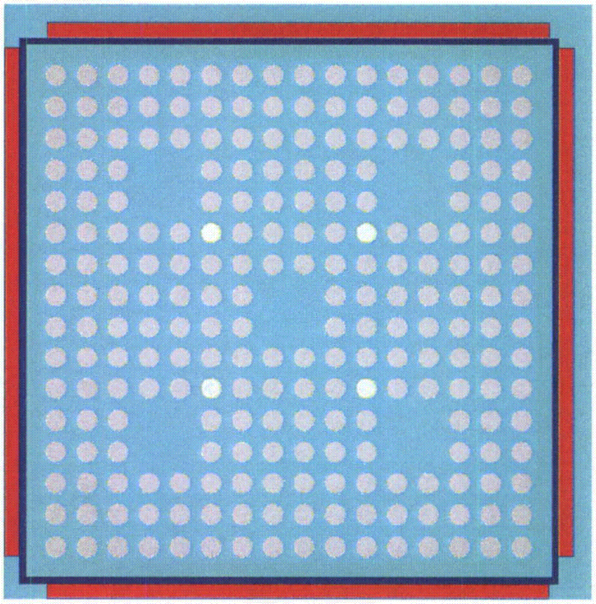
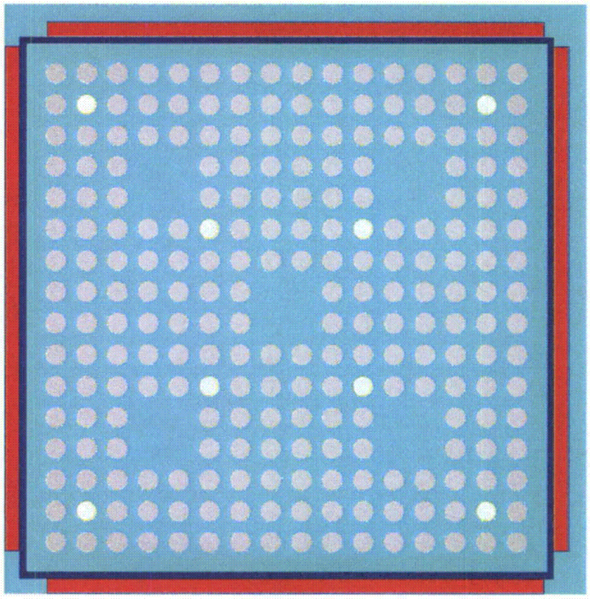


Figure A.6.5.3-5
Cross Section of the CE 16x16 Fuel Assembly

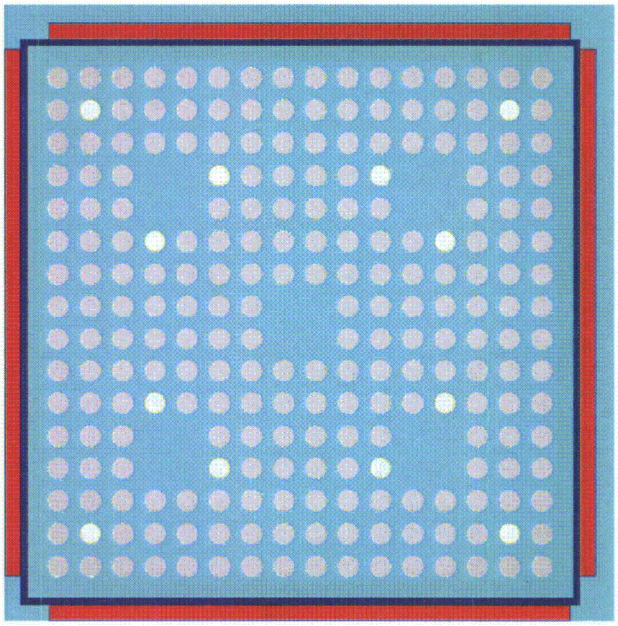


4 Burnable Absorber Rods

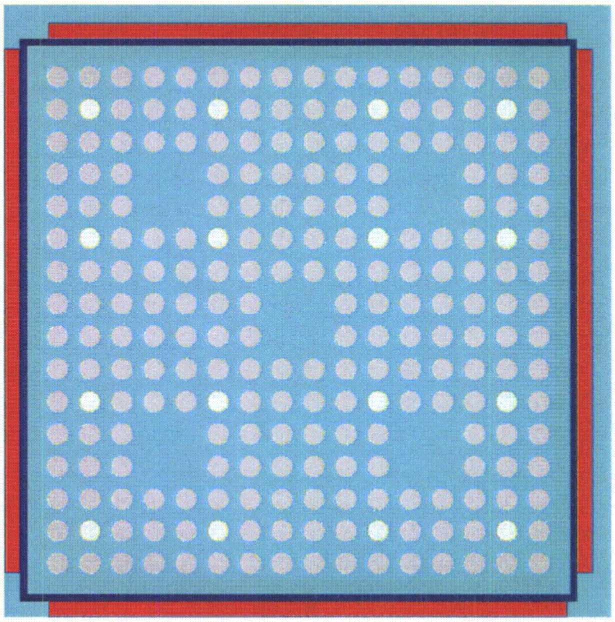


8 Burnable Absorber Rods

Figure A.6.5.3-6
Fuel Assembly Cross Section Showing the Burnable Absorber Rod Configuration



12 Burnable Absorber Rods



16 Burnable Absorber Rods

Figure A.6.5.3-6
Fuel Assembly Cross Section Showing the Burnable Absorber Rod Configuration
(concluded)

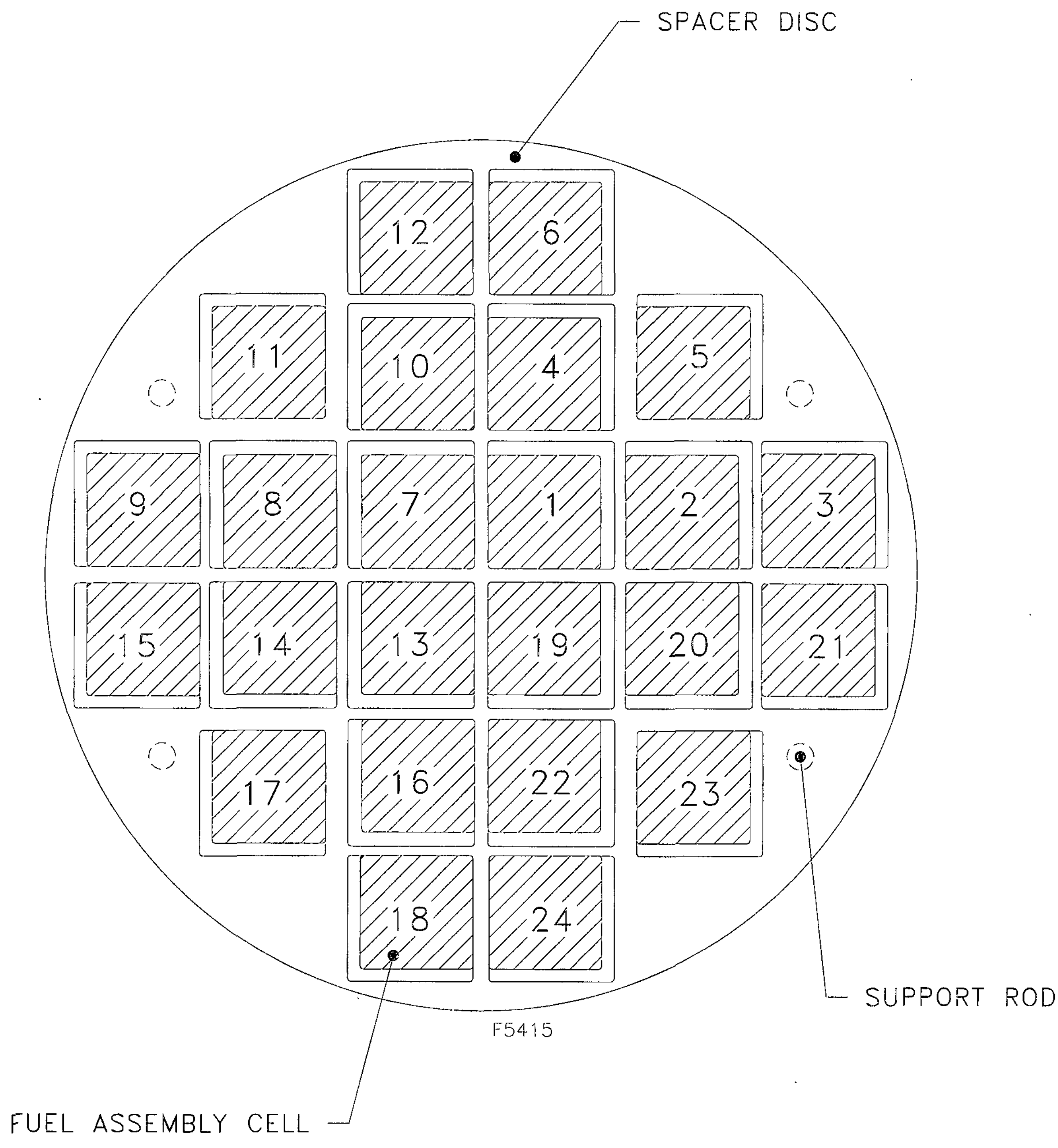


Figure A.6.5.3-7
Fuel Assemblies Located in the Inner Guidesleeve Corner Closest to the DSC Centerline (Assembly in Case)

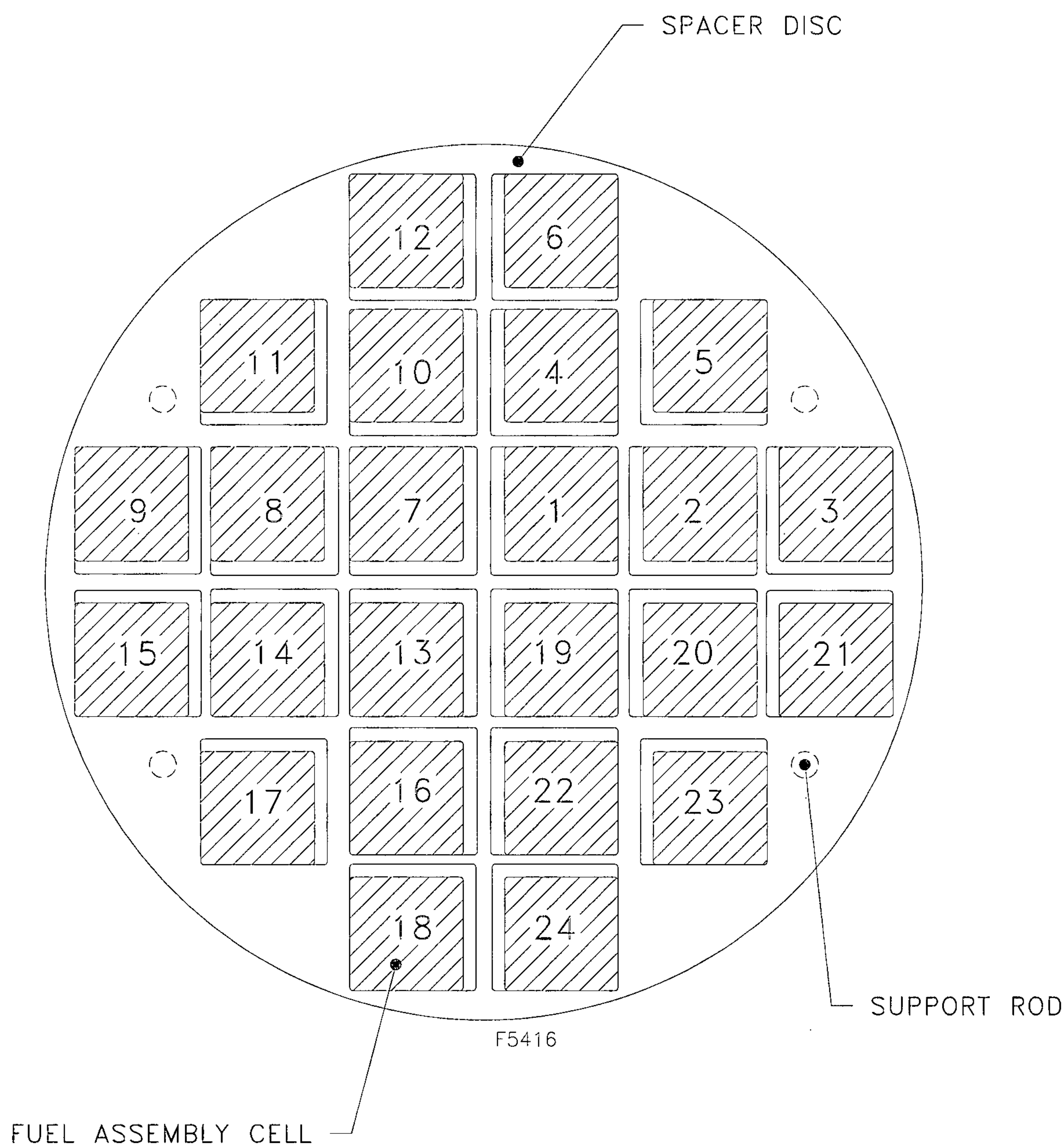


Figure A.6.5.3-8
Fuel Assemblies Moved Radially Outwards from the Center of the 24PT4-DSC
(Assembly Out Case)

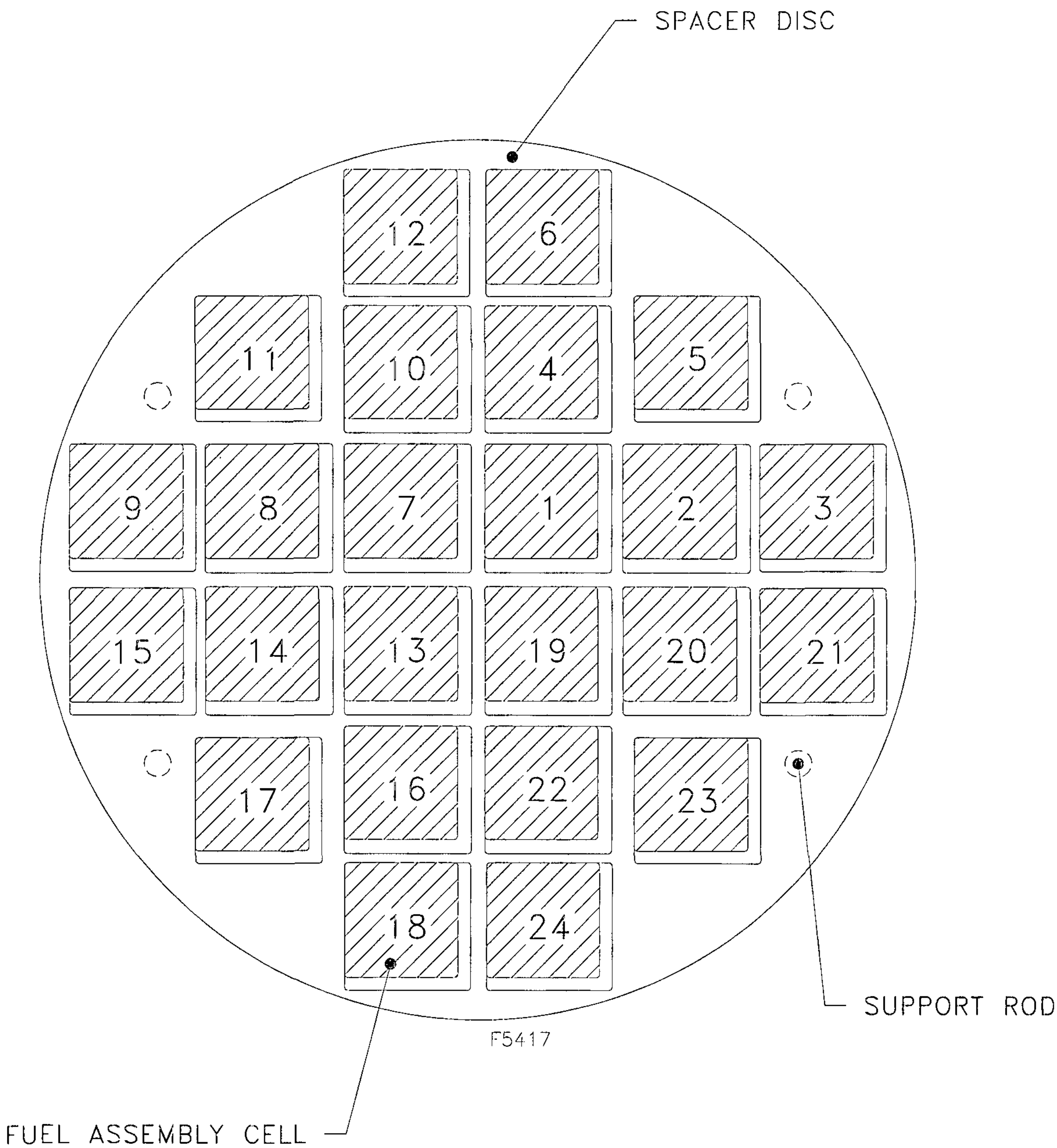


Figure A.6.5.3-9
Fuel Assemblies Moved Towards the Upper Left Corner of EachGuidesleeve Assembly
Upper Left Corner Case

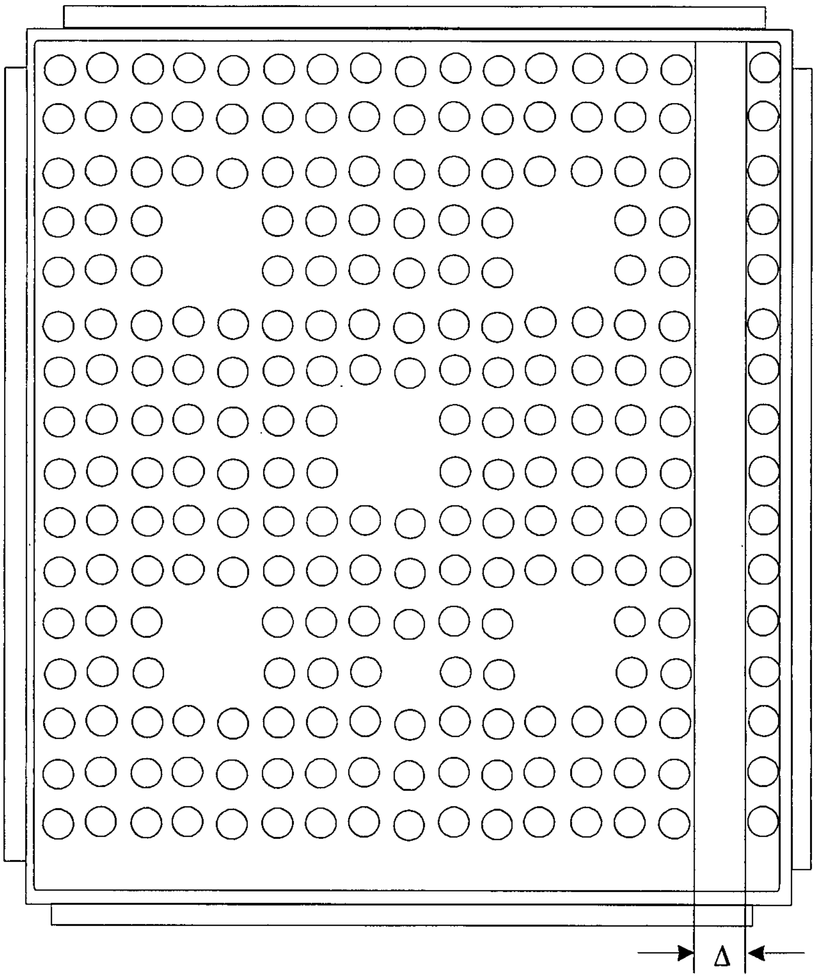


Figure A.6.5.3-10
Single-ended Shear Model

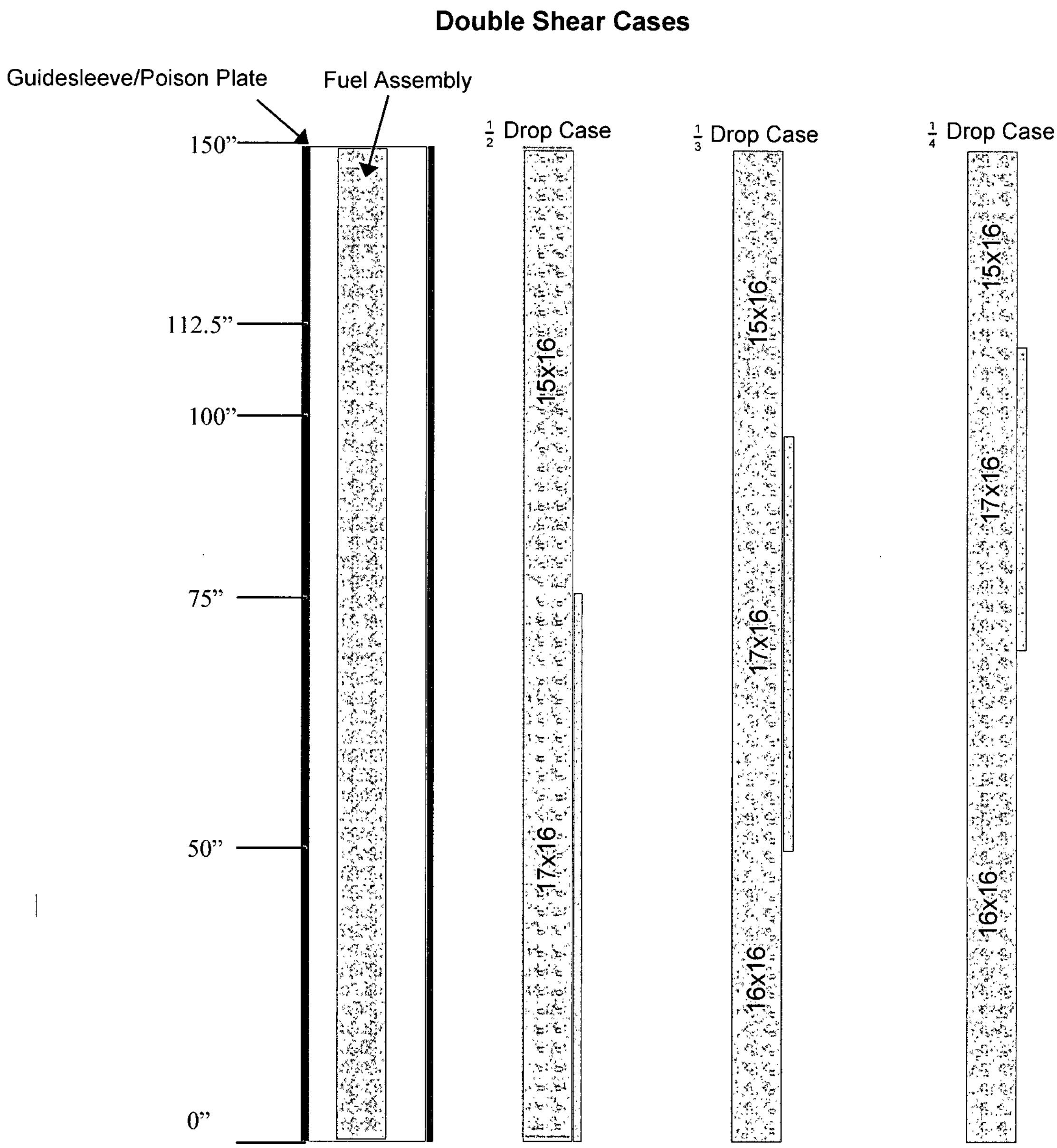


Figure A.6.5.3-11
Double-ended Shear Model

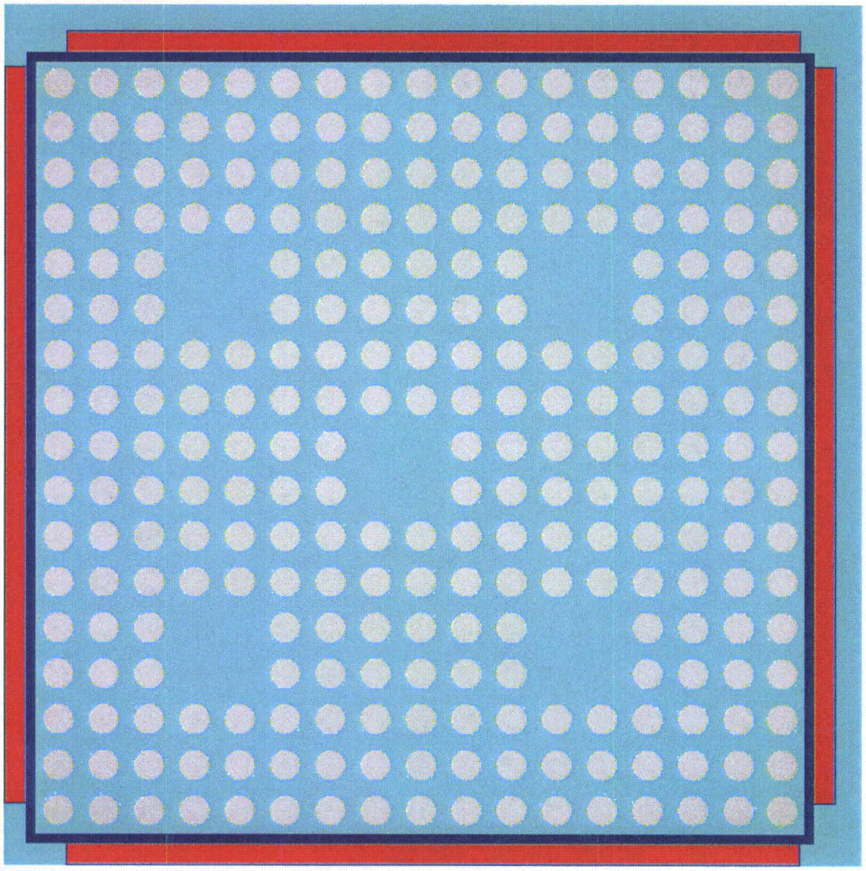


Figure A.6.5.3-12
Geometry with Bare Fuel Rods Added

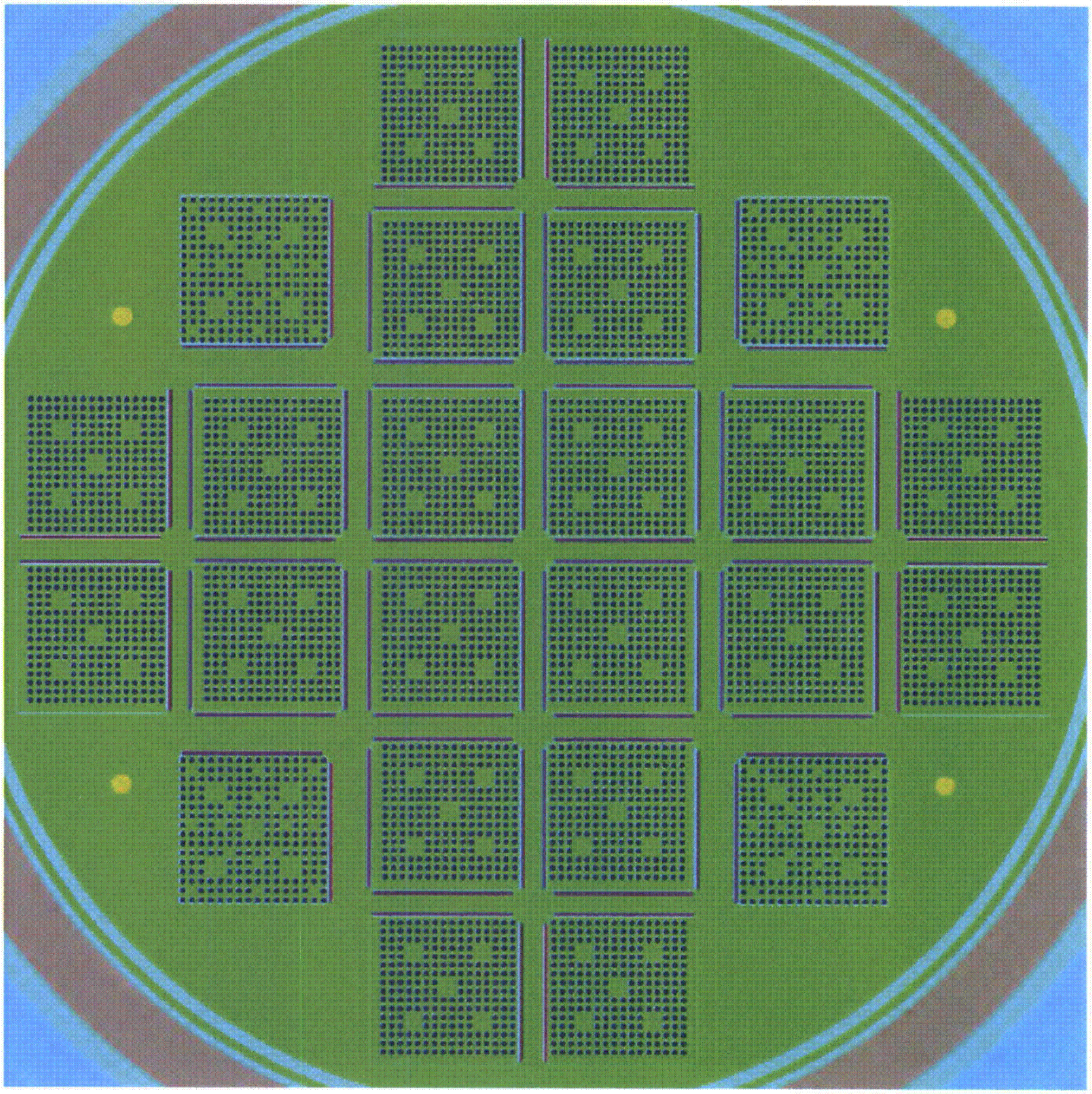


Figure A.6.5.3-13
Loading Pattern for 4 Damaged Fuel Assemblies

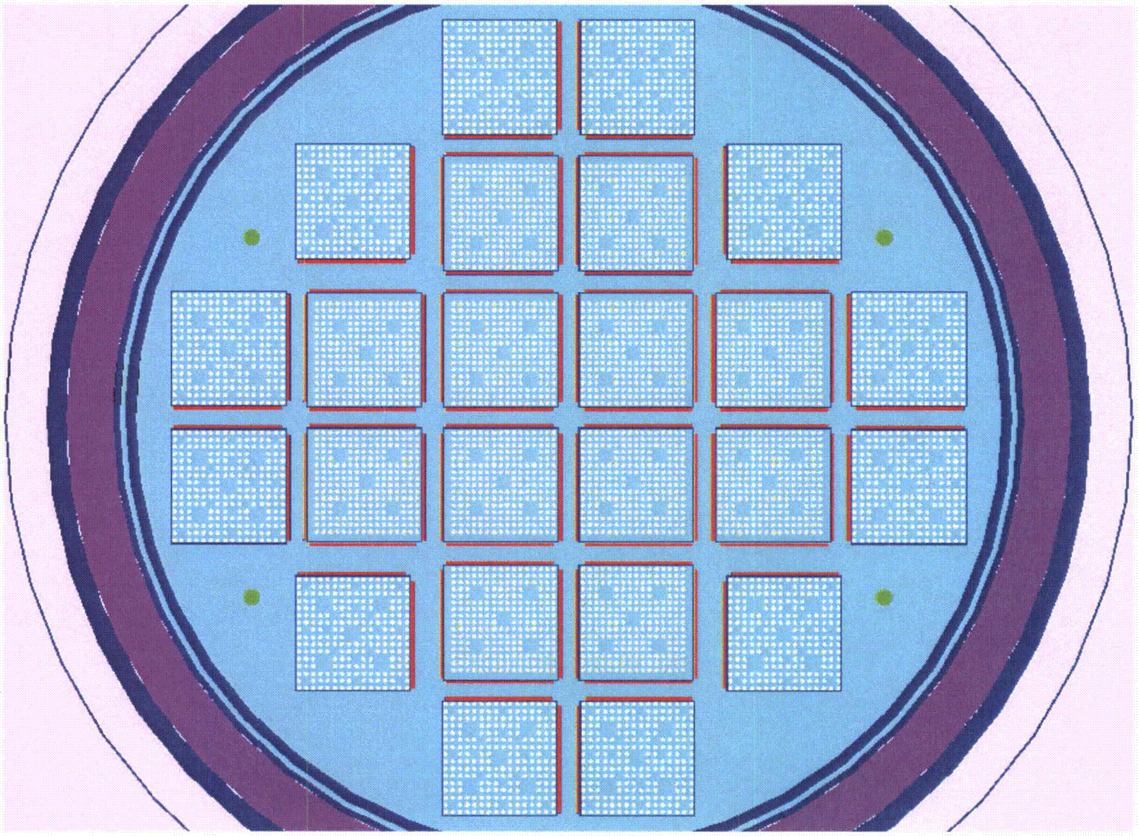


Figure A.6.5.3-14
Loading Pattern for 12 Damaged Fuel Assemblies

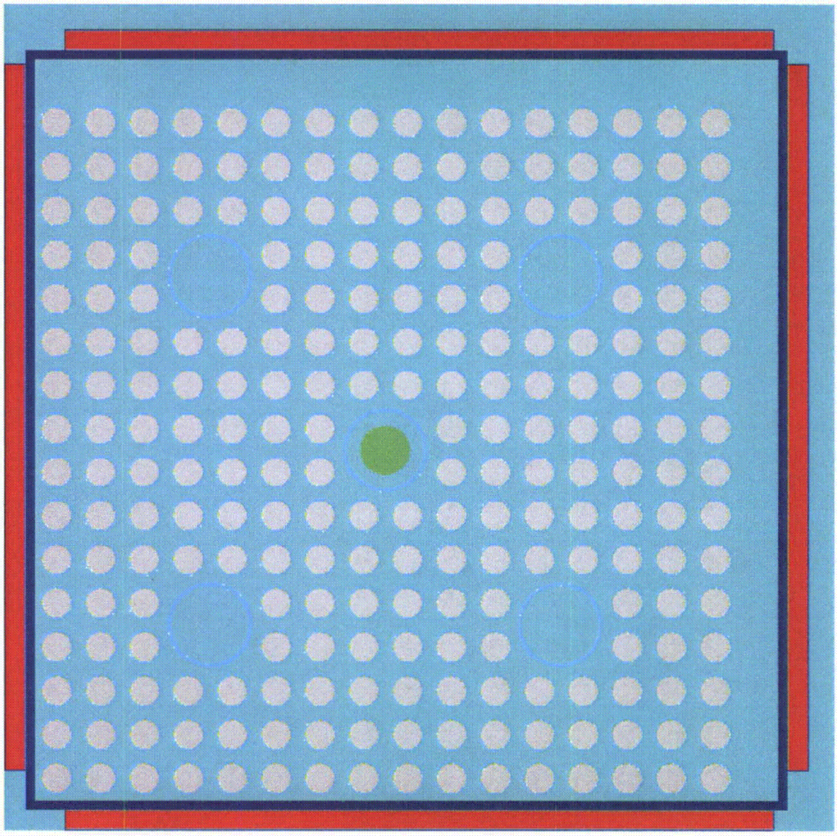


Figure A.6.5.3-15
Fuel Assembly with Guide Tubes and Poison Rodlets

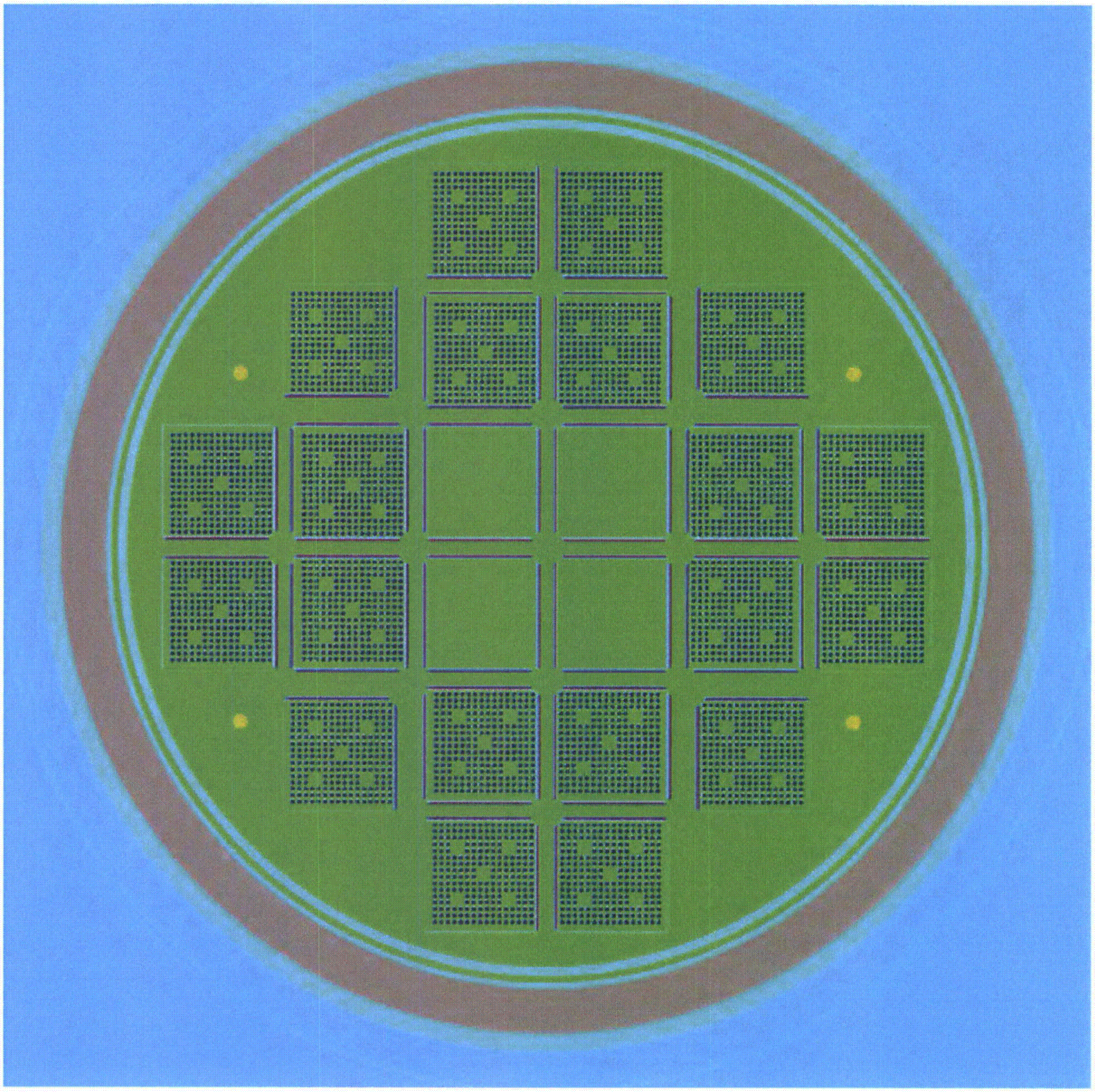


Figure A.6.5.3-16
Example of 4 Empty Fuel Assembly Locations

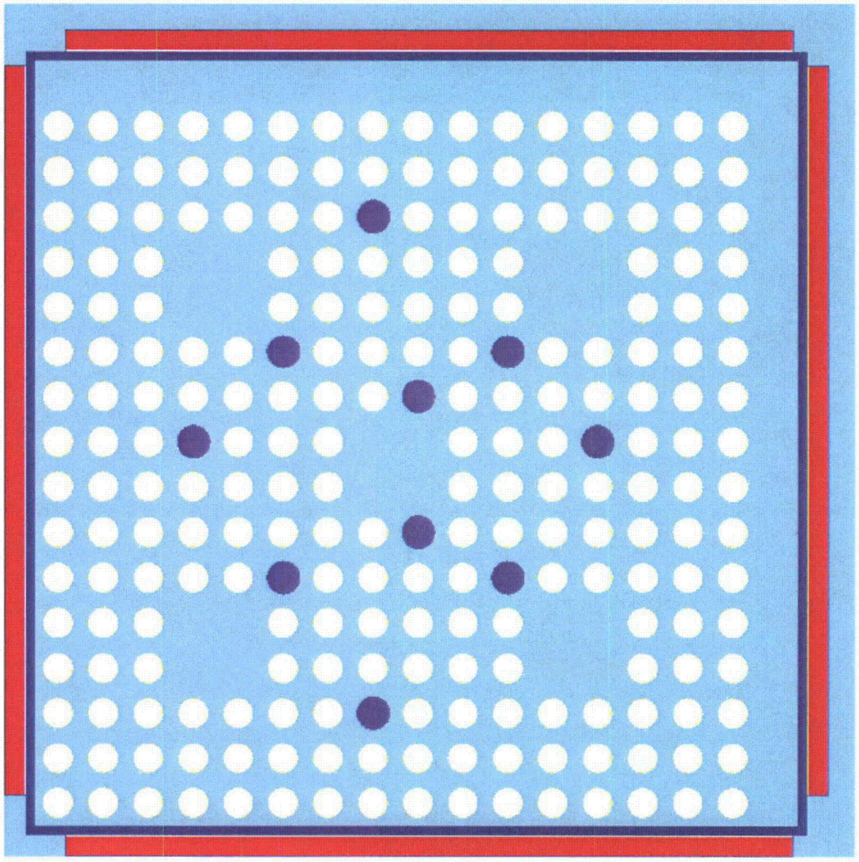
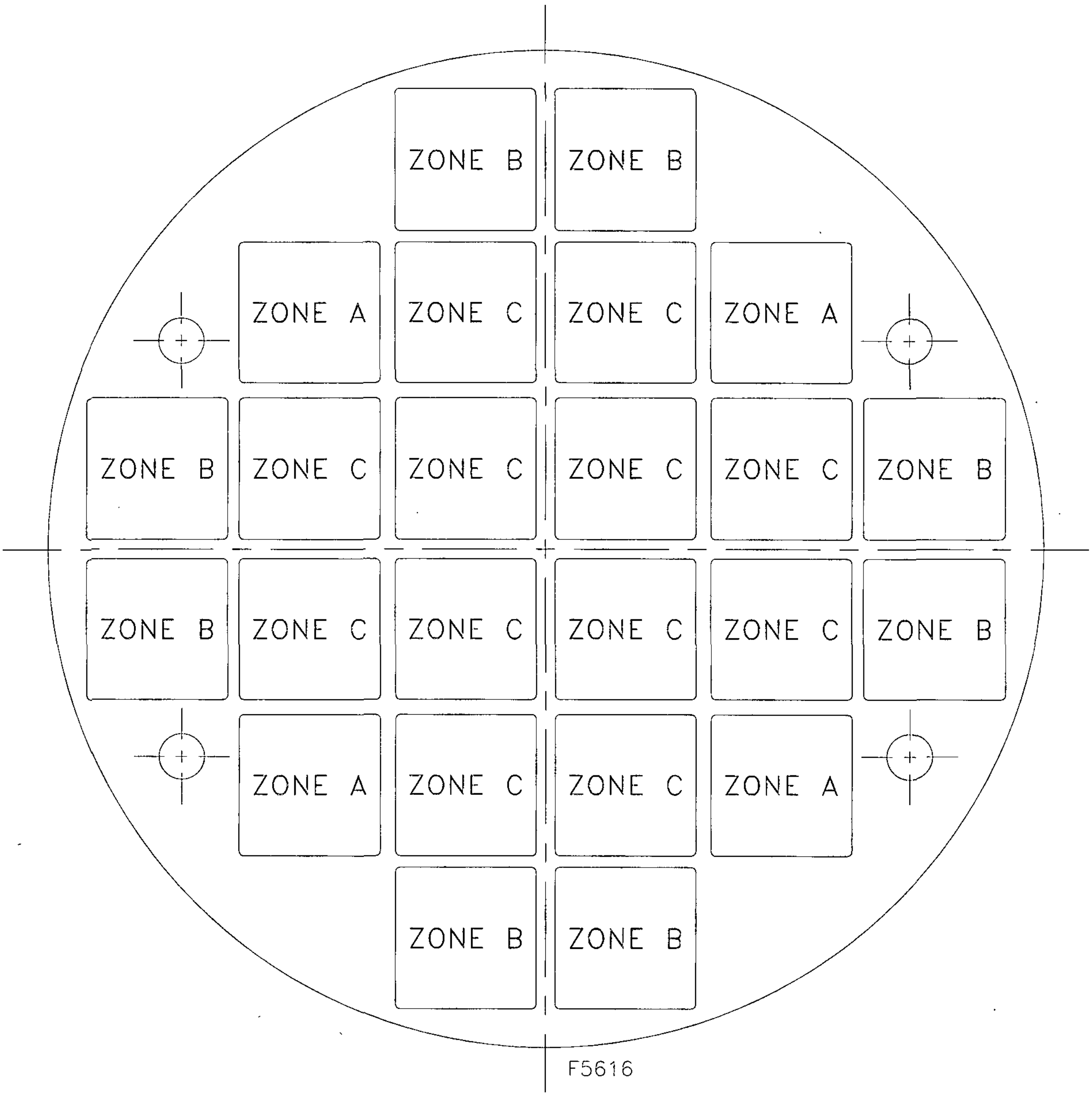


Figure A.6.5.3-17
Example of a Reconstituted Fuel Assembly



1. Locations identified as Zone A are for placement of up to 4 damaged fuel assemblies.
2. Locations identified as Zone B are for placement of up to 8 additional damaged fuel assemblies (Maximum of 12 damaged fuel assemblies allowed, Zones A and B combined).
3. Locations identified as Zone C are for placement of up to 12 intact fuel assemblies, including 4 empty slots in the center as shown in Figure A.6.5.3-16.
4. Poison Rodlets are to be located in the guide tubes of intact fuel assemblies placed in Zone C only per Table A.6.5.3-21.

Figure A.6.5.3-18
Damaged Fuel Assembly Locations

Appendix A.6.5.4
NUHOMS®-32PTH/32PTH1 DSC Criticality Evaluation

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LIST OF TABLES

LIST OF FIGURES

Appendix A.6.5.4
NUHOMS®-32PTH/32PTH1 DSC Criticality Evaluation

NOTE: References in this Appendix are shown as [1], [2], etc. and refer to the reference list in Section A.6.5.4.5.

This Appendix A.6.5.4 to Chapter A.6 demonstrates that the MP197HB package when transporting the NUHOMS®-32PTH/32PTH Type 1 [6] and NUHOMS®-32PTH1 DSC [5] payloads meets the criticality performance requirements specified in Sections 71.55 and 71.59 of 10 CFR Part 71 [2]. The criticality control design ensures that the effective multiplication factor (k_{eff}) of the contained fuel is no greater than an Upper Subcritical Limit (USL) for the most reactive configuration. The USL includes a confidence band with an administrative safety margin of 0.05. The design has a Criticality Safety Index (CSI, given in 10 CFR 71.59(b) as CSI = 50/"N") of 0 because "N" is infinity (∞). The number "N" is based on all of the following conditions being satisfied, assuming packages are stacked together in any arrangement and with close full reflection on all sides of the stack by water:

1. Five times "N" undamaged packages with nothing between the packages are subcritical;

2. Two times "N" damaged packages, if each package is subjected to the tests specified in 10 CFR Part 71.73 hypothetical accident conditions (HAC) is subcritical with optimum interspersed hydrogenous moderation; and

3. The value of "N" cannot be less than 0.5.

A.6.5.4.1 Discussion and Results

The NUHOMS® -32PTH and 32PTH Type 1 DSC design is described in detail in Chapter A.1, Appendix A.1.4.4. The NUHOMS® -32PTH1 DSC design is described in detail in Chapter A.1, Appendix A.1.4.5. Due to the similarity of these DSC designs from a criticality standpoint, a single, bounding, criticality analysis is performed herein. Throughout this appendix, the term "32PTH1" is applicable to the 32PTH and 32PTH Type 1 DSC unless specified explicitly.

Figure A.6.5.4-1 shows the radial cross section of the NUHOMS® -32PTH1 DSC. The NUHOMS® 32PTH1 DSC stainless steel basket consists of an "egg-crate" plate design. The fuel assemblies are housed in 32 stainless steel fuel compartment tubes. The basket structure, including the fuel compartment tubes, is held together with stainless steel insert plates and the poison and aluminum plates that form the "egg-crate" structure. The basket compartment structure is connected to perimeter transition rail assemblies, portions of it comprising of aluminum interface. The fuel compartment tube structure is connected to perimeter transition rail assemblies as shown on the drawings in Chapter A.1, Appendix A.1.4.10. The poison/aluminum plates are located between the fuel compartment tubes, as shown in Figure A.6.5.4-4.

The NUHOMS® -MP197HB Cask containing the NUHOMS® -32PTH1 DSC is shown to be subcritical for an infinite array of flooded undamaged casks and for an infinite array of damaged casks after being subjected to hypothetical accident conditions. "N" is equal to ∞. The cask is shown to be subcritical for five times "N" or an infinite number of undamaged packages with

close full reflection between packages and no inleakage of water as required by 10 CFR Part 71.59(a)(1). In addition, as required by 10 CFR Part 71.59(a)(2), two times "N" or an infinite array of packages is shown to be subcritical with the fissile material in its most reactive configuration, optimum water moderation and close full water reflection consistent with its damaged condition. A CSI of 0 (less than 50) ensures that, per 10 CFR Part 71.59 (c)(1), the package may be shipped by a carrier in a nonexclusive conveyance.

Table A.6.5.4-1 lists the fuel assemblies considered as authorized contents of the NUHOMS® 32PTH1 DSC. A detailed criticality analysis of the NUHOMS® 32PTH1 DSC that meets the applicable requirements of Part 72 for storage is documented in Appendix U, Chapter U.6 associated with Amendment 10 to Part 72 CoC 1004 for the Standardized NUHOMS® System [5]. The results of the sensitivity calculations to determine the most reactive configuration of the fuel assemblies / basket materials is directly utilized herein. The design basis models from the storage calculations are utilized as starting models for the criticality analysis documented herein.

Table A.6.5.4-1 lists the fuel assemblies considered as authorized contents of the NUHOMS® 32PTH DSC. *A detailed* criticality analysis of the NUHOMS® 32PTH DSC that meets the applicable requirements of Part 72 for storage is documented in Chapter 6 of the NUHOMS® HD System (CoC 1030) UFSAR [6]. The results of the sensitivity calculations to determine the most reactive configuration of the fuel assemblies / basket materials is directly utilized herein. The design basis models from the storage calculations are utilized as starting models for the criticality analysis documented herein.

The criticality analysis begins by determining the most reactive DSC model from among the 32PTH1 and the 32PTH DSCs. Based on the results and modeling considerations of the Part 72 criticality analyses, the 32PTH1 DSC model is conservatively employed in the criticality calculations. The most reactive configuration for the basket (including transition rail configuration) and fuel assembly position utilized in the design basis storage models is then employed to determine the starting models for the criticality analysis documented herein.

The criticality analysis is performed using *two* bounding fuel assembly classes identified in Table A.6.5.4-1. These are the Westinghouse (WE) 17x17 and the WE 14x14 classes. The results of the WE 17x17 class bound those of the WE 15x15, the Babcock and Wilcox (B&W) 15x15, the *Combustion Engineering (*CE*)* 14x14, the CE 16x16 and CE 15x15 classes as *determined* in *Section A.6.2.6 of the SAR.*

Next, criticality calculations are performed to determine the minimum assembly average burnup as a function of initial enrichment and cooling time for the *two* fuel assembly classes as a function of basket poison type which are listed in Table A.6.5.4-14. The calculations determine k_{eff} with the CSAS25 control module of SCALE-4.4 [1] for each assembly *class* and initial enrichment, including all uncertainties to assure criticality safety under all credible conditions. Note that burnup credit is employed in the criticality analysis of the NUHOMS® -32PTH1 DSC.

The Control Components (CCs) are also authorized for storage in the 32PTH1 DSCs. The authorized CCs are Burnable Poison Rod Assemblies (BPRAs), Control Rod Assemblies (CRAs), Thimble Plug Assemblies (TPAs), Axial Power Shaping Rod Assemblies (APSRAs),

Control Element Assemblies (CEAs), Vibration Suppressor Inserts (VSIs), Orifice Rod Assemblies (ORAs) and Neutron Source Assemblies (NSAs) and neutron sources.

The results of the evaluation demonstrate that the maximum k_{eff}, including statistical uncertainty, is less than the USL determined from a statistical analysis of benchmark criticality experiments. The statistical analysis procedure includes a confidence band with an administrative safety margin of 0.05.

A.6.5.4.2 Package Fuel Loading

The NUHOMS® 32PTH1 DSC is capable of transporting and storing a maximum of 32 intact PWR fuel assemblies. In addition, a maximum of 16 damaged and remaining intact (for a total of 32) PWR fuel assemblies can also be transported within the NUHOMS® 32PTH1 DSC. Reconstituted fuel assemblies, where the fuel pins are replaced by lower enriched fuel pins or non-fuel pins that displace the same amount of water in the active fuel region of the fuel assembly, are considered intact fuel assemblies in the criticality evaluation. A detailed listing of the contents of the NUHOMS® 32PTH1 DSC is provided in Table A.6.5.4-1.

The NUHOMS® 32PTH DSC is also capable of transporting and storing a maximum of 32 intact PWR fuel assemblies. In addition, a maximum of 16 damaged and remaining intact (for a total of 32) PWR fuel assemblies can also be transported within the NUHOMS® 32PTH DSC. Reconstituted fuel assemblies, where the fuel pins are replaced by lower enriched fuel pins or non-fuel pins that displace the same amount of water, are considered intact fuel assemblies in the criticality evaluation. A detailed listing of the contents of the NUHOMS® 32PTH DSC is provided in Table A.6.5.4-1.

For all the fuel assembly classes CCs are also included as authorized contents. The only change to the package fuel loading to evaluate the addition of these CCs is replacing the water in the guide tubes/water holes with $^{11}B_4C$. Since these CCs displace moderator in the assembly guide and or instrument tubes, an evaluation is not needed to determine the potential impact of storage of CCs that extend into the active fuel region on the system reactivity. The presence of these CCs such as CRAs, CEAs and BPRAs will result in a reduction in the reactivity of the fuel assemblies. CCs that do not extend into the active fuel region of the assembly do not have any effect on the reactivity of the system as evaluated because only the active fuel region is modeled in this evaluation with periodic boundary conditions making the model infinite in the axial direction. Additionally, the presence of non-multiplying sources like the NSAs have no impact on criticality calculations.

Therefore, any CC that is inserted into the fuel assembly such that it does or does not extend into the active fuel region is considered as authorized for transportation without adjustment to the burnup or initial enrichment as required for control components. No credit is taken for the presence of any residual absorber remaining in the CC nor is any credit taken for the displacement of fresh water from within the guide tube of the fuel assemblies containing CCs.

Proprietary information on pages A.6.5.4-4 to A.6.5.4-*13, A.6.5.4-13a, and A.6.5.4-14 to A.6.5.4-16* withheld pursuant to 10 CFR 2.390

A.6.5.4.6 References

1. Oak Ridge National Laboratory, RSIC Computer Code Collection, "SCALE: A Modular Code System for Performing Standardized Computer Analysis for Licensing Evaluations for Workstations and Personal Computers," NUREG/CR-0200, Revision 6, ORNL/NUREG/CSD-2/V2/R6.
2. 10 CFR 71, Packaging and Transportation of Radioactive Materials.
3. U.S. Nuclear Regulatory Commission, "Criticality Benchmark Guide for Light-Water-Reactor fuel in Transportation and Storage Packages," NUREG/CR-6361, Published March 1997, ORNL/TM-13211.
4. U.S. Nuclear Regulatory Commission, "Recommendations for Preparing the Criticality Safety Evaluation of Transportation Packages," NUREG/CR-5661, Published April 1997, ORNL/TM-11936.
5. *NUH-003, Updated Final Safety Analysis Report for the Standardized NUHOMS® Horizontal Modular Storage System for Irradiated Nuclear Fuel (UFSAR), Revision 11. The Certificate of Compliance (CoC) for Amendment 10 to Part 72 CoC 1004 was issued on August 24, 2009.*
6. NUHOMS® HD Updated Final Safety Analysis Report, Revision *2*.

Proprietary information on pages A.6.5.4-18 to A.6.5.4-32 and pages A.6.5.4-32a to A.6.5.4-32u withheld pursuant to 10 CFR 2.390

Table A.6.5.4-1
Authorized Contents for NUHOMS®-32PTH1 System

Assembly Type(1)	Array	Assembly Class
Westinghouse 17x17 LOPAR/Standard	17x17	WE 17x17
Westinghouse 17x17 OFA/Vantage 5(2)	17x17	WE 17x17
Framatome 17x17 MK BW	17x17	WE 17x17
Westinghouse 17x17 RFA	17x17	WE 17x17
CE 16x16 System 80	16x16	CE 16x16
CE 16x16 Standard	16x16	CE 16x16
B&W 15x15 Mark B (through B11)(3)	15x15	BW 15x15
B&W 17x17 Mark C	17x17	BW 15x15
CE 15x15 Palisades(3)	15x15	CE 15x15
Exxon/ANF (ANP) 15x15 CE(3)	15x15	CE 15x15
Exxon/ANF (ANP) 15x15 WE(3)	15x15	WE 15x15
Westinghouse 15x15 Standard/ZC	15x15	WE 15x15
Westinghouse 15x15 LOPAR/OFA/ DRFA/Vantage 5	15x15	WE 15x15
CE 14x14 Standard/Generic	14x14	CE 14x14
CE 14x14 Fort Calhoun	14x14	CE 14x14
Framatome-ANP 14x14 CE	14x14	CE 14x14
Exxon/ANF (ANP) 14x14 WE(3)	14x14	WE 14x14
Exxon/ANF (ANP) 14x14 Toprod(3)	14x14	WE 14x14
Westinghouse 14x14(3) Standard/LOPAR/ZCA/ZCB	14x14	WE 14x14
Westinghouse 14x14 OFA(3)	14x14	WE 14x14

Notes:
(1) Reload fuel from other manufacturers with these parameters are also acceptable.
(2) Includes all Vantage versions (5, +, ++, 5H, etc.)
(3) B&W 15x15 class, CE 15x15 class, and WE 14x14 class fuel assemblies are not authorized for loading in the NUHOMS® 32PTH/32PTH Type 1 DSC.

Table A.6.5.4-2
NUHOMS®-32PTH1 Basket Dimensions

Basket Component Description	**Actual Dimension, inches**[1]
Compartment Inside (Maximum) Compartment Inside (Nominal) Compartment Inside (Minimum)	8.75 8.70 8.65
Compartment wall (Maximum) Compartment wall (Nominal) Compartment wall (Minimum)	0.2325 0.1875 0.1775
Stainless steel insert plate height	1.75
Stainless steel insert plate thickness	0.50
Poison/Al plate height	13.18
Poison plate thickness	0.075
Al plate thickness	0.425
Horizontal gap	0.07
Vertical slot width/height	1.00/ 5.75
DSC inside radius	34.375
DSC wall thickness	0.500
Section Height	15.00

Note:
(1) Dimensions given are nominal unless otherwise specified.

Table A.6.5.4-3
Minimum B-10 Content

Poison ID	Boron Loading Utilized ($mg B\text{-}10/cm^2$)
A	6.30
B	13.5
C	18.0
D	28.8
E	45.0

Table A.6.5.4-4
Parameter for PWR Assemblies

Manufacturer(1)	Array	Version	Active Fuel Length (in)	Number Fuel Rods per Assembly	Pitch (in)	Fuel Pellet OD (in)
WE	17x17	LOPAR	144	264	0.496	0.3225
WE	17x17	OFA/Van 5	144	264	0.496	0.3088
Framatome	17x17	MK BW	144	264	0.496	0.3195
WE	17x17	RFA	144	264	0.496	0.3225
CE	16x16	System 80	150	236	0.506	0.3255
CE	16x16	Standard	150	236	0.506	0.3255
B&W	15x15	Mark B2 – B8	141.8	208	0.568	0.3686
B&W	15x15	Mark B9	140.6	208	0.568	0.3700
B&W	15x15	Mark B10	142.3	208	0.568	0.3735
B&W	15x15	Mark B11	142.3	208	0.568	0.3615
B&W	17x17	Mark C	144	265	0.502	0.3232
CE	15x15	Palisades	132	216	0.550	0.3600(2)
Exxon/ANF (ANP)	15x15	CE	131.4	216	0.550	0.3565
Exxon/ANF (ANP)	15x15	WE	144	204	0.563	0.3565
WE	15x15	Std/ZC	144	204	0.563	0.3659
WE	15x15	LOPAR/OFA/D RFA/Van 5	144	204	0.563	0.3659
CE	14x14	Std/Gen	136.7	176	0.580	0.3765
CE	14x14	Ft. Calhoun	128	176	0.580	0.3815
Framatome	14x14	CE	136.7	176	0.580	0.3805
Exxon/ANF (ANP)	14x14	WE	142	179	0.556	0.3505
Exxon/ANF (ANP)	14x14	Toprod	142	179	0.556	0.3505
WE	14x14	Std/LOPAR/ ZCA/ZCB	144	179	0.556	0.3674
WE	14x14	OFA	144	179	0.556	0.3444

Table A.6.5.4-4
Parameter for PWR Assemblies
(continued)

Manufacturer[1]	Array	Version	Clad Thickness (in)	Clad OD (in)	Water Hole OD (in)	Water Hole ID (in)
WE	17x17	LOPAR	0.0225	0.374	24@0.474 1@0.480	24@0.422 1@0.450
WE	17x17	OFA/Van 5	0.0225	0.360	24@0.482 1@0.476	24@0.450 1@0.460
Framatome	17x17	MK BW	0.0225	0.374	25@0.482	25@0.450
WE	17x17	RFA	0.0225	0.374	24@0.474 1@0.480	24@0.422 1@0.450
CE	16x16	System 80	0.0230	0.382	5@0.768	5@0.687
CE	16x16	Standard	0.0250	0.382	5@0.768	5@0.687
B&W	15x15	Mark B2 – B8	0.0265	0.430	16@0.530 1@0.493	16@0.498 1@441
B&W	15x15	Mark B9	0.0265	0.430	16@0.530 1@0.493	16@0.498 1@441
B&W	15x15	Mark B10	0.0250	0.430	16@0.530 1@0.493	16@0.498 1@441
B&W	15x15	Mark B11	0.0240	0.416	16@0.530 1@0.493	16@0.498 1@441
B&W	17x17	Mark C	0.0240	0.379	24@0.482 1@0.442	24@0.430 1@0.390
CE	15x15	Palisades	0.0260[3]	0.418[4]	8@0.4135	8@0.3655
Exxon/ANF (ANP)	15x15	CE	0.0300	0.417	8Guide Bars[5] 1@0.417	1@0.363
Exxon/ANF (ANP)	15x15	WE	0.0300	0.424	21@0.544	2@0.510
WE	15x15	Std/ZC	0.0242	0.422	20@0.546 1@0.546	20@0.512 1@0.516[6]
WE	15x15	LOPAR/OFA/D RFA/Van 5	0.0280	0.440	21@0.546	21@0.5166
CE	14x14	Std/Gen	0.0280	0.440	5@1.115	5@1.035
CE	14x14	Ft. Calhoun	0.0280	0.440	5@1.115	5@1.035
Framatome	14x14	CE	0.0260	0.440	5@1.115	5@1.035

Table A.6.5.4-4
Parameter for PWR Assemblies
(concluded)

Manufacturer[1]	Array	Version	Clad Thickness (in)	Clad OD (in)	Water Hole OD (in)	Water Hole ID (in)
Exxon/ANF (ANP)	14x14	WE	0.0300	0.424	16@0.541 1@0.480	16@0.507 1@0.448
Exxon/ANF (ANP)	14x14	Toprod	0.0295	0.0295	16@0.541 1@0.424	16@0.507 1@0.370
WE	14x14	Std/LOPAR/ ZCA/ZCB	0.0225	0.422	16@0.539 1@0.422	16@0.505 1@0.392
WE	14x14	OFA	0.0243	0.400	16@0.526 1@0.400	16@0.492 1@0.353

Notes:

(1) Reload fuel assemblies from other manufacturers with these parameters are also acceptable.
(2) Pellet OD ranges from 0.3510 to 0.3600 inches.
(3) Clad thickness ranges from 0.0240 to 0.0295 inches
(4) Clad OD ranges from 0.4135 to 0.4175 inches
(5) Guide Bars are solid Zircaloy-4 approximately 0.40 inches x 0.45 inches
(6) Instrument Tube is 0.015 thick, however modeled as 0.017 thick.
(7) All dimensions shown are nominal

Proprietary information on pages A.6.5.4-39 and A.6.5.4-40 withheld pursuant to 10 CFR 2.390

Table A.6.5.4-7
Material Property Data

Material	ID	Density g/cm^3	Element	Weight %	Atom Density (atoms/b-cm)
Zircaloy-4	2	6.56	Zr	98.23	4.2541E-02
			Sn	1.45	4.8254E-04
			Fe	0.21	1.4856E-04
			Cr	0.10	7.5978E-05
			Hf	0.01	2.2133E-06
Water (Pellet Clad Gap)	3	0.998	H	11.1	6.6769E-02
			O	88.9	3.3385E-02
Stainless Steel (SS304)	4	7.94	C	0.080	3.1877E-04
			Si	1.000	1.7025E-03
			P	0.045	6.9468E-05
			Cr	19.000	1.7473E-02
			Mn	2.000	1.7407E-03
			Fe	68.375	5.8545E-02
			Ni	9.500	7.7402E-03
$^{11}B_4C$ in CC	7	2.555	B11	78.56	1.0988E-01
			C	21.44	2.7470E-02
Aluminum	8	2.702	Al	100.0	6.0307E-02
Aluminum - Boron Poison Plate for Type A Basket (6.30 mg B-10/cm^2)	9	2.693	B10	0.01	1.33020E-05
			B11	0.14	2.01002E-04
			Al	99.85	5.83483E-02
Water	10	0.998	H	11.1	6.6769E-02
			O	88.9	3.3385E-02
Lead	11	11.344	Pb	100.0	3.2969E-02
Aluminum - Boron Poison Plate for Type B Basket (13.5 mg B-10/cm^2)	9	2.693	B10	2.63	4.26233E-03
			B11	0.29	4.30729E-04
			Al	97.08	5.83483E-02
Aluminum - Boron Poison Plate for Type C Basket (18.0 mg B-10/cm^2)	9	2.693	B10	3.47	5.68315E-03
			B11	0.39	5.74311E-04
			Al	96.15	5.83483E-02
Aluminum - Boron Poison Plate for Type D Basket (28.8 mg B-10/cm^2)	9	2.693	B10	5.42	9.09302E-03
			B11	0.60	9.18894E-04
			Al	93.97	5.83483E-02
Aluminum - Boron Poison Plate for Type E Basket (45.0 mg B-10/cm^2)	9	2.693	B10	8.20	1.42078E-02
			B11	0.91	1.43577E-03
			Al	90.89	5.83483E-02

Proprietary information on pages A.6.5.4-42 to A.6.5.4-65, and pages A.6.5.4-65a to A.6.5.4-65c withheld pursuant to 10 CFR 2.390

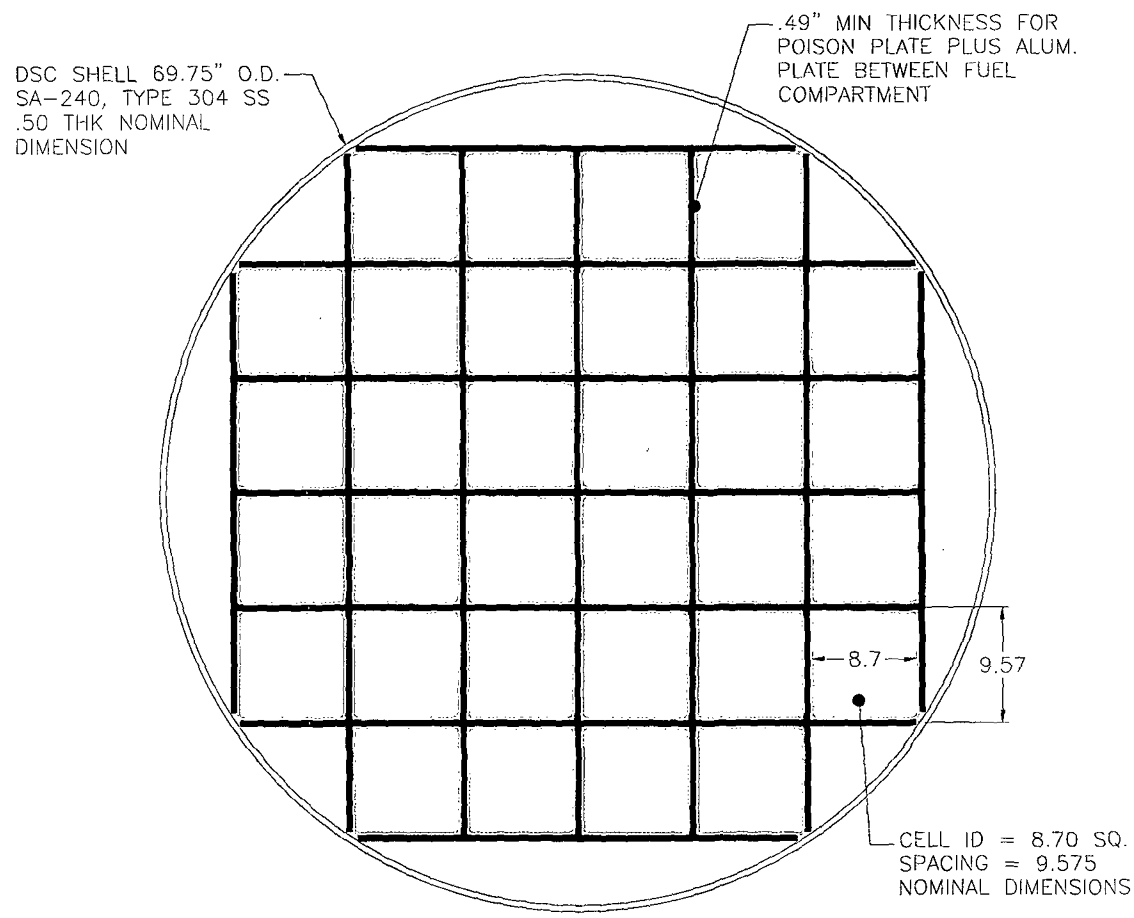

Figure A.6.5.4-1
NUHOMS®-32PTH1 Transportable DSC Basket Radial Cross Section

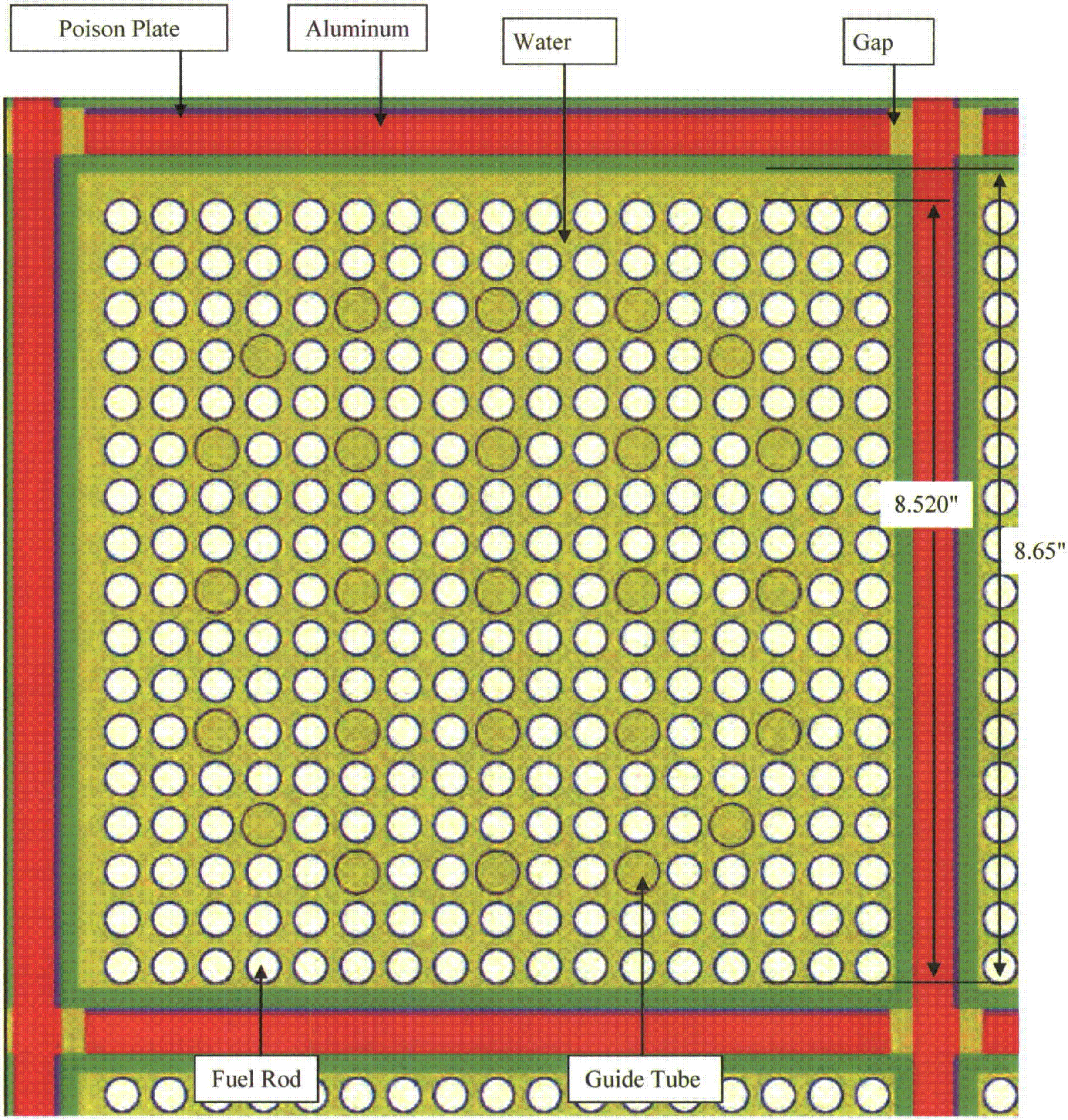

Figure A.6.5.4-2
Basket Compartment with WE 17x17 Fuel Assembly

Figure A.6.5.4-3
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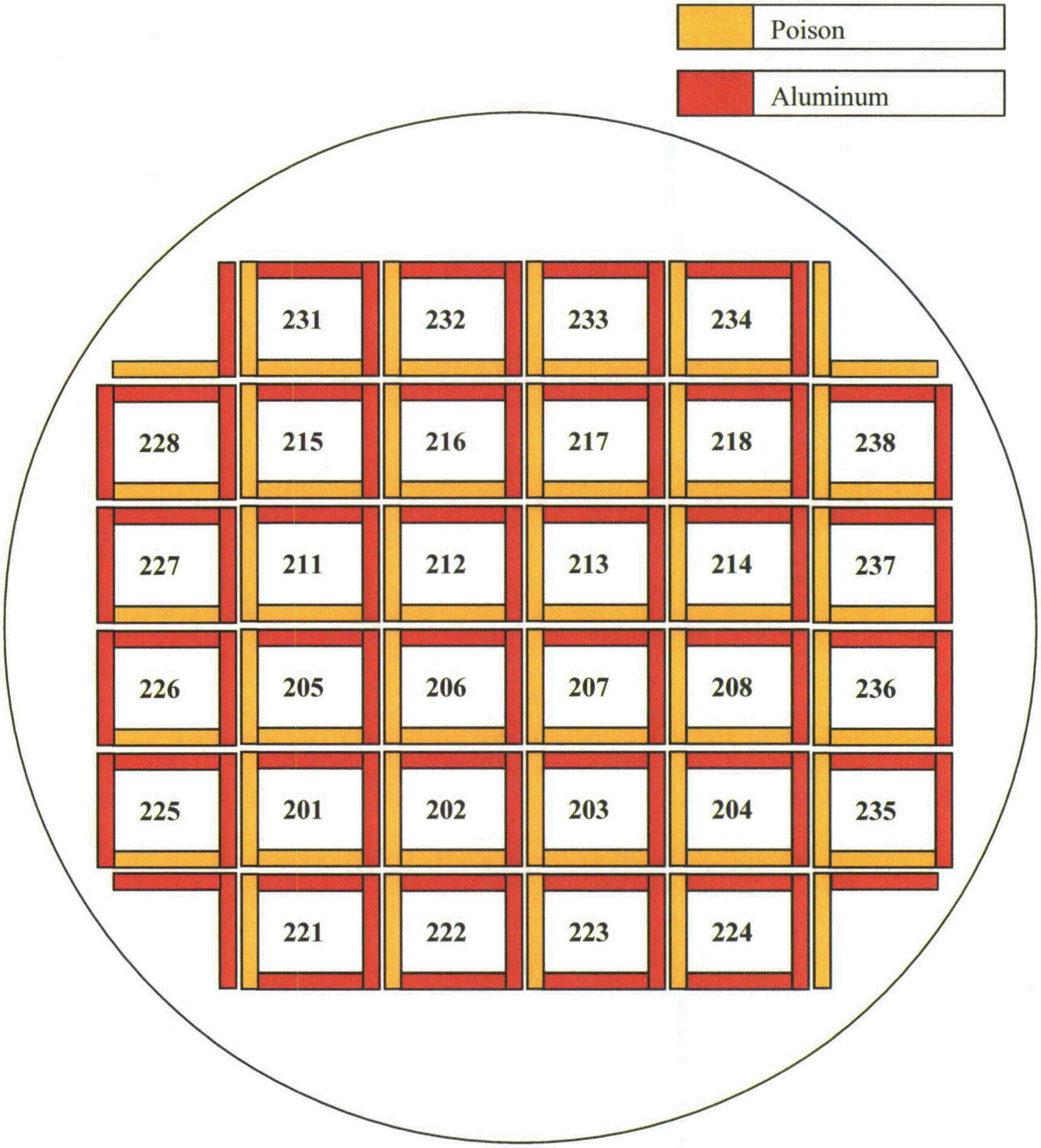

Figure A.6.5.4-4
Fuel Position and Poison Plate Location in the 32PTH1 DSC Design

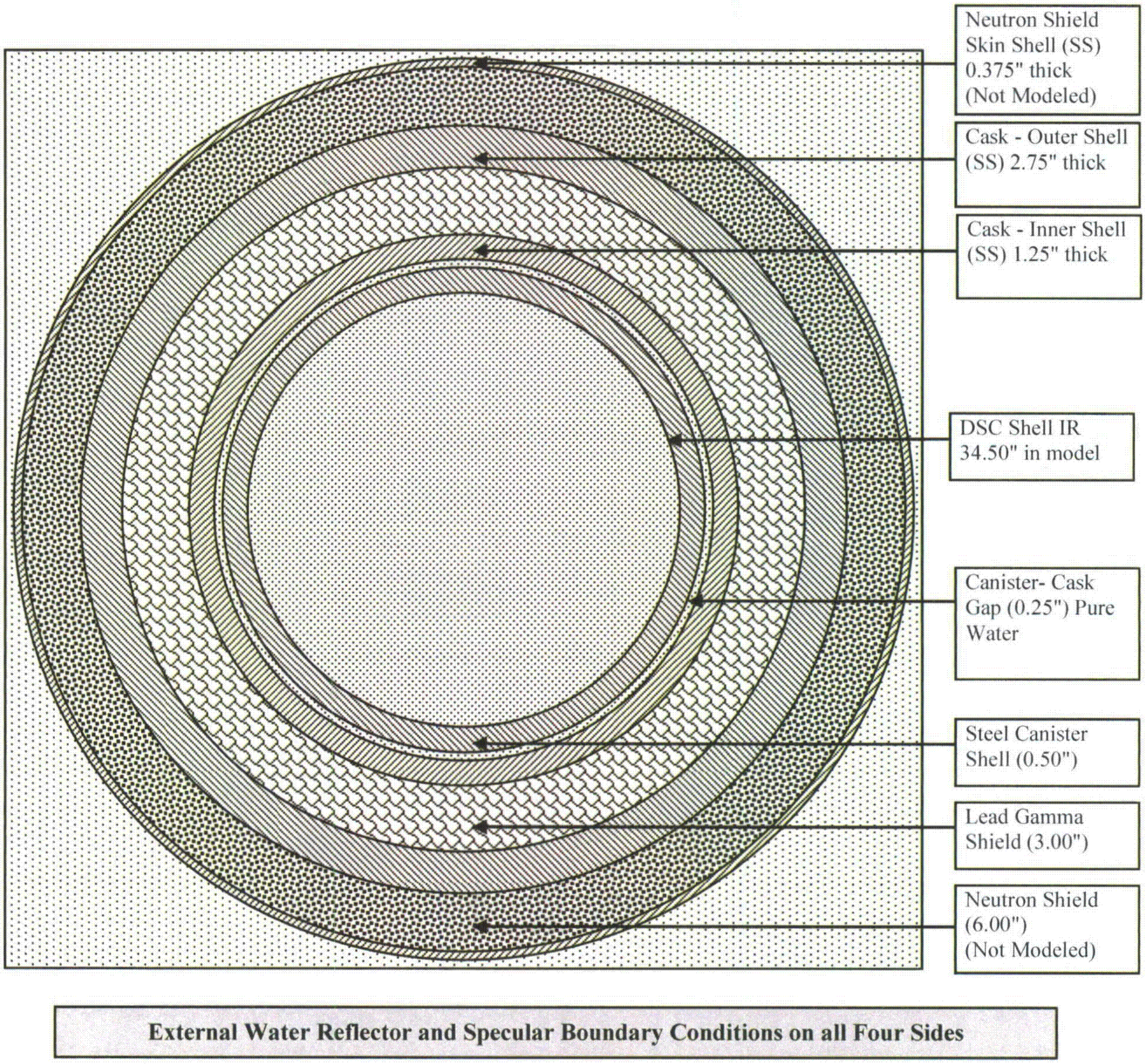

Figure A.6.5.4-5
Criticality Calculational KENO Model

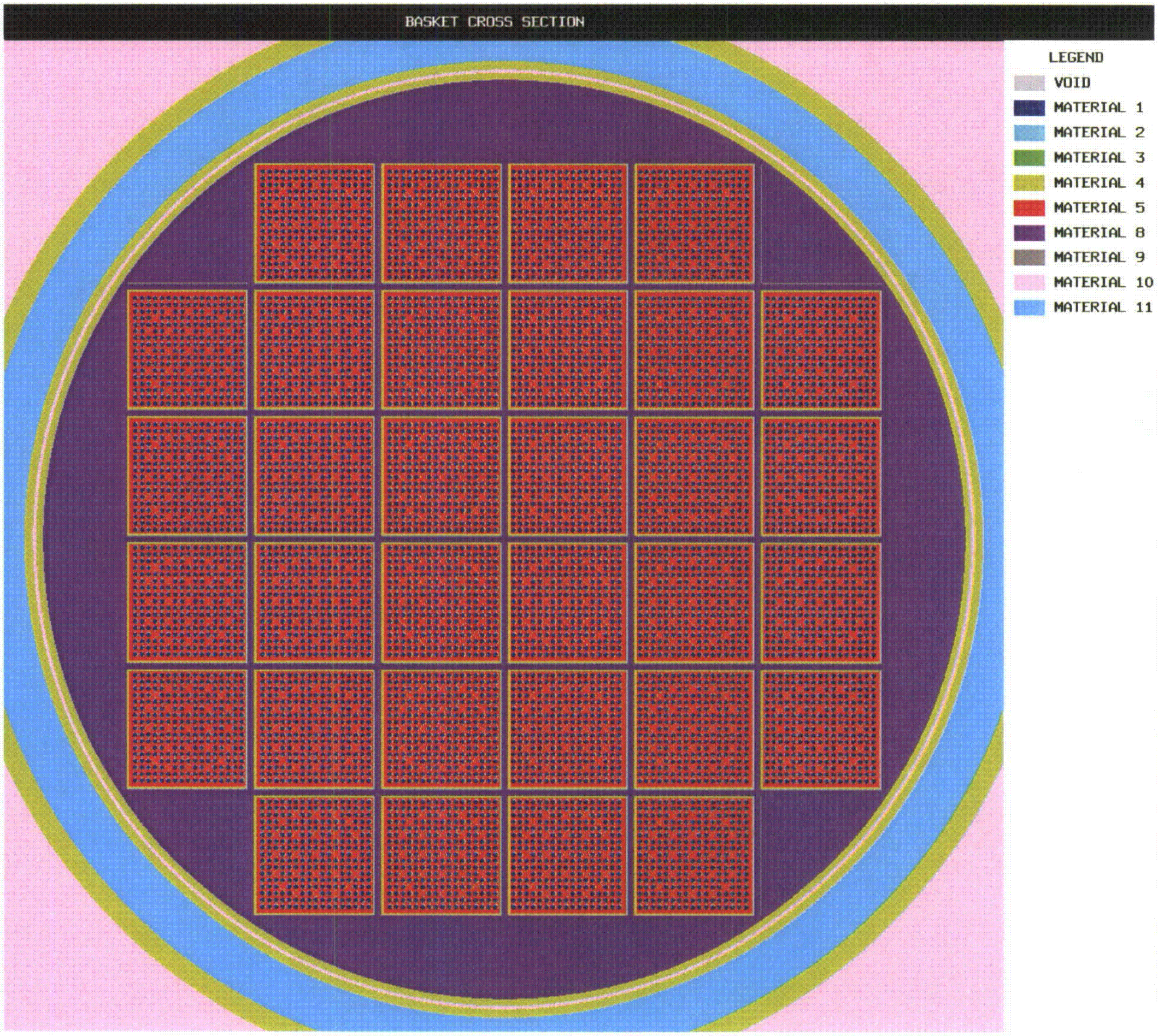

Figure A.6.5.4-6
WE 17x17 Class Assembly KENO Model

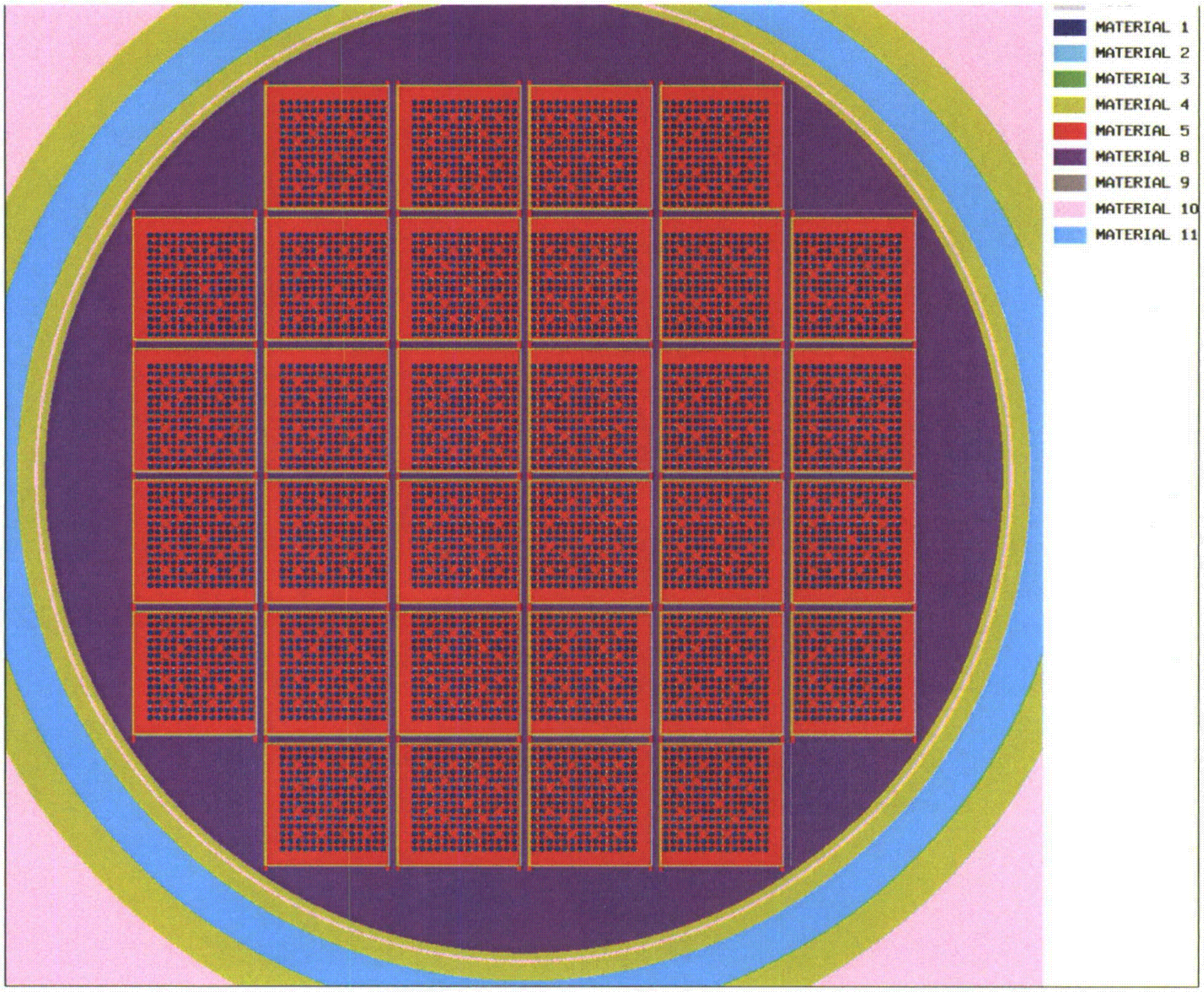

Figure A.6.5.4-7
WE 14x14 Class Assembly KENO Model

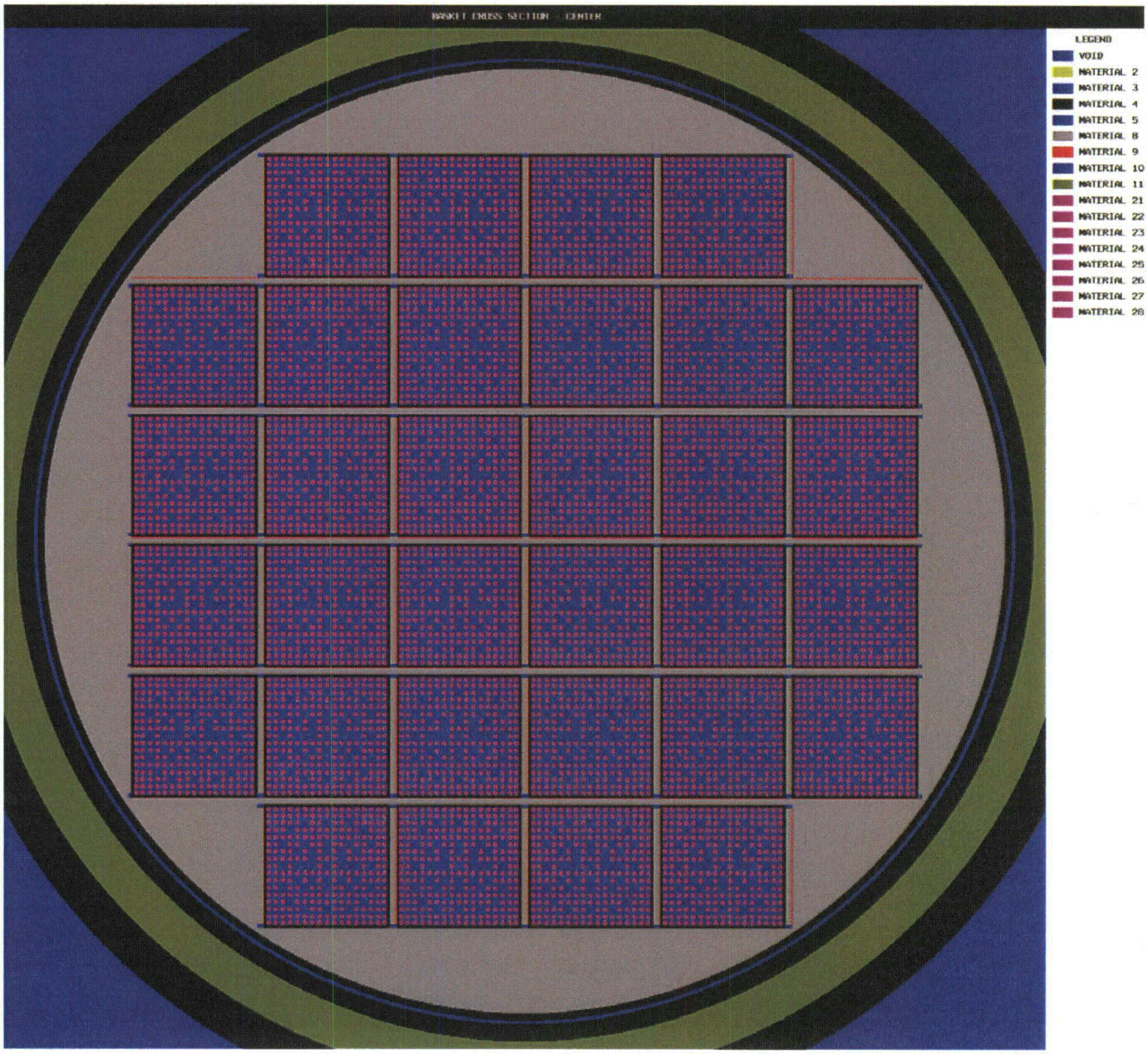

Figure A.6.5.4-8
WE *17x17* Class *Damaged* Assembly KENO Model