# 6.0 CRITICALITY EVALUATION

## 6.1 Discussion and Results

This section demonstrates how the TN-FSV package with the Oak Ridge Container meets the criticality safety requirements of 10 CFR 71.55, General Requirements for Fissile Material Packages, and 10 CFR 71.59, Standards for Arrays of Fissile Material Packages. The Transport Index based on nuclear criticality safety is 100.

The TN-FSV package is a cylindrical cask with an outer diameter slightly less than 31 in., and a cavity diameter of 18 in. Shielding from gamma rays is provided by a minimum of 3.38 in. of lead sandwiched between an inner steel sleeve 1.12 in. thick and an outer steel shell that is 1.50 in. thick. The cask has an overall length of 207 in. The TN-FSV cask is the primary containment boundary, (see Chapter 4).

The Oak Ridge Container fits inside the TN-FSV package cavity, and provides a second containment boundary. The container has an outer diameter of 16.85 in. along the length of its body, increasing to 20.19 in. at the top, where the bolted lid closure is located. The overall length of the Oak Ridge Container is 198 in. A basket assembly containing five fuel compartments fits inside the Oak Ridge Container. The fuel compartments are 5-inch Schedule 10S pipes with integrally welded bottom closures, and have an inside height of 188 in. The basket assembly also includes poison plates that reduce neutron interaction between fuel compartments. The plates form a pentagon in the horizontal plane, whose center corresponds to the center of the Container. A radial poison plate emanates from each of the five corners of the pentagon. The five fuel compartments are positioned with their centers equally spaced on a circle whose center corresponds to the center of the Oak Ridge Canister. The space inside the pentagonal poison plate enclosure is empty.

Special Nuclear Material (SNM) loaded into a fuel compartment is either an intact Peach Bottom fuel assembly or an Oak Ridge Canister. The Peach Bottom fuel assemblies are intact assemblies contained in an aluminum canister with an outer diameter of approximately 5 in. and a length of approximately 153 in. The Oak Ridge Canister is a stainless steel cylindrical canister containing a variety of fuel from research, test, and commercial reactors. The fuel rods for this fuel have been sectioned and/or otherwise breached during processing. The dimensions of the Oak Ridge Canister are 4.75 in. diameter and 34.75 in. in length.

The fissile loading of each individual Oak Ridge Canister is highly variable. Some canisters contain only uranium, while others contain both uranium and plutonium. Some canisters contain very little fissile material, while others contain a significant quantity. In order to ship these canisters in the most efficient manner, an artificial group structure has been created. A canister falls within a given group if the amount of $^{235}U$ and $^{239}Pu$ does not exceed the limits designated for that group. Five such groups have been created, as defined in Table 6-2.

The five different group types of Oak Ridge Canisters are loaded into the Oak Ridge Container, along with the intact Peach Bottom assemblies, in precisely defined loading patterns. Four such patterns have been analyzed. Those patterns are defined in Table 6-3.

When more than one Oak Ridge Container is placed in a given fuel compartment, they are separated axially by a flux trap spacer. The spacer is 16 in. in length, and has two 0.30-inch thick boron poison plates. Within the flux trap spacer and the pentagonal poison enclosures, boron poison plates are in place to inhibit neutron interaction between adjacent canisters in both the axial and radial directions.

Results of the criticality evaluation are summarized in Table 6-1. These results demonstrate compliance with the applicable sections of 10 CFR 71 for the TN-FSV cask with the Oak Ridge Container, for transport of intact Peach Bottom fuel assemblies and Oak Ridge Canisters as described above.

An extensive validation of the code and cross section data used in the analyses described in this chapter was performed. An upper subcritical limit of 0.942 has been established, based on a 95% confidence interval and a 5% administrative margin. All calculated values of $k_{eff}$ reported in this chapter are less than the 0.942 USL. Therefore, it can be stated with high confidence that they represent subcritical conditions.

Table 6-1 Summary of Criticality Results[1]

| Requirement | Met By Case | For Loading Pattern | $k_{eff}$ | $\sigma$ | $k_{eff} + 2\sigma$ |
|---|---|---|---|---|---|
| 71.55(b) Package subcritical under conditions of maximum reactivity, with most reactive credible configuration, optimal moderation by water, and full water reflection. | ORCL1-1a<br>ORCL3-3b<br>ORCL4-1c<br>ORCL5-5 | 1<br>2<br>3<br>4 | 0.9159<br>0.9068<br>0.9044<br>0.9223 | 0.0026<br>0.0026<br>0.0027<br>0.0029 | 0.921<br>0.912<br>0.910<br>0.928 |
| 71.55(d) Package subcritical under Normal Conditions of Transport | ORCL1-90<br>ORCL3-90<br>ORCL4-91<br>ORCL5-95 | 1<br>2<br>3<br>4 | 0.1266<br>0.1198<br>0.0856<br>0.0654 | 0.0007<br>0.0006<br>0.0006<br>0.0004 | 0.128<br>0.121<br>0.087<br>0.066 |
| 71.55(e) Package subcritical under Hypothetical Accident Conditions | ORCL1-1a<br>ORCL3-3b<br>ORCL4-1c<br>ORCL5-5 | 1<br>2<br>3<br>4 | 0.9159<br>0.9068<br>0.9044<br>0.9223 | 0.0026<br>0.0026<br>0.0027<br>0.0029 | 0.921<br>0.912<br>0.910<br>0.928 |
| 71.59(a.1) Five times "N" undamaged packages subcritical with nothing between packages (Note: N=0.5, but calculations used infinite array) | ORCL1-151<br>ORCL3-151<br>ORCL4-151<br>ORCL5-150 | 1<br>2<br>3<br>4 | 0.2083<br>0.1153<br>0.0991<br>0.1068 | 0.0009<br>0.0007<br>0.0006<br>0.0007 | 0.210<br>0.117<br>0.1003<br>0.108 |
| 71.59(a.2) Two times "N" damaged packages subcritical with optimal interspersed moderation (Note, N=0.5, so 2 * N = 1.) | ORCL1-1a<br>ORCL3-3b<br>ORCL4-1c<br>ORCL5-5 | 1<br>2<br>3<br>4 | 0.9159<br>0.9068<br>0.9044<br>0.9223 | 0.0026<br>0.0026<br>0.0027<br>0.0029 | 0.921<br>0.912<br>0.910<br>0.928 |

## 6.2 Package Fuel Loading

There are two general types of SNF to be transferred into the Oak Ridge Container and transported in the TN-FSV cask. One type consists of a variety of SNF materials in a stainless steel Oak Ridge canister, and the second type is an intact Peach Bottom assembly (graphite-based SNF assembly). The Peach Bottom assemblies are still in the aluminum canisters used to ship the assembly from the reactor to the ORNL and will remain in the canisters for transport to the INEEL. Multiple Oak Ridge canisters and Peach Bottom assemblies can be loaded into an Oak Ridge Container and transported in the TN-FSV cask. Most of the SNF in the Oak Ridge canisters and the Peach Bottom assemblies, (these are often referred to in this Chapter as IPB's), were placed in dry storage in the 1970's.

Although some underground storage locations were found to be partially flooded when the

[1] As is discussed later in this chapter, the parameters that influence criticality safety are not affected by the hypothetical accident condition tests. Therefore, the same calculations that satisfy 71.55(b) also satisfy 71.55(e) and 71.59(a.2).

SNF materials were retrieved for repackaging or inspection in the 1990's, all Oak Ridge canisters and Peach Bottom assemblies have been stored in monitored locations confirmed to remain dry since the Oak Ridge canisters were loaded and the Peach Bottom assemblies were replaced after visual inspection in the hot cell facility.

There are anticipated to be approximately 73 Oak Ridge canisters of SNF and nine intact Peach Bottom assemblies that will be transported. The Oak Ridge canisters will contain a variety of SNF types that can be categorized as originating from Light Water Reactors (LWR), Fast Reactors, High Temperature Gas Reactors (HTGR), and the Keuring van Electrotechnische Materialen (KEMA) Reactor. Most of the SNF in the Oak Ridge canisters, and the Peach Bottom assemblies, were placed in dry storage in the 1970's.

Because the fissile content of the Oak Ridge Canisters varies widely, an artificial group structure was designed to permit analysis of specific loading patterns. The group structure was developed using a trial and error approach, with a goal of finding the minimum number of artificial group structures that could be used to characterize the caniasters while still permitting the Oak Ridge Container to be completely filled for each shipment (i.e., each fuel compartment contains either four canisters or one canister and one IPB). Five artificial group structures were determined to be the minimum required to achieve the desired results. To be categorized into a given group, the pre-irradiation mass of $^{235}$U and fissile plutonium ($^{239}$Pu + $^{241}$Pu) must not exceed the limits listed in Table 6-2. Since the limits are maxima rather than ranges, there is the potential for a canister to meet the requirements of more than one group. For instance, a canister containing less than 200 grams of $^{235}$U and no plutonium would meet the requirements of any of the five groups, and any canister that meets the requirements of Group 1 also meets the requirements of Group 5. Since the loading patterns are defined by the number of canisters of a certain group that can be loaded into each fuel tube, the overlap in group structures provides some flexibility in choosing canisters for each shipment.

The fourth column of Table 6-2 lists the group distribution for the canisters currently identified for shipping. When a canister meets the fissile limits of more than one group, it is usually assigned to the lower FEM group. Exceptions are made to even out the number of canisters in each group, to allow the cask to be full for each shipment. Note that the number of currently-identified canisters assigned to each group is presented for the reader's information only. The analyses defend the group structures and the loading patterns, and are valid for any number of shipments of Oak Ridge Canisters and Peach Bottom assemblies that meet the requirements of Tables 6-2 and 6-3.

Uranium-233 is present in both the intact Peach Bottom HTGR fuel and Oak Ridge Canisters that contain sectioned HTGR fuel and KEMA materials. In all cases the presence of uranium-233 resulted from the transmutation of thorium during the irradiation process. None of the fuel materials contained uranium-233 prior to the irradiation process, and all of the fuel materials were subject to breeding ratios of $< 1$. Consequently, the configuration of the fuel material at the end of life with in-bred uranium-233 is less reactive than the beginning of life configuration prior to irradiation of the material. The criticality analyses is based on the pre-irradiation beginning of life configuration values for added conservatism.

Table 6-2 Isotopic Content Limits for Each Group (pre-irradiation)

| Group | Grams $^{235}U$ (Max) | Grams $^{239}Pu + ^{241}Pu$ (Max) | No. of Canisters | FEM |
|---|---|---|---|---|
| 1 | 475 | 0 | 48 | 475 |
| 2 | 865 | 191 | 8 | 1171 |
| 3 | 200 | 415 | 2 | 864 |
| 4 | 275 | 160 | 12 | 531 |
| 5 | 910 | 0 | 4 | 910 |
| IPB | 250 | 0 | 9 | 250 |

The last column in Table 6-2 lists the maximum Fissile Equivalent Mass (FEM) for each group structure. This column is provided to give the reader a sense of the relative reactivity of each group. The FEM is calculated by comparing the known critical mass of $^{239}Pu$ thermal solution systems to that of $^{235}U$ thermal solution systems, as discussed in ANSI/ANS 8.15. This approach can often be used to greatly simplify analysis, by considering a simple uranium system instead of several systems with different ratios of plutonium to uranium. However, the FEM concept is based on comparisons of known critical masses of isolated single units. In the Oak Ridge Container, neutron interaction occurs axially between the canisters in a given fuel compartment, as well as radially between canisters in adjacent fuel compartments. Therefore, while the FEM is useful for comparing relative reactivity of the various groups, it cannot be used to simplify the group structure and eliminate the need to explicitly consider mixed uranium/plutonium systems in Groups 2 – 4.

### 6.2.1 Loading Patterns

The loading patterns were developed by considering the number of canisters assigned to each group, and then devising methods that those canisters could be loaded into the Oak Ridge Container while keeping the container completely full and maintaining the calculated system multiplication factor below the Upper Subcritical Limit. To aid in understanding what drives the reactivity of the cask system when loaded with Oak Ridge canisters, a scoping study was performed in which the number of canisters in the cask was varied. In the first set of calculations, four of the five fuel compartments are initially empty, and the fifth compartment contains a single canister at the bottom of the compartment. Canisters are then added one at a time to each of the four surrounding fuel compartments (at the bottom of the compartment). The reactivity as a function of the number of canisters is plotted in Figure 6-1, and shows an approximately linear functional dependence. In the second set of calculations, the initial state is identical to the first, but canisters are added axially rather than radially, such that in the fourth calculation one fuel tube contains four canisters (separated by flux trap spacers). The results of this study are also plotted in Figure 6-1. The calculated multiplication factor does not change as canisters are added axially. Apparently, the flux trap spacers are sufficient to prevent interaction between canisters stacked in the same fuel tube. Therefore, it is obvious that the best way to load the cask is to put all of the most reactive canisters in the same fuel compartment, since that way they cannot interact with each other. This is precisely the strategy followed in devising the four loading patterns discussed below.

Four different loading patterns have been evaluated for the Oak Ridge Container. These loading patterns define the type and number of Oak Ridge Canisters permitted in each fuel compartment (or combination of one Oak Ridge Canister and one intact Peach Bottom assembly). The four loading patterns are defined in Table 6-3. Note that for loading patterns 3 and 4, the IPB and canisters may be loaded into the fuel compartment in any order (*e.g.*, for loading pattern 3, the IPB can be on top with the canister on the bottom, or vice versa).

Table 6-3 Oak Ridge Container Fuel Compartment Loading Patterns

| **Loading Pattern** | **Compartment 1** | **Compartments 2- 5** |
|---|---|---|
| 1 | Four Group 2 canisters | Four Group 1 canisters |
| 2 | Four Group 5 canisters | Four Group 1 canisters |
| 3 | One IPB and one Group 4 canister | One IPB and one Group 4 canister |
| 4 | Two Group 3 and two Group 4 canisters | One IPB and one Group 4 canister |

Note: IPB for Intact Peach Bottom assembly.

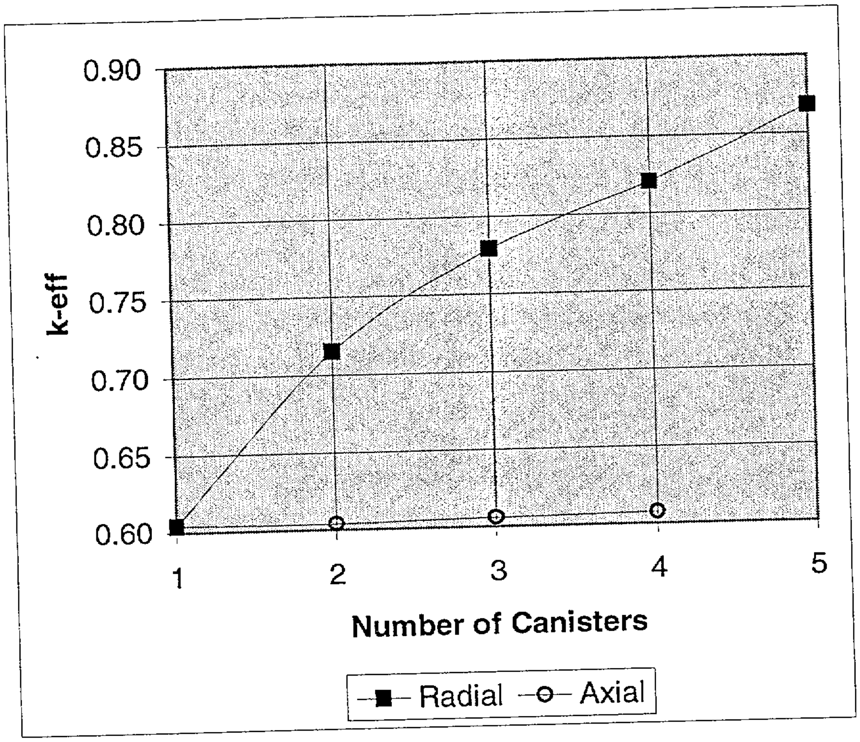



**Figure 6-1 Variation of k-eff with increasing number of canisters in the cask.**
*These calculations assumed all canisters were characterized by Group 1 isotopics*

## 6.2.2 Oak Ridge Canisters

The fissile material contained in the Oak Ridge Canisters is in a large variety of forms, (see Section 1.2.3 in this addendum for details) from graphite-based HTGR fuel to Na-bonded fast reactor fuel to common LWR $UO_2$ fuel. In order to make an evaluation feasible, it is necessary to make some highly conservative assumptions regarding the isotopic content and chemical make-up of the fuel. Rather than modeling the fuel tubes as a heterogeneous system combining fissile material and neutron poisons, the fissile isotopes in each canister are modeled as a homogeneously distributed mass. The presence of fission products and of the fissionable isotopes U-238 and Th-232, which act as significant neutron poisons in thermal systems, is ignored. The geometric shape and the moderation level of the fissile masses are both optimized. This procedure results in a highly conservative fissile material model.

As described in Section 1.2.1.3, the Oak Ridge canister provides a boundary formed by the cylindrical shell of the canister, the handling head welded to the top of the shell, and the interference fit closure between the freeze plug and the bottom of the shell. This confinement boundary has the required structural integrity to prevent the release of fissile material from an Oak Ridge canister. Analyses in Appendix 2.11.7 demonstrate that there is no change in the central cylindrical shell and cap weldment of the Oak Ridge canister due to loads experienced during normal conditions of transport or hypothetical accident conditions. Shell and head stresses remain below allowable limits, and no buckling of the shell or handling head occurs.

Appendix 2.11.7 also demonstrates that the freeze plug is not separated from the canister shell due to loads generated under either normal or accident conditions. The interference fit of the freeze plug does not experience forces to separate the freeze plug from the shell. In addition, the pins and slots on each canister joint provide an independent closure system for keeping the plug joined to the shell. As a separate safety feature, the arrangement of the Oak Ridge canisters and flux trap spacers in the fuel compartment of the Oak Ridge Container leaves insufficient clearance for a freeze plug to completely separate from the canister shell. There is no possibility of separation of the freeze plug joint and there is no release of the fissile material contents from the canisters.

### 6.2.3 Peach Bottom Assemblies

The intact Peach Bottom Assemblies have an overall length of 144 in., and an outer diameter of 3.5 in. The active part of the assemblies consists of 30 annular fuel compacts stacked on top of each other. Each compact is three in. high, and has an inner diameter of 1.75 in. and an outer diameter of 2.75 in. [1,2]. Fuel consists of enriched uranium/thorium carbide particles, coated with pyrolitic carbon. These fuel particles were poured into the annular space in the compact, which was then annealed. The active fuel length of the assembly is 30 * 3 = 90 in.

The top of the assembly consists of a porous plug, an upper reflector apparatus, and a grappling hook. There is no fissile material in this section, which has an overall length of 23.44 in.[1,2]. The bottom of the assembly contains a lower reflector, an internal fission trap, and a bottom connector. The length of this section, which also does not contain fissile material, is (144 – 90 –23.44) = 30.56 in. These inactive sections of the assembly are an important consideration, since they provide spacing between the fissile material in the intact Peach Bottom assembly and the fissile material in the Oak Ridge canister stacked above or below.

Each Peach Bottom assembly is packaged inside an aluminum canister fitted with a steel liner. The canister boundary consists of a cylindrical aluminum tube with aluminum end caps. The tubing has a 4½ in. outside diameter and a 0.065 in. wall thickness. The overall length of the canister is approximately 153 in. The steel lining has an outer diameter of 4.3 in. A 0.13 in thick steel plate is welded to close the steel liner, approximately 3.5 in. from the bottom of the liner. The Peach Bottom assembly rests on this plate, which then defines the axial positioning of the active fuel section. Note that this positions the top of the assembly 4 in. below the top of the canister. Figure 1-7 shows the Peach Bottom fuel assembly in its canister.

### 6.2.4 Loading of Fissile Material Into The Oak Ridge Container

The Oak Ridge Container is loaded dry. This is an important consideration, because it means that the only way water could possibly enter either containment vessel is as the result of a severe accident. Therefore, the fissile contents are modeled as a dry mixture of fissile metal with carbon in the NCT analyses. For the HAC analyses and for the analyses to satisfy the requirement of 10 CFR 71.55 (b), the fissile contents are modeled as optimally moderated by water.

### 6.2.5 Special Considerations

A unique feature of the Oak Ridge Container is the use of the axial flux trap spacers. These spacers are relied upon to inhibit neutron interaction between axially adjacent canisters in a fuel compartment. Because it is necessary to rely on these spacers to demonstrate compliance with the criticality requirements of 10 CFR 71, it is important to consider the implications if they are not used. Two layers of controls are provided to assure the flux trap spacers are present as required in the sealed Oak Ridge Container. The first control is an administrative requirement that flux trap spacers be inserted into the fuel compartment in between adjacent Oak Ridge Canisters. Loading of the Oak Ridge Container will be conducted under the control of approved procedures. A loading plan will be established for each shipment, which will identify the specific Oak Ridge canisters and Peach Bottom fuel assemblies to be loaded, and specify their locations in the Oak Ridge Container. The loading plan will also specify the placement of axial flux trap spacers between the Oak Ridge canisters in each fuel compartment. The Oak Ridge Container will be loaded one compartment at a time, from the bottom up. The individual supervising loading operations will utilize a checklist to ensure that the specified loading pattern is implemented. Each item will be identified and recorded on the checklist as it is loaded into the Oak Ridge Container.

In addition, independent verification will be performed by a second individual who will observe and document that the canisters and spacers were correctly positioned.

The second control is a verification that the dimensions of each loaded fuel compartment correspond with expected values. The top of the last Oak Ridge Canister loaded into the fuel compartment should be within an inch of the top of the fuel compartment.
If one or more flux trap spacers is missing, the top of the last Oak Ridge Canister will be 16 in. or more from the top of the fuel compartment. The loading procedure will require that the distance from the top of the Oak Ridge Container to the top of the canister in each compartment be observed before the Container is closed. Again, independent verification by a second observer will be required. This will provide a very obvious indicator in the event that a spacer is missing. In the event that a compartment is loaded incorrectly, the administrative controls require all of the canisters be removed from the fuel compartment and the compartment be reloaded.

The controls discussed above assure that the sealed Oak Ridge Container that is loaded in the TN-FSV cask for shipment contains the axial flux trap spacers as required.

However, since the second control does not come into play until after the compartment is mis-loaded, it is still necessary to consider a loaded Oak Ridge Container with no flux trap spacers. Since the Oak Ridge Container is loaded dry (not underwater), the fuel in the Oak Ridge Canister is modeled dry in this case. However, since many of the canisters contain graphite fuel, optimal moderation of the fissile isotopes by carbon is considered. This represents a second type of fissile material model for the canisters.

Carbon moderation is also considered for the normal condition array analysis. This is done in lieu of water moderation for these cases because the package is loaded dry and has two containment barriers. Water ingress into an Container is assumed to only occur under HAC of transport.

### 6.2.6 Justification of Homogenization

The fissile material in the canisters is modeled as a homogeneous mixture of $^{239}$Pu and/or $^{235}$U metal with water. The actual contents of the canisters are pieces of fuel rods that have been sectioned for examination. There is no control over the geometry or size of these pieces. Under certain conditions, a heterogeneous distribution of small fissile particles suspended in water can be more reactive than a homogeneous metal-water mixture. Therefore, it is necessary to verify the conservative nature of modeling the canisters filled with a homogeneous fissile mixture.

Lichtenwalter [7] has demonstrated that a heterogeneous model can result in significantly higher k-infinity than a homogeneous model for uranium metal/water mixtures enriched in $^{235}$U to between 8.29% and 92.98%. This effect is thought to be caused by an increase in the resonance escape probability in the heterogeneous mixture, *e.g.*, fission neutrons enter the water part of the mixture and are able to slow down past the $^{238}$U resonance absorption energies before re-entering a fuel particle, thus avoiding capture in $^{238}$U.

Lichtenwalter's results show that the heterogeneous mixture is only more reactive than a homogeneous mixture in undermoderated systems, i.e., only below some cutoff value of H/X. Above that cutoff value, the homogeneous mixture is more reactive than the heterogeneous mixture. The value of H/X corresponding to the cutoff was found to decrease with both enrichment and particle size. For instance, at 8.29% enrichment, the cutoff occurs near an H/X of 1000 for a 0.02 cm particle size, and near 200 for a particle size of 0.90 cm, while at an enrichment of 92.98%, the cutoff for the 0.02 cm particle size is near 100. Another observation from Lichtenwalter's work is that the larger particle sizes cause the largest individual increases in k-infinity as compared to the homogeneous system, but this increase occurs over a smaller H/X range.

The analyses performed for this addendum assume 100% $^{235}$U or a combination of $^{235}$U and $^{239}$Pu. The fissionable isotopes (i.e., $^{238}$U, $^{240}$Pu) are not included in the models. Since Lichtenwalter considered a maximum $^{235}$U enrichment of 92.98%, and since he didn't consider mixtures of $^{235}$U and $^{239}$Pu, a study is performed to extend the range of applicability to be applicable to the fissile contents modeled in this addendum. The same calculational procedures used by Lichtenwalter are employed here.

The heterogeneous system is assumed to consist of spherical particles in a close packed lattice. The CSAS1X module of the SCALE system is used for the calculations. A particle size (sphere diameter) is chosen, and the H/X is varied by changing the lattice pitch. The value of k-infinity is calculated by the XSDRNPM module, which performs a 1-D transport theory calculation. The particle sizes run are the same ones used by Lichtenwalter for 92.98% case. Two sets of calculations are run.

The first set utilizes 100% $^{235}U$ as the fissile material, while the second utilizes a 50% - 50% (by mass) mixture of $^{235}U$ and $^{239}Pu$.
The results of these calculations are shown in Figures 6-2 and 6-3. The results for 100% $^{235}U$ are very similar to those reported by Lichtenwalter for 92.98% enrichment, while those for the mixture exhibit a much less pronounced peak in the thermal energy range. In both cases, the results demonstrate that the increased value of k-infinity in the heterogeneous system as compared to the homogeneous system is limited to the range H/X < 100, with the maximum increase (less than 3.80% in k-infinity) occurring in the highly undermoderated range where 5 < H/X < 10.

In contrast to the infinite system discussed above, the Oak Ridge Canisters are small, fixed volume, limited mass systems. For these systems, calculations in Section 6.4 demonstrate that the system reactivity is maximized in H/X ranges above 100, and that system reactivity decreases rapidly below H/X = 100. The value of $k_{eff}$ corresponding to the peak of the H/X curve (i.e., under optimal conditions) is at least 5% greater than the value of $k_{eff}$ calculated at an H/X of 100 for all five groups. Since the maximum increase in $k_{infinity}$ from heterogeneous effects is 3.80% for the systems of interest, it is clear that the homogeneous model is conservative when considered under optimal conditions.

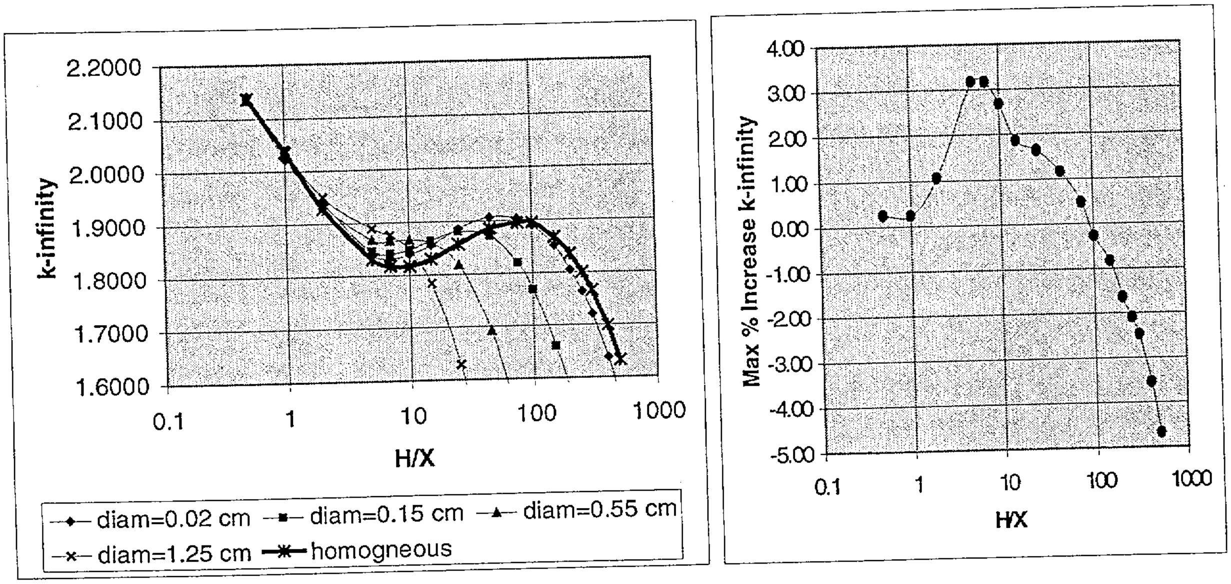



**Figure 6-2 Reactivity of an infinite heterogeneous 100% $^{235}$U system.**
*The system consists of heterogeneous spherical particles of various sizes as compared to an equivalent homogeneous system. The figure on the right plots the maximum percent change in k-infinity of a heterogeneous mixture, regardless of particle size, compared to the equivalent homogeneous system, with the positive increase corresponding to a larger k-infinity value for the heterogeneous system.*

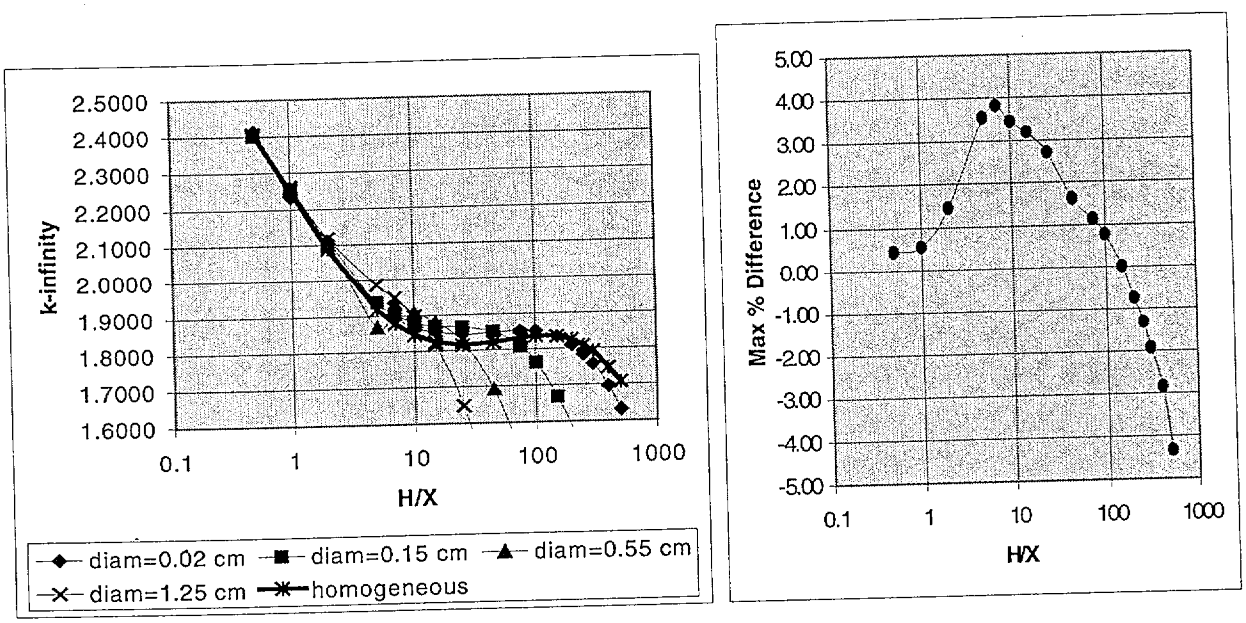



**Figure 6-3 Reactivity of an infinite heterogeneous $^{235}$U and $^{239}$Pu system.**
*The system consists of spherical particles of various sizes as compared to an equivalent homogeneous system. The spherical particles contain a 50% - 50% mixture of $^{235}$U and $^{239}$Pu. The figure on the right plots the maximum percent change in k-infinity of a heterogeneous mixture, regardless of particle size, compared to the equivalent homogeneous system, with the positive increase corresponding to a larger k-infinity value for the heterogeneous system.*

## 6.3 Model Specification

### 6.3.1 Description of Calculational Model

The Oak Ridge Container with contents, inside the TN-FSV cask, is modeled using the CSAS VI module of the SCALE 4.4 computer code package(3) . CSAS VI implements the KENO VI computer code. It is necessary to use this generalized geometry version of the KENO code family, rather than the simpler KENO V.a, due to the geometric complexity of the basket assembly in the Oak Ridge Container.

A brief overview of the cask design is presented to aid the reader in understanding the model details that follow. The TN-FSV cask itself is of a common design, consisting of two thick steel shell assemblies with almost 3.5 in. of lead shield sandwiched between them. The Oak Ridge Container, a thin-walled steel cylindrical vessel with an aluminum spacer sleeve on the outer surface, is loaded into the cask cavity, which has an inner diameter of 18 in. and a length of 199 in. A basket assembly that contains neutron poison plates to reduce neutron interaction between fissile material in adjacent fuel compartments is loaded into the Oak Ridge Container. The design of the basket assembly is rather complex. Five fuel compartments are arranged with their centers on a circle of diameter 5.687 in., with equal spacing between each center. A poison enclosure consisting of five panels in the shape of a pentagon is placed inside the perimeter formed by the five fuel compartments, as shown in Figure 6-4. An additional panel is attached at each vertex of the pentagon, such that it extends radially from the pentagon to the space between two adjacent fuel compartments, again as shown in Figure 6-4. Therefore, a poison enclosure, constructed of a total of 10 poison panels, is used to reduce neutron interaction between adjacent fuel compartments.

Due to structural concerns, the height of each poison panel is limited. Nine identical poison enclosures, each designed as pictured in Figure 6-5, are used to form the basket assembly. The enclosures are not stacked directly on top of each other; rather, a ¾-inch thick steel plate referred to as a middle disk is placed between each enclosure. Top and bottom disks terminate the axial ends of the basket assembly. Note that the poison plates do not penetrate the disks, so there is a small gap where neutron streaming could occur. In contrast, the fuel compartments do penetrate the disks, as the fuel compartments are continuous. This is illustrated in Figure 6-6. Tie rods (not shown in any of the figures) penetrate the disks and pass through the holes in the poison enclosure weldment (see Figure 6-5), thus securing the poison enclosures in place.

Intact Peach Bottom Assemblies and Oak Ridge Canisters are loaded directly into the fuel compartments. A maximum of four Oak Ridge Canisters can be loaded into a single fuel compartment. A flux trap spacer, which contains two horizontally oriented poison plates, is placed between each canister to minimize interaction between canisters within a fuel compartment. Alternatively, one IPB and one canister can be placed in a fuel compartment, with no spacer required. These two possible fuel compartment loadings are illustrated in Figure 6-6.

Each component of the model is described individually in the following sections. The final section describes how all the parts are put together to create the model. Unless specifically stated, nominal design dimensions are used in developing the base model. Divergence from the nominal dimensions is investigated as described in Section 6.4.2.7.

The same model is used for NCT and HCT. Structural and Thermal Analyses reported in Chapters 2 and 3 demonstrate that under the HAC tests required by 10 CFR 71.55:

1. The radial spacing between fuel compartments remains unchanged.

2. The axial spacing between canisters in a fuel compartment remains unchanged.

3. The poison enclosures remain intact and in the same relative position.

4. The axial spacers remain intact and in the same relative position.

5. The poison plates do not melt.

6. The Oak Ridge Canisters confine the fuel particles contained inside them.

7. The fuel compacts for the IPB's retain the fissile material and the inactive sections of the assemblies maintain the positions of the fuel compacts.

Although there is no credit for confinement of the intact Peach Bottom fuel assemblies in their aluminum canisters, none is needed since the Peach Bottom assemblies are graphite fuel compacts and the graphite fuel sections keep the fissile material within the active fuel region.

#### 6.3.1.1 Poison Plates/Enclosures

Figure 6-5 is an isometric view of a poison enclosure. Each enclosure is constructed by welding together ten individual panels. There are two different types of panels: those for the central pentagon, and those for the radial arms. In each case, the individual panel is created by welding together four steel plates to form a hollow trapezoidal (central pentagon panels) or rectangular (radial panels) panel. A rectangular-shaped poison plate, constructed of either a boron aluminum alloy or boron carbide aluminum composite, is inserted into the space inside the panel. When the ten panels are welded together, very small gaps exist between poison plates in adjacent panels, due to the fact that each panel is individually constructed and surrounded by steel on all four sides. The KENO VI model accurately reproduces the real geometry of the poison enclosures to assure any neutron streaming that may occur through these gaps is accounted for.

Figure 6-7 is a not-to-scale horizontal cross section of a central panel, and Figure 6-8 shows the manner in which the structural elements of the panel (the four steel plates) are modeled in KENO VI. The model consists of four cuboids, two of which have been rotated, and two wedges. The geometric parameters for the model are shown in Table 6-4. Note that the system origin is located at the left top vertex.

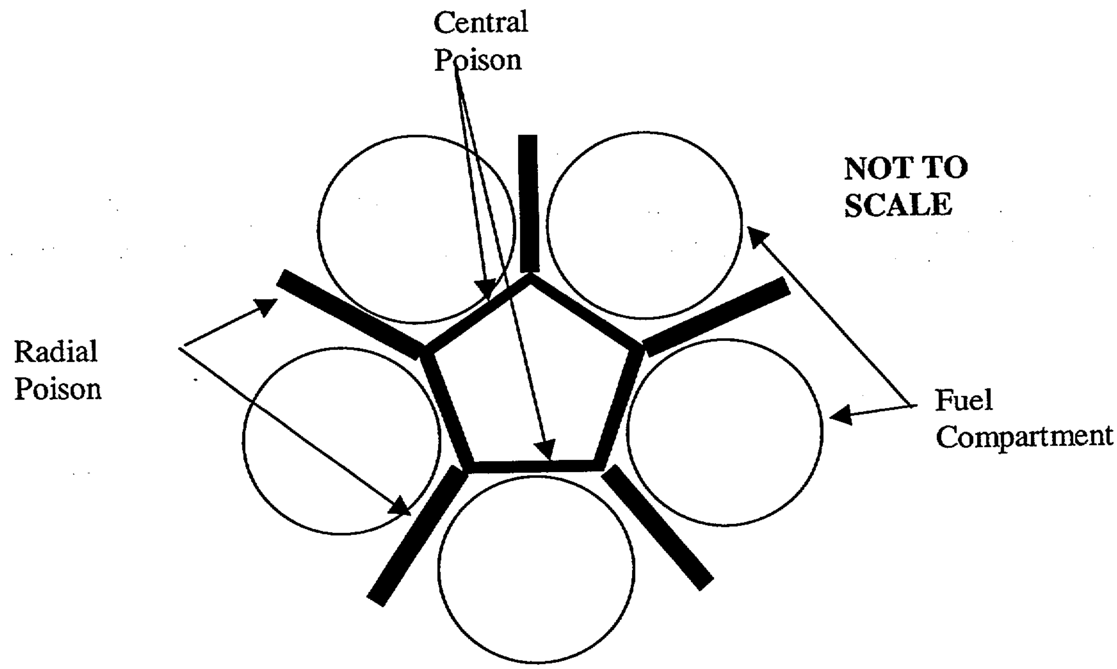



**Figure 6-4 Horizontal cross section view of the basket assembly**

*Each poison enclosure is constructed of 10 individual poison panels; five central panels are welded together to form the pentagon in the middle, and five radial panels are welded to the pentagon. Each panel is constructed with steel walls and a boron poison sheet inside.*

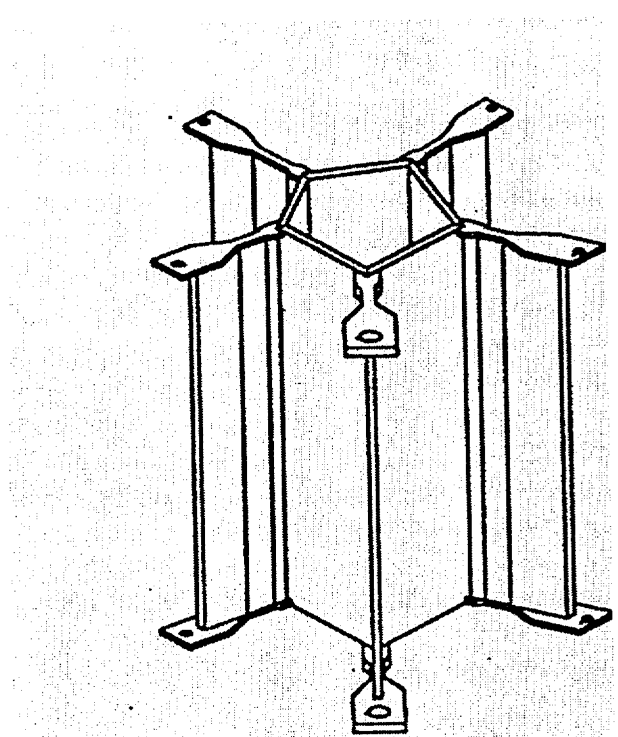


**Figure 6-5 Isometric view of an assembled poison enclosure**

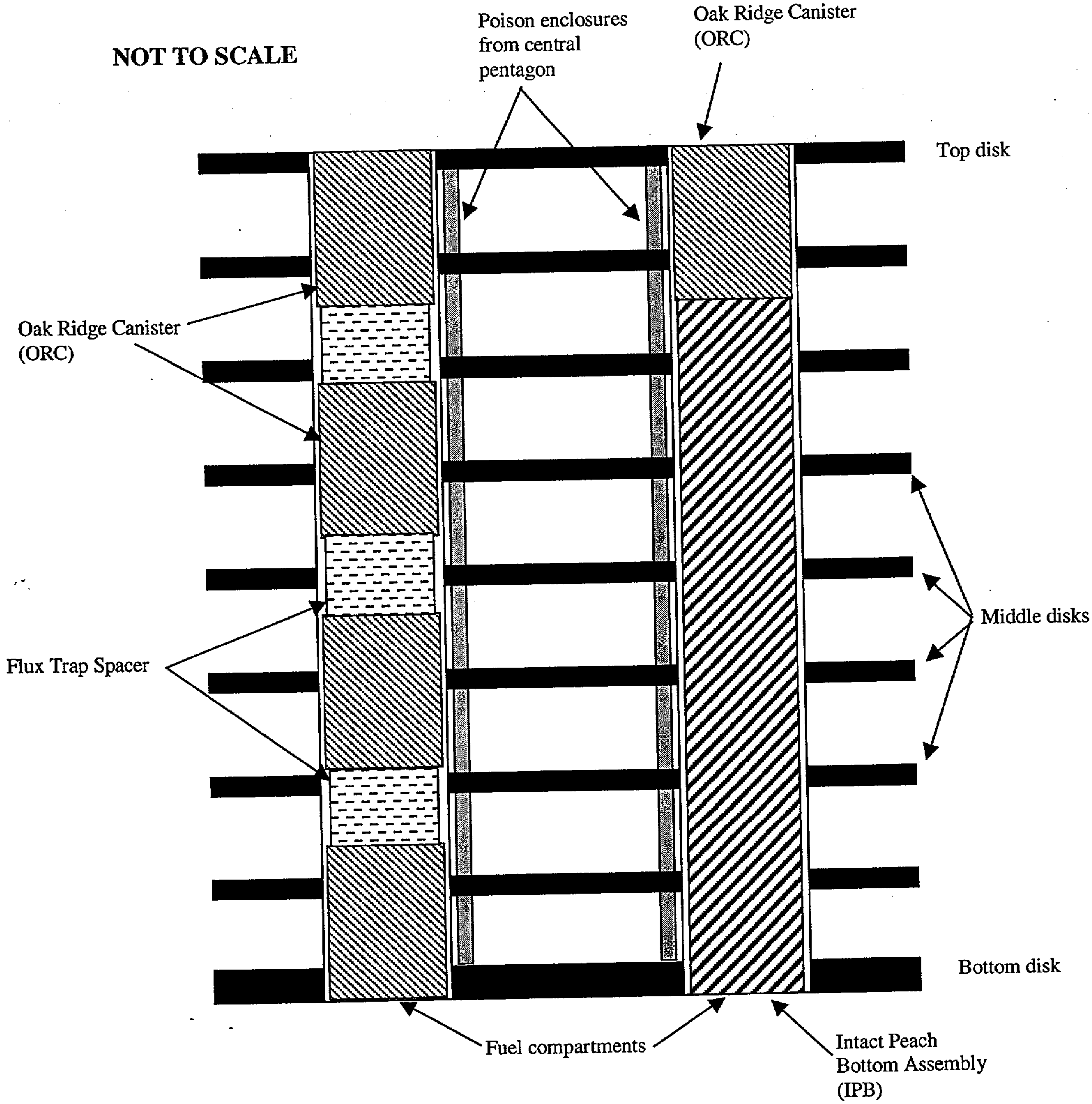



**Figure 6-6 Axial cross section of the basket assembly.**
*One fuel compartment is shown loaded with four canisters, with flux trap spacers between, while the other is shown loaded with one IPB and one canister. This is for illustration purposes only – it does not represent any specific loading pattern.*

## Table 6-4 Geometry Parameters for Central Pentagon Poison Enclosure[2]

| cuboid | => | +X | -X | +Y | -Y | ORIGIN | | Rotation |
|---|---|---|---|---|---|---|---|---|
| wedge | => | (X-Length) | (X Coord.) | (Y coord.) | (NA) | X | Y | (Degrees) |
| cuboid | 1 | 8.191 | 0.110 | 0 | -0.151 | 0 | 0 | 0 |
| wedge | 2 | 0.110 | 0 | -0.151 | | 8.192 | 0 | 0 |
| wedge | 3 | -0.110 | 0 | -0.151 | | 0.109 | 0 | 0 |
| cuboid | 4 | 1.348 | 0 | 0 | -0.151 | 8.191 | -0.151 | -126 |
| cuboid | 5 | 7.395 | 0.902 | -1.091 | -1.242 | 0 | 0 | 0 |
| cuboid | 6 | 0 | -1.348 | 0 | -0.151 | 0.110 | -0.151 | 126 |
| cuboid | 7 | 7.393 | 0.908 | -0.211 | -0.973 | 0 | 0 | 0 |
| wedge | 8 | 0.554 | 0 | -0.762 | | 7.394 | -0.211 | 0 |
| wedge | 9 | -0.554 | 0 | -0.762 | | 0.907 | -0.211 | 0 |

The poison plate has a length on the long side of 2.989 in., and is 0.305 ± 0.005 in. thick. Figure 6-9 shows the KENO VI model for the poison plate, which is not-to-scale. To assure conservatism, the poison plate is modeled with a thickness of 0.300 in. (0.762 cm). Figure 6-10 shows how the poison plate is positioned inside the poison enclosure. The enclosure gap thickness is slightly larger (0.070 in.) than the poison plate thickness, thus allowing a very small variation in the positioning of the poison plate. A change in the positioning of the plate within the enclosure as compared to that modeled would have a negligible impact on system reactivity, because the possible variation is so small (less than 1/10 of an inch). The geometric description for the three poison plate components (1 cuboid and 2 wedges) is included in Table 6-4.

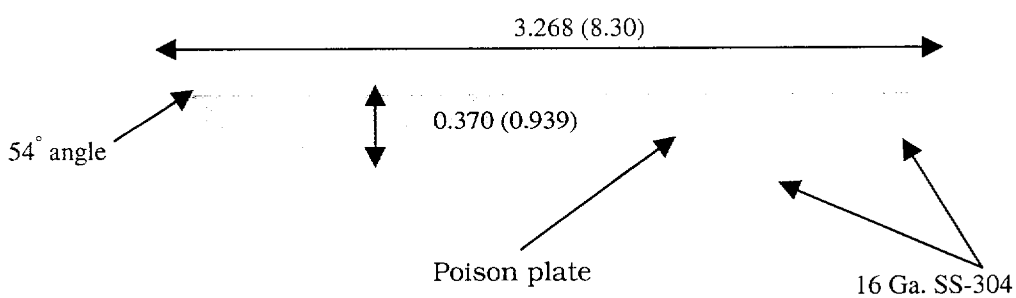
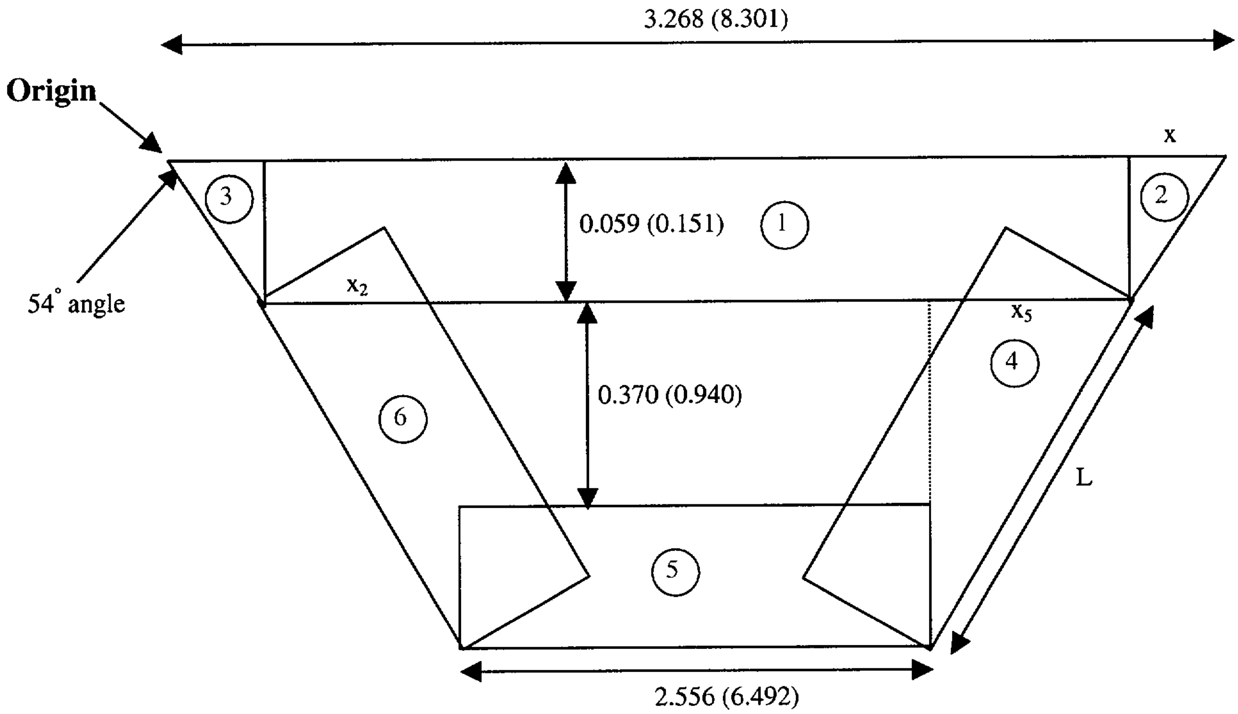


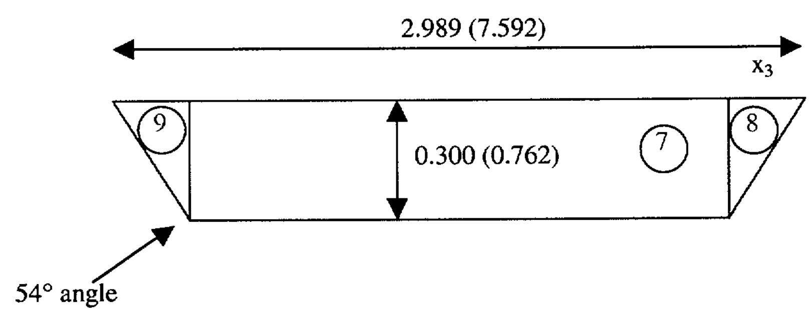

**Figure 6-7 Cross section of a central pentagon panel.**
*Not to scale. Dimension in in(cm). The enclosure is 20.15 in. tall, with open top and bottom.*

[2] All dimensions in centimeters. The second column contains the region numbers as labeled in Figures 6-8 and 6-9.



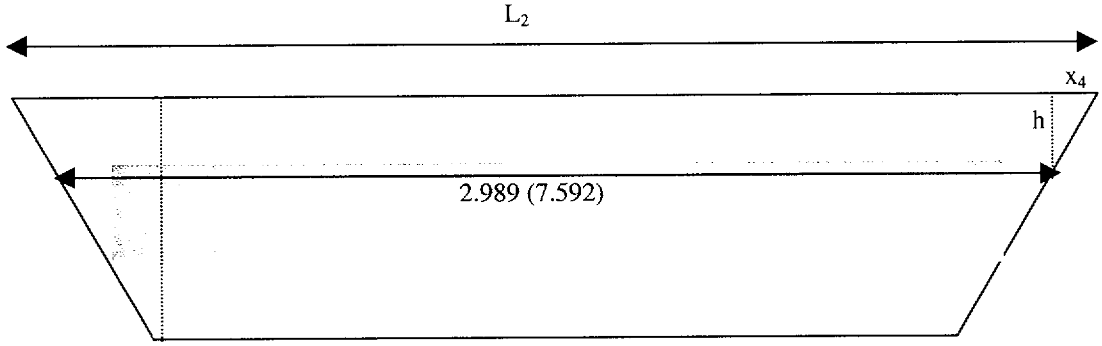

$$x = 0.151 * \tan(36) = 0.110$$
$$L = (0.940 + 0.151)/\cos(36) = 1.348$$
$$x_2 = 0.151/\cos(36) = 0.187.$$

**Figure 6-8 Cross section view of KENO VI model of poison plate insert.**
*Dimensions in in.(cm)*




$$x_3 = 0.762 * \tan(36) = 0.554$$

**Figure 6-9 Poison plate centered inside the enclosure.**
*The outer lines represent the inside boundary of the enclosure. Dimensions in in.(cm)*




$$L_2 = 8.301 - 2x - 2x_2 = 7.708$$
$$x_4 = (L_2 - 7.592)/2 = 0.0577$$
$$h = x_4 * \tan(54) = 0.0794$$

**Figure 6-10 Poison plate centered inside the enclosure in the horizontal plane.**
*The outer lines represent the inside boundary. Dimensions in in.(cm)*

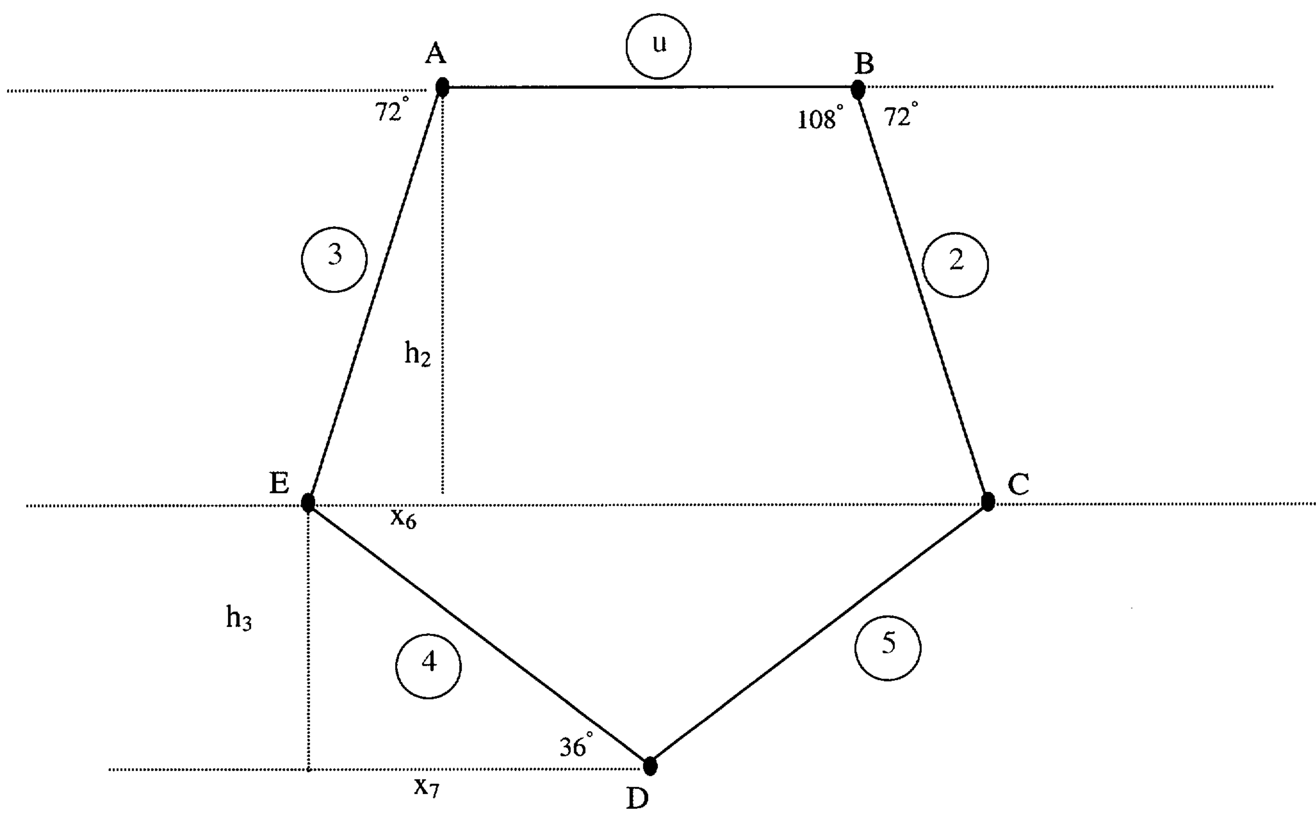
The body description data in Table 6-4 describes a single panel of the central pentagon. Specifically, it describes the panel that lies parallel to the X axis. To develop the geometric descriptions for the remaining panels, only the origin and rotate characteristics of the bodies described in Table 6-4 need be modified. The rotate value for each body is simply incremented by the amount of the desired rotation. The origin coordinates are changed from those in Table 6-4 using the general equation for translation and rotation of coordinates in a cartesian system:

$$x' = x_0 \cos(\alpha) - y_0 \sin(\alpha) + a$$
$$y' = x_0 \sin(\alpha) + y_0 \cos(\alpha) + b$$

where $a$ is the translation distance on the X-axis, $b$ is the translation distance on the Y-axis, $\alpha$ is the angle of rotation, and $(x_0, y_0)$ is the origin of the original system. Note that for bodies that have an origin originally at (0,0), the coordinates of the new system after translation and rotation are simply (a,b). Figure 6-11 illustrates calculation of the necessary translation for each of the remaining four vertices with respect to the original system. Implementation of these equations is demonstrated in Table 6-5. This completes the information necessary to describe all the bodies required to assemble all five panels for the central pentagon.

Table 6-5 Rotation and Translation for the Vertices of the Central Pentagon

| Vertex Location | | Rotation (degrees) | X Translation | Y Translation |
|---|---|---|---|---|
| **Description** | **As Labeled in Figure 6-11** | | | |
| Top Left | A | 0 | 0 | 0 |
| Top Right | B | -72 | 8.311 | 0 |
| Center Right | C | -144 | 10.879 | -7.904 |
| Bottom | D | -216 | 4.155 | -12.789 |
| Center Left | E | -288 | -2.568 | -7.904 |




*Recall that W is defined as the length of the long side of the panel. Then:*

$h_2 = W\sin(72)$

$x_6 = W\cos(72)$

$h_3 = W\sin(36)$

$x_7 = W\cos(36)$

A: $0, 0$

B: W, 0

C: $W(1+\cos(72)),\ -W\sin(72)$

D: $W(\cos(36)-\cos(72)),\ -L(\sin(72)-\cos(36))$
$= \mathrm{W}/2,\ -W(\sin(72)+\sin(36))$

E: $-W\cos(72),\ -W\sin(72)$

**Figure 6-11 Coordinate translation equations for the pentagon.**

Consider next the five radial arm panels that emanate from each vertex of the central pentagon. Figure 6-12 is a cross section view of one of these radial panels. These panels differ from the central panels in that they have top and bottom closures, which provide attachment points to the central pentagon, and have holes at their outer ends through which the tie rods penetrate, as can be seen in Figure 6-5. Since these base plates are ¼-inch thick, the height of the poison plate inside these panels is ½-inch less than that in the central panels. Figure 6-13 illustrates the KENO VI model for the radial arm panel. The poison plate is not shown in this figure, but is modeled as a single cuboid of length 10.208 cm and width 0.762 cm. The poison plate is modeled centered inside the panel.

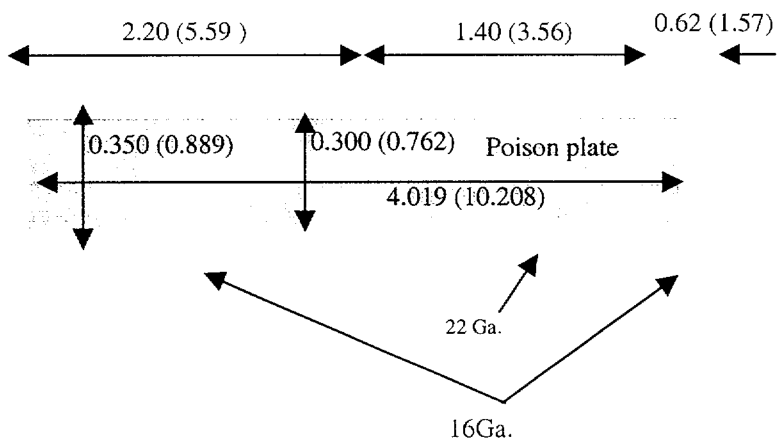



**Figure 6-12 Cross section view of a single radial arm panel.**
*Not to scale. Dimensions in in.(cm). The enclosure is 20.15 in. tall, with closed top and bottom.*

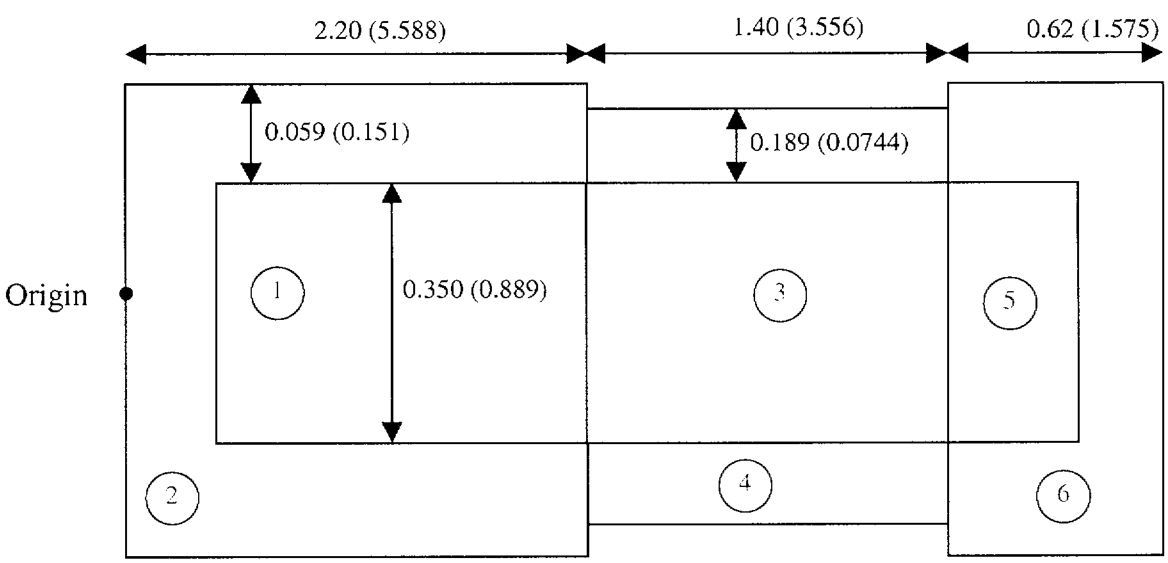



**Figure 6-13 Cross section view of KENO VI model of a single radial arm panel.**
*Not to scale. Dimensions in in.(cm). Note the poison plate is omitted from this view. The numbers in circles denote the geometry region number for the object.*

The body descriptions (cm) for the seven cuboids required to describe each radial panel are given in Table 6-6. To define the five radial panels, each panel is translated to the same positions described for the central pentagon panels in Table 6-5, but with different rotations. Starting at vertex A, the rotations are 126°, 54°, -18°, -90°, and -162°. Note that the bodies in each group are numbered x1 – x7, where x = 6 for the arm emanating from vertex D, 7 for vertex C, 8 for vertex E, 9 for vertex A, and 10 for vertex B.

This completes the description of the KENO VI geometry for the poison enclosure.

Table 6-6 Body Descriptions for the Radial Arm Poison Enclosure

| | | +X | -X | +Y | -Y |
|---|---|---|---|---|---|
| cuboid | 1 | 5.588 | 0.151 | 0.444 | -0.444 |
| cuboid | 2 | 5.588 | 0.000 | 0.595 | -0.595 |
| cuboid | 3 | 9.144 | 5.588 | 0.444 | -0.444 |
| cuboid | 4 | 9.144 | 5.588 | 0.518 | -0.518 |
| cuboid | 5 | 10.568 | 9.144 | 0.444 | -0.444 |
| cuboid | 6 | 10.719 | 9.144 | 0.595 | -0.595 |
| cuboid | 7 | 10.464 | 0.255 | 0.381 | -0.381 |

### 6.3.1.2 Top, Middle, and Bottom Disks

The basket assembly is constructed by axially stacking nine poison enclosures with ¾-inch thick steel middle disks between them. A ¾-inch (1.905 cm) thick steel disk at the top and a 1.75 in. (4.445 cm) thick steel disk at the bottom form the ends of the assembly, as is illustrated in Figure 6-6. All of these disks have a diameter of 16.410 in. (40.996 cm). The disks are modeled as solid steel cylinders with nominal dimensions. As is discussed later, the five fuel compartments are modeled as penetrating all of these disks.

### 6.3.1.3 Oak Ridge Canister

The Oak Ridge Canister is modeled as a cylinder with a diameter equivalent to the inner diameter of the fuel compartment (5.349 in. or a radius of 6.793 cm), and a height of 34.75 in. (88.265 cm). The steel walls of the canister are conservatively ignored, with the fissile mixture extending to a radial distance larger than the outer diameter of the canister; i.e., where the steel walls would be, the fissile mixture exists instead. Since the canister height/diameter ratio is 6.4, increasing the diameter of the fissile mixture increases the fissile volume and the system reactivity. Therefore, this is a conservative modeling assumption.

### 6.3.1.4 Peach Bottom Fuel Assembly

The Peach Bottom fuel assembly is modeled as a cylinder with a diameter equivalent to the inner diameter of the fuel compartment (5.349 in. or a radius of 6.793 cm), and a height of 153 in. (388.62 cm). Only 90 in. (228.6 cm) of the cylinder are modeled as containing the fissile material. This coincides with the actual length of the active fuel region in the Peach Bottom Assemblies. The distance from the top of the assembly to the fissile region is modeled as 23 in. (58.42 cm), slightly less than the actual distance of 23.44 in. The assembly is modeled as in contact with the top of the canister, a conservative assumption that puts the active fuel region of the IPB as close to an canister above it as possible.

### 6.3.1.5 Flux Trap Spacer

The flux trap spacer is used between axially adjacent Oak Ridge Canisters. It is 16 in. in height, and contains two poison disks, one near the top and one near the bottom. Figure 6-14 is a cross section view of the flux trap spacer. It is constructed of Type 304 stainless steel, with a hollow core that comprises over 80% of the overall length. The poison disks are 0.305 ± 0.005 in. thick, and made of either boron-aluminum alloy or an aluminum boron carbide matrix. The flux trap is modeled using nominal dimensions for all components except the poison disks, which are modeled at 0.300 in. (0.762 cm) thickness to assure conservatism. Note: The description is for the intended model. The upper poison plate was mistakenly modeled as 0.03 in. instead of 0.3 in. This is a conservative error and was therefore not corrected.

### 6.3.1.6 Fuel Compartment

The fuel compartment is a nominal 5-inch Schedule 10 pipe, open at the top end, and closed at the bottom end with a 2-inch long solid steel cylinder referred to as a compartment spacer. The compartment spacer fits inside the pipe, with its end flush with the end of the pipe. The overall length of the fuel compartment is 189.88 in. (482.295 cm). After subtracting the 2-inch long compartment spacer, the length available for fuel canisters is 187.88 in.

Specification of the inner diameter of the fuel compartment is important, because the model ignores the walls of the Oak Ridge Canister, instead assuming that the fissile material can extend to the inner diameter of the fuel compartment. The specifications for 5-inch Schedule 10 pipe are an outside diameter of 5.583 in. and a wall thickness of 0.134 in. Permissible variations in wall thickness and outer diameter are ± 12.5% and $(+\frac{1}{16}, -\frac{1}{32})$, respectively.
Therefore, the maximum inner diameter is:

$$\text{Maximum ID} = 5.563 + \tfrac{1}{16} - 2 * 0.134(1 - 0.125) = 5.391 \text{ in.}$$

This is equivalent to an inner radius of 6.847 cm. This is the inner radius used in the model for the fuel compartment. The outer radius is specified using nominal dimensions, as 7.065 cm.

Each fuel compartment contains either four Oak Ridge Canisters separated by flux trap spacers, or one Intact Peach Bottom Assembly and one Oak Ridge Canister.

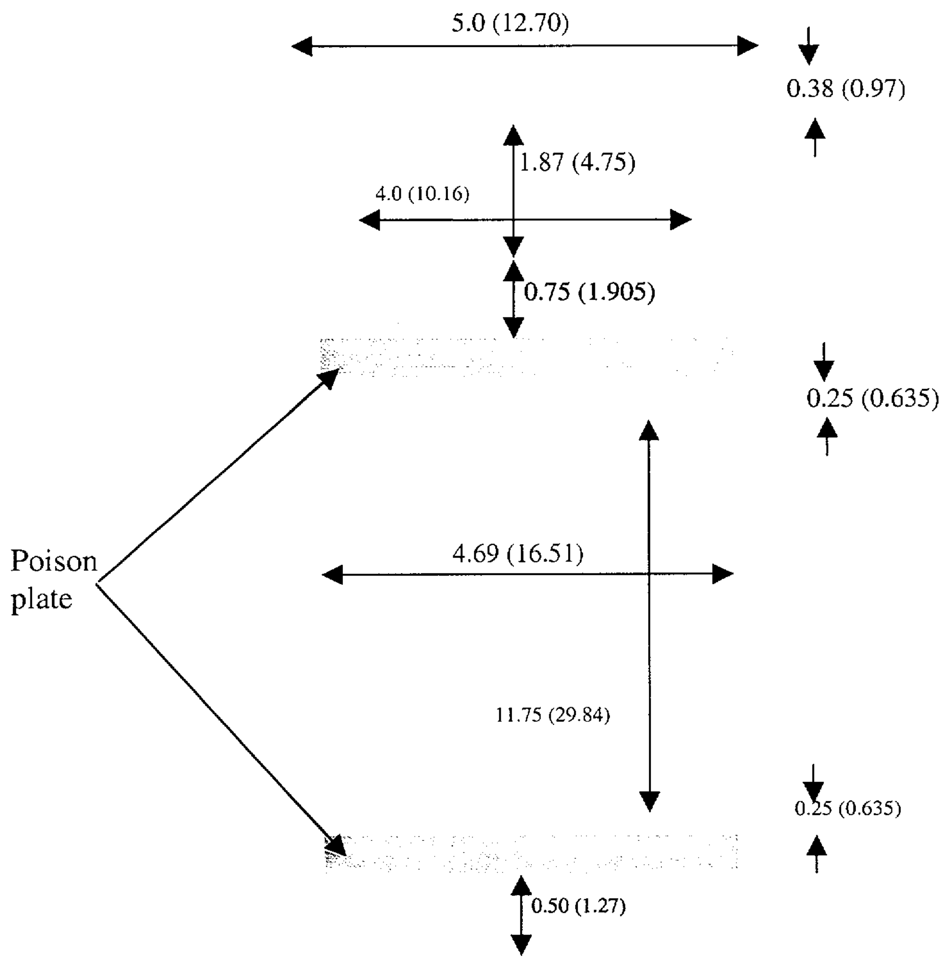



**Figure 6-14 Cross section view of the flux trap.**
*All dimensions in in (cm). Not to scale*

## 6.3.1.7 Basket Assembly

All of the pieces necessary to assemble a model of the basket assembly have been defined above. The first step is to insert the bottom, middle, and top plates at the appropriate axial locations. Recall that there are nine poison enclosures, each 20.15 in. high, with a middle plate between each poison enclosure. The top plate is attached to the top of the stack and the bottom plate to the bottom.

In order to make an efficient model, only one poison enclosure assembly is modeled, with a height equivalent to all nine poison enclosures plus eight middle plates, one top plate, and one bottom plate (9*20.15 + 8*0.75 = 189.85 in. = 482.219 cm). The plates are then placed in the appropriate axial locations, and the media cards are specified such that the poison enclosure does not exist where the plates exist. This model would be sufficient for the central pentagon panels, but it needs to be adjusted to conservatively model the radial arm panels. These panels have ¼-inch thick steel top and bottom closures, and as a result the poison plate height is only 19.62 in. This leaves 0.53 in. axially in each layer where the poison plates are not present. To conservatively account for this, a void space 0.265 in. (0.6731 cm) thick is modeled above and below each middle plate, above the bottom plate, and below the top plate.[3] Notice that since the poison plates in the central pentagon have a length of 20.12 in., this modeling approach models 0.5 axial in. per poison enclosure as void where poison would actually exist. This further increases the conservative nature of the model. The model is compared to the actual components in Figure 6-15.

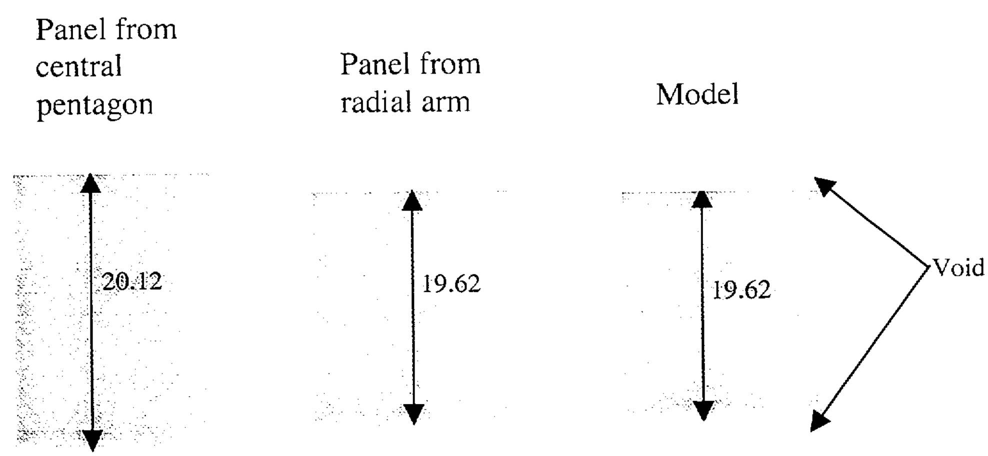



**Figure 6-15 Comparison of actual profile of poison panels to the model**
*(Dimensions in in)*

The final step to assemble the basket assembly model is to add in the fuel compartments. This is done simply by placing the five fuel compartments in equally spaced holes on a 5.687 in. diameter circle.

### 6.3.1.8 Oak Ridge Container

Details of the design of the Oak Ridge Container are delimited in Drawings 3044-30-1, -2, and –6. The container is modeled using the dimensions shown in Table 6-7. The complete basket assembly model is placed inside the Oak Ridge Container.

[3] The 0.53-inch space is modeled as void rather than steel because the hole is a cylinder that exists across the entire inner diameter of the Oak Ridge Container. Modeling the space as steel would add a significant amount of steel to the package which doesn't actually exist. Ignoring the tiny amount of steel that exists at the top and bottom of each radial arm has a negligible effect on system reactivity.

Table 6-7 Oak Ridge Container Model Specifications

| Parameter | in. | cm |
|---|---|---|
| Top Plug Thickness | 7 | 17.780 |
| Bottom Plug Thickness | 1 | 2.540 |
| Container ID | 16.58 | 42.113 |
| Container OD | 16.85 | 42.799 |
| Cavity Length | 190 | 482.600 |
| Sleeve ID | 17.13 | 43.510 |
| Sleeve OD | 17.76 | 45.110 |

### 6.3.1.9 TN-FSV Cask

The Oak Ridge Container is placed inside the cavity of the TN-FSV cask. The cask is of a standard design, with approximately 3.4 in. of lead sandwiched between inner and outer steel shells, with a combined thickness of approximately 2.5 in. Details of the cask geometry important for the criticality model are provided in Drawing 1090-SAR-2. The cask is modeled as a set of nested cylinders, with dimensions and materials as given in Table 6-8 and Figure 6-16. The impact limiters are not included in the model, but the entire cask is modeled as surrounded by 12 in. of water, so ignoring the impact limiters is conservative.

Table 6-8 Model Dimensions for the TN-FSV Cask

| Component | Region Thickness (in.) | Inner Diameter (in.) | Inner Radius (cm) | Material |
|---|---|---|---|---|
| Cavity | NA | 18.00 | 22.860 | Air |
| Canister Insert* | NA | 18.00 | 22.860 | Aluminum |
| Inner Shell | 1.12 | 20.24 | 25.705 | SS-304 |
| Lead Shield | 3.44 | 27.12 | 34.442 | Lead |
| Outer Shell | 1.50 | 30.12 | 38.252 | SS-304 |
| Air Gap | 0.13 | 30.38 | 38.583 | Air |
| Thermal Shield Shell | 0.25 | 30.88 | 39.218 | SS-304 |
| Bottom Plate | NA | 30.88 | 39.218 | SS-304 |
| Lid Assembly | NA | 30.88 | 39.218 | SS-304 |

* - Model included aluminum canister insert at bottom of cask. Subsequent to analyses it was decided not to use this bottom spacer; however, the analyses are still valid since neutron interaction with aluminum is negligible and the change in axial location of the Container within the cask is not significant.

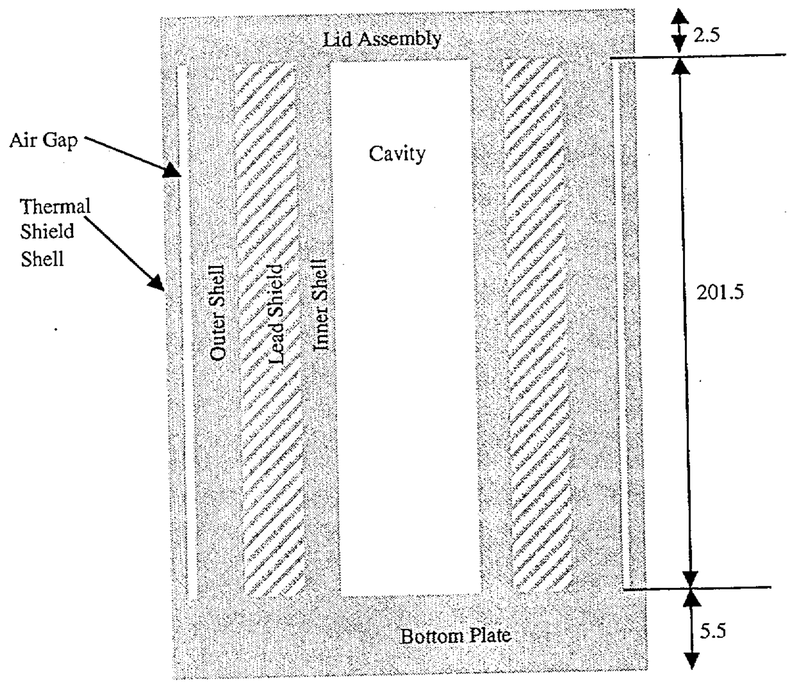



**Figure 6-16 TN-FSV cask.**
*Not to scale. All dimensions in in.*

## 6.3.1.10 The Complete KENO VI Model

Figures 6-17 through 6-20 are plots of the complete KENO VI model as generated by the code. Note that the loading pattern illustrated is that of a uniformly loaded cask and is not representative of any of the modeled loadings. The figures demonstrate that the details of the KENO VI model correctly model those of the actual cask as has been discussed in the previous sections.

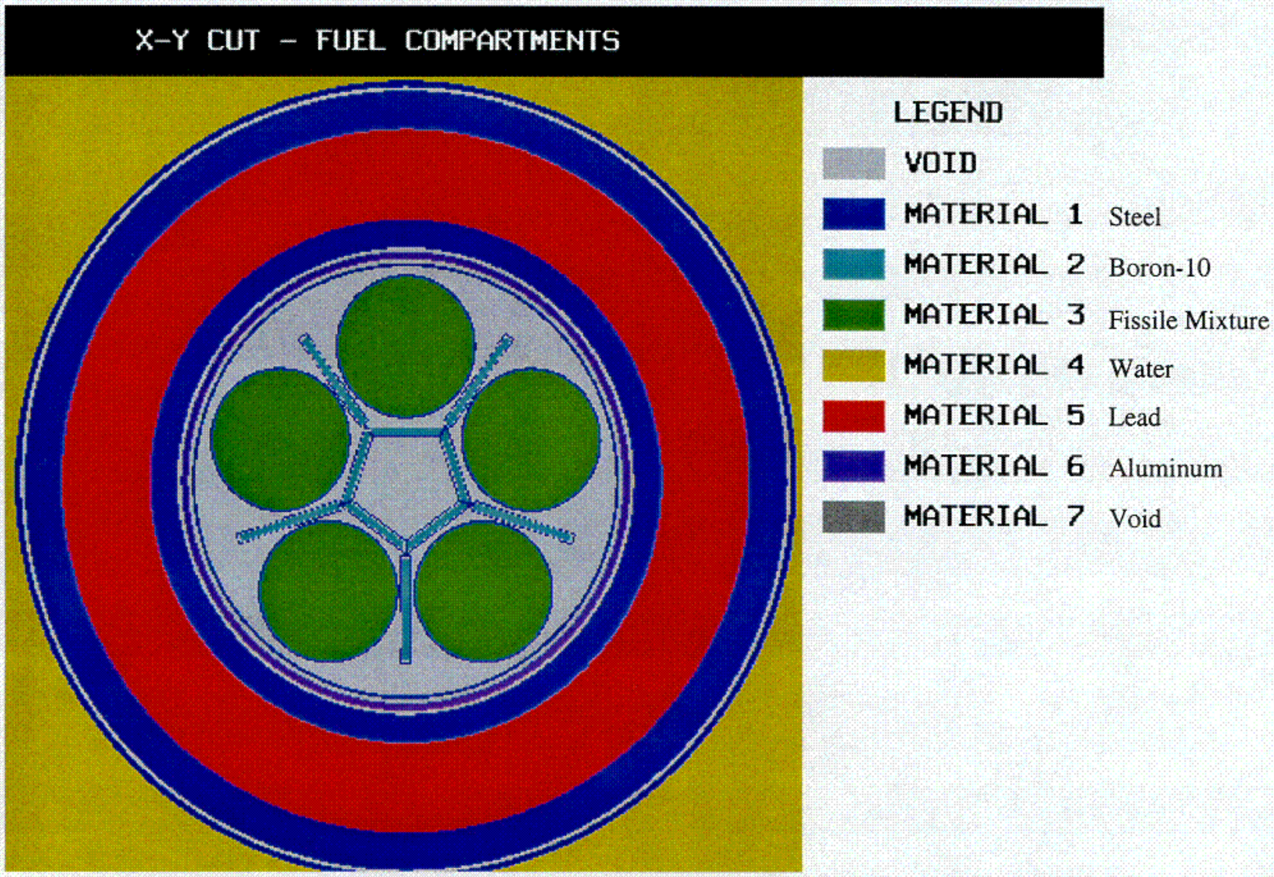



**Figure 6-17 Horizontal cross section of the KENO VI model.**
*The five fuel tubes and the poison enclosure are clearly identifiable.*



C01

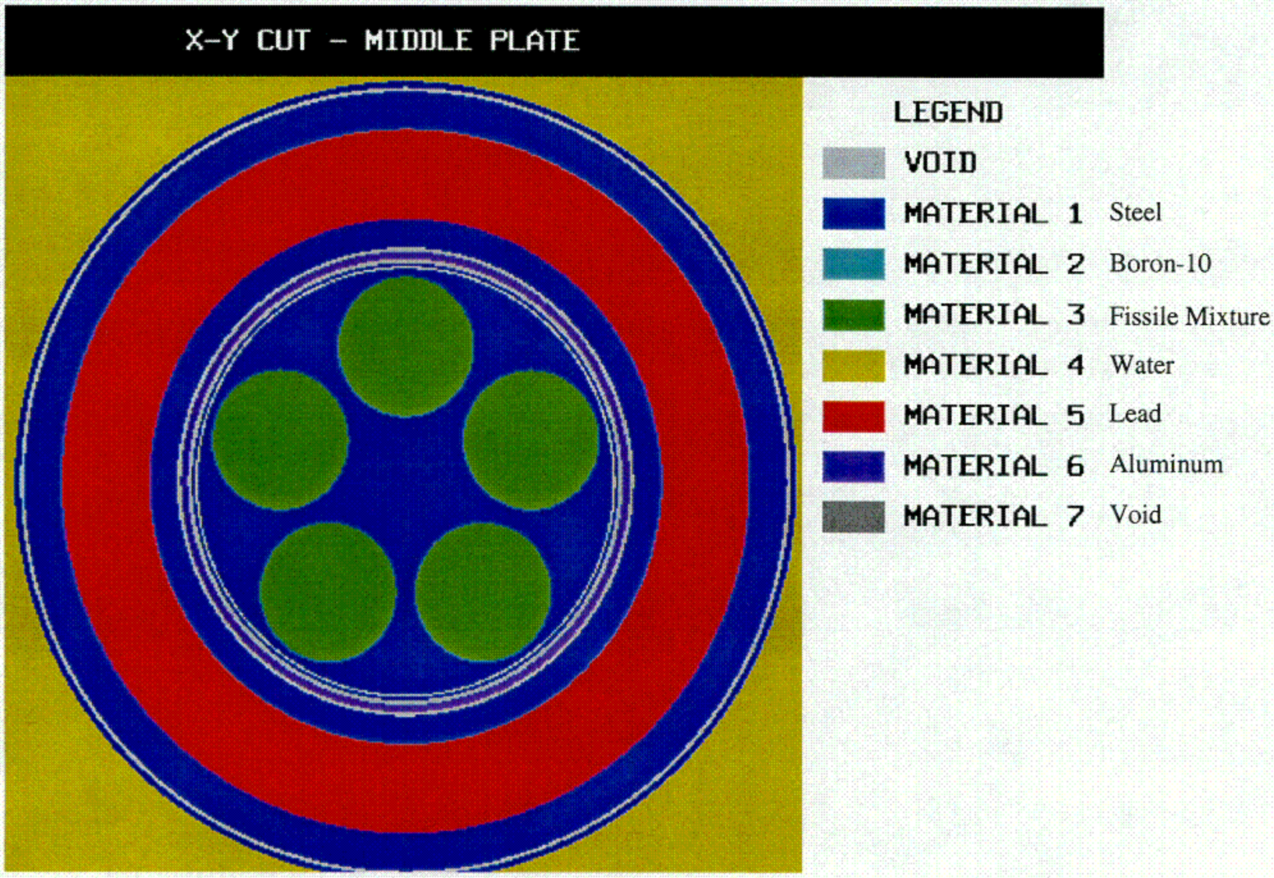



**Figure 6-18 Horizontal cross section of the KENO VI model.**
*As opposed to Figure 6-17, this one is taken at an elevation where a middle plate is present. Note that the poison enclosure is not present at this elevation.*



C02

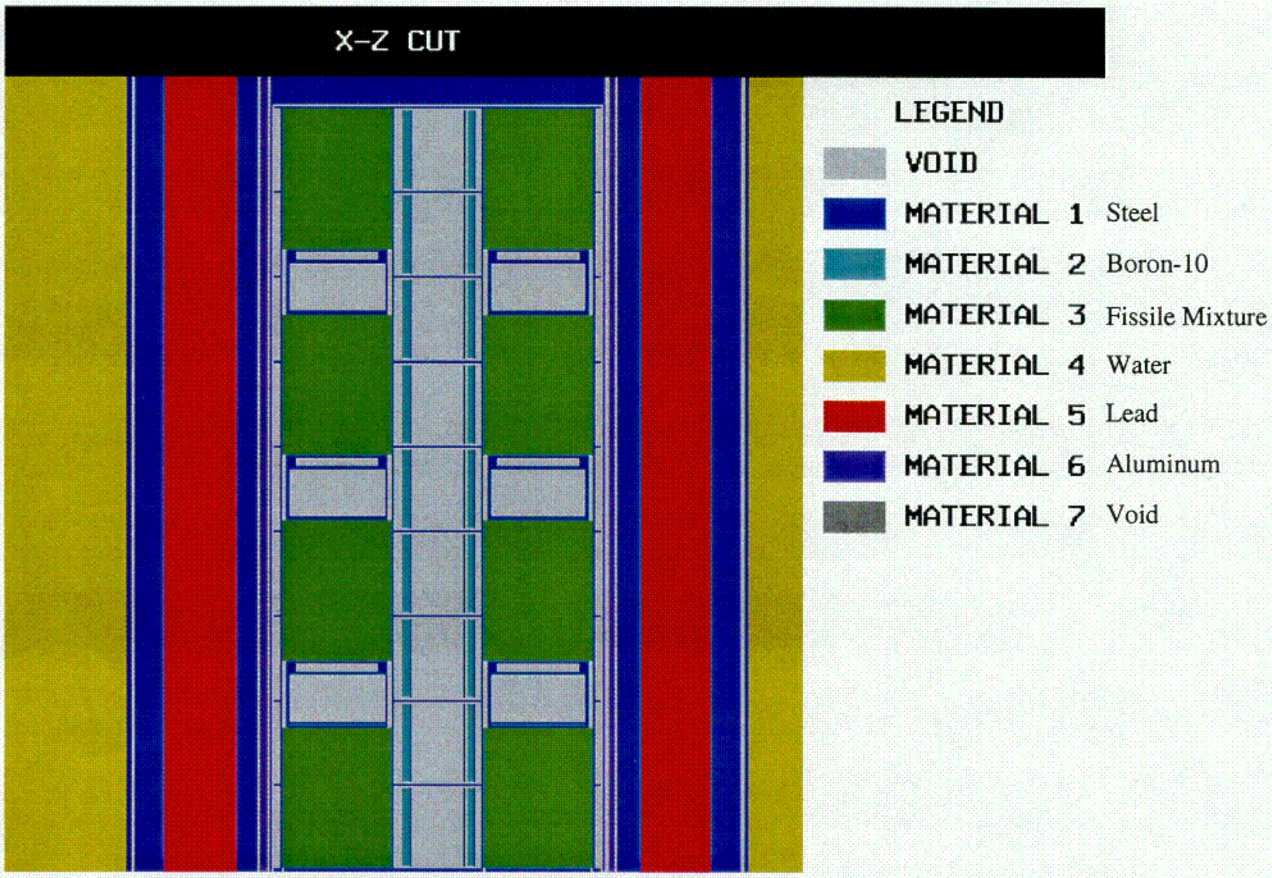



**Figure 6-19 Axial cross section of the cask.**

*Note this cut is not to scale – the radial dimension is distorted to allow more details of the geometry to be viewed. Note the presence of the top, middle and bottom disks, and that they do not penetrate the fuel compartments, while the poison enclosures (in the center) do not penetrate the disks.*



C03

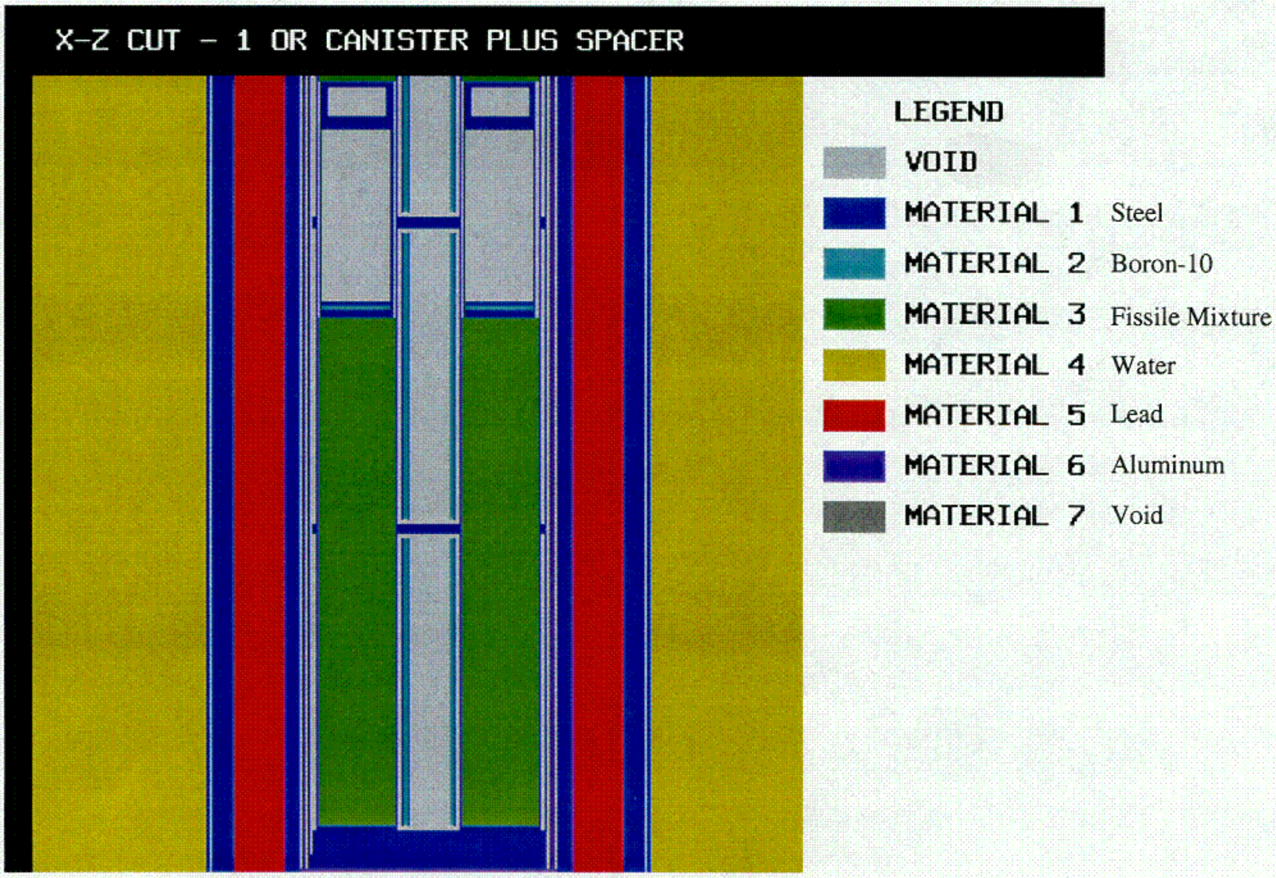



**Figure 6-20 Axial cut through the KENO VI model.**
*This cut is to scale, and extends from the bottom of the Oak Ridge container to the top of the first spacer. This view allows more details to be viewed. The middle plate is clearly visible, as is the void space above and below it. In addition, details of the flux trap spacer can be observed, including structural material and the two boron poison plates.*



C04

## 6.3.2 Package Regional Densities

Tables 6-9 through 6-14 list the material densities and atom densities for the six different hydrogenous fuel mixtures considered, each as a function of the H/U ratio. As the H/U ratio is reduced from its maximum value, the volume of the fissile mixture becomes less than the volume of the canister. The second to last column in the tables lists the height of the fissile mixture region (the diameter is assumed to remain constant and equal to the diameter of the fuel compartment). The final column in these tables lists the height to diameter ratio for each fuel mixture.

As discussed in Section 6.2.4, moderation by carbon (with no water present) is considered for two different scenarios: the infinite normal condition array analysis, and the analysis of a single package that is mis-loaded with no axial flux trap spacers (note that this latter case also bounds the required calculation of the dry normal condition cask). The material and atom densities for these carbon moderated cases are presented in Tables 6-15 through 6-20. Since the maximum C/X ratio that can be achieved by completely filling the canister (or IPB) with carbon, while still maintaining the full amount of fissile material in the canister, is well below the levels where optimal carbon moderation typically occurs, higher C/X ratios are established by decreasing the amount of fissile material modeled in the canister (or IPB).

Table 6-9 Densities for Oak Ridge Canister with Group 1 Contents

| | Densities ($g/cm^3$) | | Atom Densities (atm/b-cm) | | | Height (cm) | h/D |
|---|---|---|---|---|---|---|---|
| H/U | U | $H_2O$ | $^{235}U$ | H | O | | |
| 712 | 0.0365 | 0.9963 | 9.3615E-05 | 6.6606E-02 | 3.3303E-02 | 88.27 | 6.4 |
| 350 | 0.0741 | 0.9943 | 1.8998E-04 | 6.6474E-02 | 3.3237E-02 | 43.49 | 3.2 |
| 300 | 0.0865 | 0.9937 | 2.2150E-04 | 6.6431E-02 | 3.3216E-02 | 37.31 | 2.7 |
| 275 | 0.0943 | 0.9933 | 2.4153E-04 | 6.6404E-02 | 3.3202E-02 | 34.21 | 2.5 |
| 250 | 0.1036 | 0.9928 | 2.6555E-04 | 6.6371E-02 | 3.3185E-02 | 31.12 | 2.3 |
| 225 | 0.1151 | 0.9922 | 2.9488E-04 | 6.6331E-02 | 3.3165E-02 | 28.02 | 2.0 |
| 200 | 0.1294 | 0.9914 | 3.3149E-04 | 6.6281E-02 | 3.3140E-02 | 24.93 | 1.8 |
| 175 | 0.1477 | 0.9905 | 3.7848E-04 | 6.6216E-02 | 3.3108E-02 | 21.83 | 1.6 |
| 150 | 0.1721 | 0.9892 | 4.4099E-04 | 6.6131E-02 | 3.3065E-02 | 18.74 | 1.4 |
| 125 | 0.2062 | 0.9874 | 5.2823E-04 | 6.6012E-02 | 3.3006E-02 | 15.64 | 1.1 |
| 100 | 0.2570 | 0.0000 | 6.5851E-04 | 6.5851E-02 | 3.2925E-02 | 12.55 | 0.9 |

## Table 6-10 Densities for Oak Ridge Canister with Group 2 Contents

| H/X | Densities (g/cm$^3$) $^{235}$U | $^{239}$Pu | H2O | Atom Densities (atm/b-cm) $^{235}$U | $^{239}$Pu | H | O | Height (cm) | h/D |
|---|---|---|---|---|---|---|---|---|---|
| 320 | 0.0665 | 0.0147 | 0.9940 | 1.7048E-04 | 3.7020E-05 | 6.6451E-02 | 3.3226E-02 | 88.27 | 6.4 |
| 300 | 0.0710 | 0.0157 | 0.9937 | 1.8199E-04 | 3.9520E-05 | 6.6432E-02 | 3.3216E-02 | 82.68 | 6.0 |
| 275 | 0.0775 | 0.0171 | 0.9933 | 1.9845E-04 | 4.3095E-05 | 6.6405E-02 | 3.3203E-02 | 75.82 | 5.5 |
| 250 | 0.0852 | 0.0188 | 0.9928 | 2.1819E-04 | 4.7381E-05 | 6.6372E-02 | 3.3186E-02 | 68.96 | 5.0 |
| 225 | 0.0946 | 0.0209 | 0.9922 | 2.4229E-04 | 5.2614E-05 | 6.6332E-02 | 3.3166E-02 | 62.11 | 4.5 |
| 200 | 0.1063 | 0.0235 | 0.9914 | 2.7237E-04 | 5.9146E-05 | 6.6283E-02 | 3.3141E-02 | 55.25 | 4.0 |
| 175 | 0.1214 | 0.0268 | 0.9905 | 3.1098E-04 | 6.7530E-05 | 6.6219E-02 | 3.3109E-02 | 48.39 | 3.5 |
| 150 | 0.1414 | 0.0312 | 0.9892 | 3.6234E-04 | 7.8684E-05 | 6.6133E-02 | 3.3067E-02 | 41.53 | 3.0 |
| 125 | 0.1694 | 0.0374 | 0.9874 | 4.3403E-04 | 9.4251E-05 | 6.6015E-02 | 3.3007E-02 | 34.67 | 2.5 |
| 100 | 0.2112 | 0.0466 | 0.9848 | 5.4108E-04 | 1.1750E-04 | 6.5837E-02 | 3.2919E-02 | 27.81 | 2.0 |

## Table 6-11 Densities for Oak Ridge Canister with Group 3 Contents

| H/X | Densities (g/cm$^3$) $^{235}$U | $^{239}$Pu | $H_2O$ | Atom Densities (atm/b-cm) $^{235}$U | $^{239}$Pu | H | O | H (cm) | h/D |
|---|---|---|---|---|---|---|---|---|---|
| 556 | 0.0154 | 0.0319 | 0.9958 | 3.9417E-05 | 8.0436E-05 | 6.6573E-02 | 3.3286E-02 | 88.27 | 6.4 |
| 400 | 0.0214 | 0.0443 | 0.9949 | 5.4707E-05 | 1.1164E-04 | 6.6510E-02 | 3.3255E-02 | 63.60 | 4.6 |
| 375 | 0.0228 | 0.0472 | 0.9946 | 5.8341E-05 | 1.1905E-04 | 6.6495E-02 | 3.3248E-02 | 59.63 | 4.4 |
| 350 | 0.0244 | 0.0506 | 0.9944 | 6.2492E-05 | 1.2752E-04 | 6.6478E-02 | 3.3239E-02 | 55.67 | 4.1 |
| 325 | 0.0263 | 0.0545 | 0.9941 | 6.7279E-05 | 1.3729E-04 | 6.6459E-02 | 3.3229E-02 | 51.71 | 3.8 |
| 300 | 0.0284 | 0.0590 | 0.9937 | 7.2861E-05 | 1.4868E-04 | 6.6436E-02 | 3.3218E-02 | 47.75 | 3.5 |
| 250 | 0.0341 | 0.0707 | 0.9929 | 8.7355E-05 | 1.7826E-04 | 6.6377E-02 | 3.3188E-02 | 39.83 | 2.9 |
| 200 | 0.0426 | 0.0883 | 0.9915 | 1.0905E-04 | 2.2253E-04 | 6.6288E-02 | 3.3144E-02 | 31.90 | 2.3 |
| 150 | 0.0566 | 0.1175 | 0.9893 | 1.4507E-04 | 2.9604E-04 | 6.6140E-02 | 3.3070E-02 | 23.98 | 1.8 |
| 100 | 0.0846 | 0.1755 | 0.9849 | 2.1665E-04 | 4.4210E-04 | 6.5848E-02 | 3.2924E-02 | 11.02 | 0.7 |

## Table 6-12 Densities for Oak Ridge Canister with Group 4 Contents

| | Densities ($g/cm^3$) | | | Atom Densities (atm/b-cm) | | | | H (cm) | h/D |
|---|---|---|---|---|---|---|---|---|---|
| H/X | $^{235}U$ | $^{239}Pu$ | $H_2O$ | $^{235}U$ | $^{239}Pu$ | H | O | | |
| 782 | 0.0212 | 0.0123 | 0.9965 | 5.4198E-05 | 3.1012E-05 | 6.6618E-02 | 3.3309E-02 | 88.27 | 6.4 |
| 400 | 0.0413 | 0.0240 | 0.9948 | 1.0579E-04 | 6.0534E-05 | 6.6508E-02 | 3.3254E-02 | 45.22 | 3.3 |
| 375 | 0.0440 | 0.0256 | 0.9946 | 1.1282E-04 | 6.4555E-05 | 6.6494E-02 | 3.3247E-02 | 42.40 | 3.1 |
| 350 | 0.0472 | 0.0274 | 0.9943 | 1.2085E-04 | 6.9149E-05 | 6.6476E-02 | 3.3238E-02 | 39.58 | 2.9 |
| 325 | 0.0508 | 0.0295 | 0.9941 | 1.3011E-04 | 7.4446E-05 | 6.6457E-02 | 3.3228E-02 | 36.77 | 2.7 |
| 300 | 0.0550 | 0.0320 | 0.9937 | 1.4090E-04 | 8.0622E-05 | 6.6434E-02 | 3.3217E-02 | 33.95 | 2.5 |
| 275 | 0.0600 | 0.0349 | 0.9933 | 1.5365E-04 | 8.7915E-05 | 6.6407E-02 | 3.3203E-02 | 31.14 | 2.3 |
| 250 | 0.0659 | 0.0384 | 0.9928 | 1.6893E-04 | 9.6659E-05 | 6.6374E-02 | 3.3187E-02 | 28.32 | 2.1 |
| 225 | 0.0732 | 0.0426 | 0.9922 | 1.8759E-04 | 1.0733E-04 | 6.6334E-02 | 3.3167E-02 | 25.50 | 1.9 |
| 200 | 0.0823 | 0.0479 | 0.9915 | 2.1088E-04 | 1.2066E-04 | 6.6285E-02 | 3.3142E-02 | 22.69 | 1.7 |
| 175 | 0.0940 | 0.0547 | 0.9905 | 2.4077E-04 | 1.3777E-04 | 6.6221E-02 | 3.3110E-02 | 19.87 | 1.5 |
| 150 | 0.1095 | 0.0637 | 0.9893 | 2.8054E-04 | 1.6052E-04 | 6.6136E-02 | 3.3068E-02 | 17.05 | 1.2 |
| 125 | 0.1312 | 0.0763 | 0.9875 | 3.3604E-04 | 1.9228E-04 | 6.6018E-02 | 3.3009E-02 | 14.24 | 1.0 |

## Table 6-13 Densities for Oak Ridge Canister with Group 5 Contents

| | Densities ($g/cm^3$) | | Atom Densities (atm/b-cm) | | | | |
|---|---|---|---|---|---|---|---|
| H/X | $^{235}U$ | $H_2O$ | $^{235}U$ | H | O | H (cm) | h/D |
| 371 | 0.0700 | 0.9945 | 1.7935E-04 | 6.6489E-02 | 3.3244E-02 | 88.27 | 6.4 |
| 350 | 0.0741 | 0.9943 | 1.8998E-04 | 6.6474E-02 | 3.3237E-02 | 83.33 | 6.1 |
| 300 | 0.0865 | 0.9937 | 2.2150E-04 | 6.6431E-02 | 3.3216E-02 | 71.47 | 5.2 |
| 275 | 0.0943 | 0.9933 | 2.4153E-04 | 6.6404E-02 | 3.3202E-02 | 65.54 | 4.8 |
| 250 | 0.1036 | 0.9928 | 2.6555E-04 | 6.6371E-02 | 3.3185E-02 | 59.61 | 4.4 |
| 225 | 0.1151 | 0.9922 | 2.9488E-04 | 6.6331E-02 | 3.3165E-02 | 53.68 | 3.9 |
| 200 | 0.1294 | 0.9914 | 3.3149E-04 | 6.6281E-02 | 3.3140E-02 | 47.75 | 3.5 |
| 175 | 0.1477 | 0.9905 | 3.7848E-04 | 6.6216E-02 | 3.3108E-02 | 41.83 | 3.1 |
| 150 | 0.1721 | 0.9892 | 4.4099E-04 | 6.6131E-02 | 3.3065E-02 | 35.90 | 2.6 |
| 125 | 0.2062 | 0.9874 | 5.2823E-04 | 6.6012E-02 | 3.3006E-02 | 29.97 | 2.2 |
| 100 | 0.2570 | 0.9847 | 6.5851E-04 | 6.5834E-02 | 3.2917E-02 | 24.04 | 1.8 |

## Table 6-14 Densities for Intact Peach Bottom Assemblies

| | Densities ($g/cm^3$) | | Atom Densities (atm/b-cm) | | | | |
|---|---|---|---|---|---|---|---|
| H/X | $^{235}U$ | $H_2O$ | $^{235}U$ | H | O | R (cm) | h/D |
| 3507 | 0.0074 | 0.9978 | 1.9024E-05 | 6.6708E-02 | 3.3354E-02 | 6.85 | 16.7 |
| 2500 | 0.0104 | 0.9977 | 2.6686E-05 | 6.6697E-02 | 3.3349E-02 | 5.78 | 19.77 |
| 1500 | 0.0174 | 0.9973 | 4.4461E-05 | 6.6673E-02 | 3.3337E-02 | 4.48 | 25.52 |
| 300 | 0.0865 | 0.9937 | 2.2150E-04 | 6.6431E-02 | 3.3216E-02 | 2.01 | 56.96 |

## Table 6-15 Densities for Oak Ridge Canister with Group 1 Contents[4]

| H/C | Densities (g/cm³) $^{235}U$ | Densities (g/cm³) C | Atom Densities (atm/b-cm) $^{235}U$ | Atom Densities (atm/b-cm) C | Height (cm) | h/D |
|---|---|---|---|---|---|---|
| 10000 | 0.00313 | 1.5997 | 8.0207E-06 | 8.0207E-02 | 88.27 | 6.4 |
| 5000 | 0.00626 | 1.5995 | 1.6039E-05 | 8.0193E-02 | 88.27 | 6.4 |
| 1000 | 0.0313 | 1.5974 | 8.0088E-05 | 8.0088E-02 | 88.27 | 6.4 |
| 855 | 0.0365 | 1.5969 | 9.3615E-05 | 8.0066E-02 | 88.27 | 6.4 |
| 500 | 0.0624 | 1.5948 | 1.5991E-04 | 7.9957E-02 | 51.67 | 3.8 |
| 375 | 0.0831 | 1.5930 | 2.1299E-04 | 7.9870E-02 | 38.80 | 2.8 |
| 250 | 0.1244 | 1.5895 | 3.1878E-04 | 7.9696E-02 | 25.92 | 1.9 |
| 125 | 0.2472 | 1.5792 | 6.3343E-04 | 7.9179E-02 | 13.04 | 1.0 |
| 50 | 0.6063 | 1.5491 | 1.5533E-03 | 7.7667E-02 | 5.32 | 0.4 |

## Table 6-16 Densities for Oak Ridge Canister with Group 2 Contents

| C/X | Densities (g/cm³) $^{235}U$ | Densities (g/cm³) $^{239}Pu$ | Densities (g/cm³) C | Atom Densities (atm/b-cm) $^{235}U$ | Atom Densities (atm/b-cm) $^{239}Pu$ | Atom Densities (atm/b-cm) C | Height (cm) | h/D |
|---|---|---|---|---|---|---|---|---|
| 10,000 | 0.00257 | 0.000568 | 1.5997 | 6.5845E-06 | 1.4312E-06 | 8.0205E-02 | 88.27 | 6.4 |
| 5,000 | 0.00514 | 0.00114 | 1.5995 | 1.3169E-05 | 2.8724E-06 | 8.0195E-02 | 88.27 | 6.4 |
| 1,000 | 0.0257 | 0.00567 | 1.5974 | 6.5845E-05 | 1.4287E-05 | 8.0089E-02 | 88.27 | 6.4 |
| 385 | 0.0665 | 0.0147 | 1.5932 | 1.7048E-04 | 3.7020E-05 | 7.9880E-02 | 88.27 | 6.4 |
| 375 | 0.0683 | 0.0151 | 1.5930 | 1.7500E-04 | 7.5617E-04 | 7.9871E-02 | 85.99 | 6.3 |
| 250 | 0.1022 | 0.0226 | 1.5896 | 2.6193E-04 | 1.1318E-03 | 7.9698E-02 | 57.45 | 4.2 |
| 125 | 0.2031 | 0.0449 | 1.5793 | 5.2047E-04 | 2.2490E-03 | 7.9183E-02 | 28.91 | 2.1 |
| 50 | 0.4982 | 0.1100 | 1.5493 | 1.2764E-03 | 5.5155E-03 | 7.7677E-02 | 11.79 | 0.9 |

## Table 6-17 Densities for Oak Ridge Canister with Group 3 Contents

| C/X | Densities (g/cm³) $^{235}U$ | Densities (g/cm³) $^{239}Pu$ | Densities (g/cm³) C | Atom Densities (atm/b-cm) $^{235}U$ | Atom Densities (atm/b-cm) $^{239}Pu$ | Atom Densities (atm/b-cm) C | Height (cm) | h/D |
|---|---|---|---|---|---|---|---|---|
| 10,000 | 0.00257 | 0.000568 | 1.5997 | 6.5845E-06 | 1.4312E-06 | 8.0205E-02 | 88.27 | 6.4 |
| 5,000 | 0.00514 | 0.00114 | 1.5995 | 1.3169E-05 | 2.8724E-06 | 8.0195E-02 | 88.27 | 6.4 |
| 1,000 | 0.0257 | 0.00567 | 1.5974 | 6.5845E-05 | 1.4287E-05 | 8.0089E-02 | 88.27 | 6.4 |
| 668 | ·0.0154 | 0.0319 | 1.596133 | 3.9417E-05 | 8.0436E-05 | 8.0026E-02 | 88.27 | 6.4 |
| 500 | 0.0205 | 0.0426 | 1.59484 | 5.2602E-05 | 2.1360E-03 | 7.9961E-02 | 66.14 | 4.8 |
| 375 | 0.0273 | 0.0567 | 1.593127 | 7.0061E-05 | 2.8449E-03 | 7.9875E-02 | 49.66 | 3.6 |
| 250 | 0.0409 | 0.0849 | 1.589713 | 1.0487E-04 | 4.2582E-03 | 7.9704E-02 | 33.18 | 2.4 |
| 125 | 0.0813 | 0.1688 | 1.579558 | 2.0839E-04 | 8.4620E-03 | 7.9195E-02 | 16.70 | 1.2 |
| 50 | 0.1995 | 0.4140 | 1.5498 | 5.1119E-04 | 2.0757E-02 | 7.7706E-02 | 6.81 | 0.5 |

[4] In Tables 6-15 through 6-20, the shaded entries correspond to cases with less than the maximum permitted amount of fissile material in the canister or IPB.

Table 6-18 Densities for Oak Ridge Canister with Group 4 Contents

| C/X | Densities (g/cm$^3$) | | | Atom Densities (atm/b-cm) | | | Height (cm) | h/D |
|---|---|---|---|---|---|---|---|---|
| | $^{235}U$ | $^{239}Pu$ | C | $^{235}U$ | $^{239}Pu$ | C | | |
| 10,000 | 0.00257 | 0.000568 | 1.5997 | 6.5845E-06 | 1.4312E-06 | 8.0205E-02 | 88.27 | 6.4 |
| 5,000 | 0.00514 | 0.00114 | 1.5995 | 1.3169E-05 | 2.8724E-06 | 8.0195E-02 | 88.27 | 6.4 |
| 1,000 | 0.0257 | 0.00567 | 1.5974 | 6.5845E-05 | 1.4287E-05 | 8.0089E-02 | 88.27 | 6.4 |
| 940 | 0.0212 | 0.0123 | 1.5972 | 5.4198E-05 | 3.1012E-05 | 8.0081E-02 | 88.27 | 6.4 |
| 500 | 0.0397 | 0.0231 | 1.5948 | 1.0173E-04 | 1.1582E-03 | 7.9959E-02 | 47.03 | 3.4 |
| 375 | 0.0529 | 0.0308 | 1.5931 | 1.3549E-04 | 1.5426E-03 | 7.9873E-02 | 35.31 | 2.6 |
| 250 | 0.0792 | 0.0461 | 1.5896 | 2.0279E-04 | 2.3089E-03 | 7.9700E-02 | 23.59 | 1.7 |
| 125 | 0.1573 | 0.0915 | 1.5794 | 4.0297E-04 | 4.5881E-03 | 7.9187E-02 | 11.87 | 0.9 |
| 50 | 0.3858 | 0.2244 | 1.5495 | 9.8836E-04 | 1.1253E-02 | 7.7688E-02 | 4.84 | 0.4 |

Table 6-19 Densities for Oak Ridge Canister with Group 5 Contents

| H/C | Densities (g/cm$^3$) | | Atom Densities (atm/b-cm) | | Height (cm) | h/D |
|---|---|---|---|---|---|---|
| | U | C | $^{235}U$ | C | | |
| 10000 | 0.00313 | 1.5997 | 8.0207E-06 | 8.0207E-02 | 88.27 | 6.4 |
| 5000 | 0.00626 | 1.5995 | 1.6039E-05 | 8.0193E-02 | 88.27 | 6.4 |
| 1000 | 0.0313 | 1.5974 | 8.0088E-05 | 8.0088E-02 | 88.27 | 6.4 |
| 446 | 0.0700 | 1.5941 | 1.7935E-04 | 7.9925E-02 | 88.27 | 6.4 |
| 375 | 0.0831 | 1.5930 | 2.1299E-04 | 7.9870E-02 | 74.32 | 5.4 |
| 250 | 0.1244 | 1.5895 | 3.1878E-04 | 7.9696E-02 | 49.66 | 3.6 |
| 125 | 0.2472 | 1.5792 | 6.3343E-04 | 7.9179E-02 | 24.99 | 1.8 |
| 50 | 0.6063 | 1.5491 | 1.5533E-03 | 7.7667E-02 | 10.19 | 0.7 |

Table 6-20 Densities for Oak Ridge Canister with IPB Contents

| H/C | Densities (g/cm$^3$) | | Atom Densities (atm/b-cm) | | Height (cm) | h/D |
|---|---|---|---|---|---|---|
| | U | C | $^{235}U$ | C | | |
| 10000 | 0.00313 | 1.5997 | 8.0193E-06 | 8.0205E-02 | 228.60 | 16.7 |
| 5000 | 0.00626 | 1.5995 | 1.6039E-05 | 8.0195E-02 | 228.60 | 16.7 |
| 4215 | 0.0074 | 1.5994 | 1.9024E-05 | 8.0189E-02 | 228.60 | 16.7 |
| 500 | 0.0624 | 1.5948 | 1.5991E-04 | 7.9957E-02 | 228.60 | 48.4 |
| 375 | 0.0831 | 1.5930 | 2.1299E-04 | 7.9870E-02 | 228.60 | 55.9 |
| 250 | 0.1244 | 1.5895 | 3.1878E-04 | 7.9696E-02 | 228.60 | 68.3 |
| 125 | 0.2472 | 1.5792 | 6.3343E-04 | 7.9179E-02 | 228.60 | 96.3 |
| 50 | 0.6063 | 1.5491 | 1.5533E-03 | 7.7667E-02 | 228.60 | 150.8 |

Non-fissile material modeled includes stainless steel, lead, aluminum, water, and $^{10}B$ poison. The material densities and atom densities for the constituent nuclides of these materials are given in Table 6-21.

The poison plates in the cask contain the neutron absorber $^{10}B$ and are to be constructed of either a boron/aluminum alloy, Boral© or a boron carbide aluminum metal matrix composite. NUREG/CR-5661 recommends crediting 75% of the minimum neutron absorber content specified in the application, unless comprehensive acceptance tests, capable of verifying the presence and uniformity of the neutron absorber, are implemented. Three different poison plate designs are proposed for use with the TN-FSV cask with Oak Ridge Container. For two designs, 75% of the $^{10}B$ is credited, while 90% is credited for the other design. The credited boron concentration for the three designs is the same, so the minimum design specification for $^{10}B$ differs for each design. The cask design and license application permit the use of either of these poison plate designs.

The first poison plate design consists of a boron-aluminum alloy, with the boron enriched to 95% $^{10}B$. Due to the negligibly small solubility of boron in solid aluminum, the boron appears entirely as discrete second phase particles of $AlB_2$ in the aluminum matrix. This material undergoes rigorous acceptance testing, as described in Chapter 8, which verifies both absorber concentration and absorber uniformity. Therefore, 90% of the minimum $^{10}B$ concentration is credited in the criticality analysis (see Chapter 8 for further justification). The material contains approximately 1.7 wt. % boron, and the alloy density is 2.69 g/cm$^3$. This leads to a $^{10}B$ density of 0.0434 g/cm$^3$. The design specifications call for a minimum $^{10}B$ areal density of 0.030 g/cm$^2$, which, when divided by the plate thickness gives a minimum density of 0.0387 g/cm$^3$. Therefore, the criticality calculations could credit a $^{10}B$ density of (0.90)*(0.0387 g/cm$^3$) = 0.0348 g/cm$^3$.

The second poison plate design is a boron carbide aluminum metal matrix composite. This material is produced by sintering a mixture of 85 volume percent aluminum powder with 15 volume percent boron carbide particulates. The boron is of natural enrichment (approximately 18.5% $^{10}B$), and the composite density is 2.52 g/cm$^3$, which leads to a $^{10}B$ density of 0.0547 g/cm$^3$. The design specifications call for a minimum $^{10}B$ areal density of 0.036 g/cm$^2$, which, when divided by the plate thickness, gives a minimum density of 0.0465 g/cm$^3$. This material is subjected to rigorous acceptance testing for $^{10}B$ concentration, but not for uniformity (see Chapter 8). Therefore, only 75% of the minimum $^{10}B$ is credited. Therefore, the criticality calculations could credit (0.75)*(0.0465 g/cm$^3$) = 0.0348 g/cm$^3$, which is the same value calculated for the other poison plate design.

The third possibility, Boral®,is a well known product of a $B_4C$-Al matrix core clad with aluminum sheet. The Boral® will be chosen such that 75% credit of the $^{10}B$ areal density will meet a minimum allowable value of 0.036 g/cm$^2$.

A $^{10}B$ concentration of 0.0348 g/cm$^3$ could be conservatively used to represent either poison plate design. However, to add additional conservatism, the criticality calculations use an even smaller value of 0.03175 g/cm$^3$. Use of this low density provides a large safety margin between the actual and modeled $^{10}B$ density. Note that the only other isotopes present in the poison plates are $^{11}B$, natural aluminum, and, for the composite, natural carbon. Since these isotopes are relatively inert to neutrons, particularly in comparison to $^{10}B$, they are ignored in the KENO models.

Table 6-21 Package Regional Densities for Non-Fissile Materials

| Material | | Density ($g/cm^3$) | Atom Density (atm/b-cm) |
|---|---|---|---|
| Water | | 0.9982 | - |
| | H | 0.8865 | 6.6769E-02 |
| | O | 0.1117 | 3.3385E-02 |
| SS-304 | | 7.92 | - |
| | Cr | 1.5048 | 1.7429E-02 |
| | Mn-55 | 0.1584 | 1.7363E-03 |
| | Fe | 5.5044 | 5.9358E-02 |
| | Ni | 0.7524 | 7.7207E-03 |
| Lead | | 11.344 | 3.2969E-02 |
| Aluminum | | 2.702 | 6.0307E-02 |
| Boron-10 | | 0.03175 | 1.9096E-03 |

## 6.4 Criticality Calculation

### 6.4.1 Calculational Method

All calculations were performed using the CSAS6 sequence of the SCALE[3] system. The CSAS6 sequence implements the KENO VI module to calculate the reactivity of the system using the Monte Carlo method. The KENO VI module is used instead of the more commonly used KENO V.a module because the geometry of the basket assembly cannot be accurately described using the simple geometry constraints of KENO V.a. KENO VI allows accurate modeling of the basket assembly, but requires significantly longer running times than KENO V.a would.

The SCALE 27-group cross section set was selected for use in this evaluation. This cross section set was derived from ENDF/B-IV data, and was conceived as a general purpose criticality analysis library, with a special interest in applicability toward shipping cask analysis and thermal neutron systems. Therefore, the library is well-suited for analysis of the TN-FSV cask with the Oak Ridge Container. In addition, this library is one of the most widely used libraries in the criticality community, and as such has been the subject of extensive validation. This increases confidence in the reliability of the data.

### 6.4.2 Fuel Loading Optimization

A series of parameter studies is performed to find the optimal fuel loading conditions. Although much of the fuel is HTGR graphite-based assemblies, carbon is ignored in the flooded calculations; the fissile material is modeled simply as a fissile metal and water mixture. This is a conservative aspect of the material model.

It is demonstrated in Reference 4 that a mixed moderator consisting of carbon and water leads to a smaller minimum critical mass when the uranium concentration is less than approximately 0.02 g/cm$^3$. However, the same data also show that if the uranium concentration is not constrained, the minimum critical mass will occur between approximately 0.04 and 0.06 g/cm$^3$ with a water-only moderator. Adding carbon to the water at those uranium densities increases the minimum critical mass. Calculations discussed on the following pages demonstrate that the maximum reactivity case for the cask being analyzed occurs with uranium (or equivalent uranium) concentrations in the 0.06 to 0.10 g/cm$^3$ range. Therefore, it is conservative to ignore carbon in the flooded calculations.

### 6.4.2.1 Fuel H/X Ratio

#### Scoping Studies with a Uniformly Loaded Cask

The first parameter studied is the H/X ratio of the fuel within each Oak Ridge Canister or Intact Peach Bottom Assembly. An initial set of calculations is performed with each cask filled with identical canisters (e.g., all group 1, all group 2, *etc*). This uniform configuration does not correspond to any of the actual loading patterns, but is useful as a guide for calculations of the actual patterns, since the H/X peak for a given group will be known. Two different methods of varying H/X are investigated for each of the five groups. In the first method, the fissile mixture is maintained at full density while the volume of the mixture is decreased in a manner that keeps the fissile mass constant, while in the second method, the volume of the fissile mixture is kept constant and equal to the volume of the canister, while the density of the fissile mixture is reduced, also in a manner that keeps the fissile mass constant. When using the first method, the volume is reduced by reducing the height of the fissile mixture inside the canister while keeping the diameter fixed and equal to the diameter of the canister. This is done because the height to diameter ratio of the canister is 6.4, so reducing the height of the mixture reduces the H/D and brings it closer to the optimal value near 1.0.

A third method of reducing H/X is to lower the mass of fissile material in the canister while maintaining the volume of the fissile mixture constant. However, such a procedure will only increase reactivity if the system is under-moderated when the nominal fissile mass is in the container and the fissile mixture volume is equal to the container volume. It will be shown that in all cases system reactivity increases as H/X is lowered from this starting point. This proves that none of the systems are under-moderated. Therefore, this method for reducing H/X is not investigated further.

The results of the calculations are shown in Figures 6-21 (a) through (e). From these results it is clearly evident that system reactivity is much higher when the fissile mixture is kept at full density while its volume is reduced than it is when the volume is maintained and the fissile mixture density is reduced. Therefore, the former method will be used in all further calculations. The optimal H/X range for groups 1, 3, and 4 is between 300 and 400, while for groups 2 and 5 it is between 150 and 250.

Cask Loaded Using the Four Loading Patterns

The next calculations model the cask loaded according to the four loading patterns. The procedure is similar to that discussed above: the H/X ratio is varied by reducing the volume of the fissile mixture; this is accomplished by maintaining the diameter of the fissile mixture constant while reducing its height. This seemingly simple parameter study actually involves numerous interacting variables. Since the canisters are tall and relatively thin (height/diameter = 6.4), it is hypothesized that the maximum reactivity will be achieved if the fissile mixture diameter is left constant and equal to the diameter of the canister, and the fissile mixture volume is changed by changing its height. The validity of this hypothesis is verified in Section 6.4.2.3. The fissile mixture volume is modeled centered inside the canister, and this modeling assumption is verified in Section 6.4.2.7 to be conservative. In contrast to the canister, the fissile mixture height is fixed for the IPB, so the volume of the fissile mixture is reduced by decreasing its diameter. The axial positioning of the fissile mixture is also fixed for the IPB, as was discussed in Section 6.3.1.4.

It is apparent from the above discussion that as the volume of the fissile mixture changes, its height/diameter ratio also changes. The complexity of parameter interaction now becomes apparent. For a single isolated unit with no volume or geometry constraints, the minimum critical uranium mass occurs at an H/X ratio near 500. On the other hand, for an isolated single cylinder of flexible geometry, the minimum critical mass occurs at a height/diameter ratio near 1.0. In the system of interest to this analysis, the height/diameter ratio and H/X ratio are directly related; changing one changes the other. To further complicate things, the containers are not isolated. Rather, they are interacting with other containers in both the horizontal and radial directions. Boron poison plates are positioned between the containers in both directions. Finally, there are at least two different types of containers in the cask. All of these parameters influence the location of the optimal H/X ratio.

Tables 6-9 through 6-14 list the parameters used in this study as a function of H/X ratios. The parameters are fissile isotope concentration, water concentration, and fissile region height. The height/diameter ratio of the fissile region is also provided.

A description of the results for each loading pattern is presented below.

Loading Pattern 1

Recall that with this loading pattern, four of the fuel compartments each contain four group 1 Oak Ridge Canisters, while the fifth fuel compartment contains four group 2 Oak Ridge Canisters. The maximum H/X ratio achievable in a group 1 canister is 712, while for a group 2 canister it is only 320. For the first two calculations, the group 2 canisters have an H/X ratio of 320, while the group 1 canister has an H/X of 712 and 350. For the next nine calculations, the H/X ratio of the group 1 and group 2 canisters are the same, varying from 300 down to 30.
The results of these calculations, shown in Table 6-22 and Figure 6-23 (a), indicate a reactivity peak in the H/X range of 200 – 300. To hone in on the maxima, the H/X ratio in the group 1 and group 2 canisters is varied independently in the 200 – 300 range.

For example, with an H/X=300 for the group 1 canister, the H/X of the group 2 canisters is set at 300, 250, and 200. The results of this refinement to the search are also presented in Table 6-22. The results indicate a peak occurring when H/X=300 in the group 1 canisters and 250 in the group 2 canisters. Note that both of these results fall within the range where the peak was found for the uniform cask filled with canisters containing material from one of these two groups.

Loading Pattern 2

This loading pattern consists of four group 5 canisters in one fuel compartment, and four group 1 canisters in each of the remaining four fuel compartments. The calculations proceed in a manner completely analogous to that described above for Loading Pattern 1. The results are shown in Table 6-23 and Figure 6-23 (b), and indicate a peak in the same range of H/X = 200 – 300. The most reactive condition identified is at H/X = 300 in the group 1 canister and 200 in the group 5 canister. Again, both of these results fall within the range where the peak was found for the uniform cask filled with canisters containing material from one of these two groups.

Loading Pattern 3

With this loading pattern, all fuel compartments have one IPB and one group 4 canister. Since the height of the fissile mixture in the IPB is fixed, its H/X ratio is left constant at 3507, while the H/X ratio of the group 4 canister is varied from a maximum value of 782 down to a minimum value of 125. The results in Table 6-24 and Figure 6-23 (c) show a peak occurring at an H/X ratio of 375.

Because of the physical separation between the end of the active fuel region and the end of the assembly in the IPB, and the low fissile loading of the IPB's, it is hypothesized that they are not contributing to the system reactivity. To test this hypothesis, the case that gave the maximum reactivity (H/X=375) is re-run with the IPB modeled as a void. The calculated reactivity, shown in Table 6-24, is statistically identical to that found with the IPB included in the model. Therefore, it may be concluded that the presence of the IPB does not influence the reactivity of the system under loading pattern 3.

Loading Pattern 4

This is the most complex loading pattern, consisting of two group 3 canisters and two group 4 canisters in one fuel compartment, and an IPB with one group 4 canister in the remaining four fuel compartments.
The results for Loading Pattern 3 show that the group 4 canister is more reactive than the IPB. From Table 6-2, the group 3 canister is expected to be more reactive than the group 4 canister, based on its higher FEM. Therefore, the two group 3 canister are modeled at the top of fuel compartment 1, with the two group 4's on the bottom. This places the group 3 canister in fuel compartment 1 adjacent to the group 4 canisters in the other four fuel compartments.

The H/X optimization of this particular loading pattern is complicated by the fact that the axial loading is different in fuel compartment 1 than in the other four compartments.
Figure 6-22 compares the two different types of compartments side by side. This figure depicts the IPB located in the bottom of the fuel compartment with the canister on top, the actual loading configuration for the IPB/canister may be reversed. However, the analysis and figure are intended to show the most conservative configuration/interaction whatever the relative location of the IPB assembly. The shaded zones in the figure are areas that may contain fissile material. The situation pictured is that which occurs if all canisters have their maximum possible H/X ratio (556 in Group 3 and 784 in the Group 4's). As the H/X ratio is reduced from these values, the fissile material regions shrink, but are still contained within the canister. Recall that the intact Peach Bottom Assemblies are modeled differently, with the fuel spread out along the active fuel region, which is fixed in place. From examination of the figure, the following points are apparent:

(1) The bottom Group 4 canister in fuel compartment 1 will never overlap with the IPB in adjacent fuel tubes, regardless of its H/X ratio.

(2) The middle Group 4 canister in fuel compartment 1 will always overlap with the IPB's in the adjacent fuel tubes, regardless of its H/X ratio.

(3) The middle Group 3 canister in fuel compartment 1 will always have very significant overlap with the IPB's in the adjacent fuel tubes, and will have complete overlap for H/X < ~ 450.

(4) The upper Group 3 canister in Fuel compartment 1 may or may not overlap with the Group 4 canister in the adjacent fuel tubes, depending on how the fissile regions are axially positioned and on the H/X.

The model used for the H/X study positions the fissile region in each canister in fuel compartment 1 as follows:

Bottom Group 4: Top
Middle Group 4: Centered
Middle Group 3: Centered
Top Group 3: Bottom

Considering these facts and the points made above, it seems likely that overlap will only be important for the top Group 3 canister with the Group 4 canisters above the IPB's. In an attempt to focus on the reactivity contribution of each individual canisters in fuel compartment 1, the H/X study is performed in steps. In each step, only the canister being studied contains fissile material – the other three are empty. In the first step, the H/X in the upper Group 3 canister in fuel compartment 1 is varied, along with the H/X in the Group 4 canisters above the IPB's in the other compartments. The results of this study are shown in Figure 6-23d and Table 6-25. They demonstrate that a maxima is achieved when the Group 3 canister H/U is between 250 and 350, and the Group 4 canister H/U is between 350 and 400. Tables 6-26, 6-27, and 6-28 demonstrate that the H/U value in the other three remaining canisters are irrelevant to the system reactivity.

These results indicate that system reactivity is driven by the Group 4 canisters above the IPB's, with no influence from the IPB's or the lower 3 canisters in fuel compartment 1.

The system reactivity under these conditions (no fuel in the upper Group 3 canister in fuel compartment 1) remains constant at approximately 0.86, regardless of the H/U in the other canisters in fuel compartment 1. When there is fuel present in the upper Group 3 canister, the reactivity jumps to approximately 0.92 when the H/U is optimized.

H/U values of 300 and 375 in the upper Group 3 canister in Fuel compartment 1 and the Group 4 canisters above the IPB's are chosen for subsequent runs. Since the H/U in the other three canisters in Fuel compartment 1, is inconsequential, it is set to 300 for consistency. Note that again these results fall within the range where the optimum was found for the uniform cask loaded only with canisters containing material from one of these two groups.

The final set of calculations investigates smaller values of H/U in the IPB, achieved by reducing the diameter of the fissile region. From the above results, one would expect no statistically significant deviations in results as the H/U in the IPB is varied, and Table 6-29 shows that this is the case. An IPB H/U value of 3507 is chosen for all remaining calculations.

### 6.4.2.2 Close Reflection of Containment System

The full cask was modeled for all calculations in Section 6.4.2.1. 10 CFR 71.55 (c.3) requires investigation of the containment system closely reflected by water. For each of the four loading patterns, the most reactive case is re-run with the Oak Ridge Container closely reflected by 12 *in.* of water. In all four cases, the system reactivity is much lower under these conditions than it is when the full cask is modeled, as can be seen by comparing the results in Table 6-30 to those in Tables 6-26 through 6-29. This is due to the better reflective properties of the thick steel and lead regions in the cask as compared to water. In light of these results, the full cask is modeled for all remaining calculations.

### 6.4.2.3 Reduced Diameter of Fissile Region

In the parameter studies to find the optimal H/X ratio, the diameter of the fissile region was kept constant and equal to the diameter of the canister. The rational is that since the height to diameter ratio of the canister is 6.4 (16.7 for the IPB), reducing the diameter will further increase the ratio and thus can only decrease system reactivity. To prove that this assertion is correct, a series of parametric evaluations is performed. For these calculations, several H/X ratios are selected that span the range where the maximum reactivity is found for the loading pattern of interest. For each selected H/X, several values of fissile region diameter are chosen. The fissile region height is then calculated. Note that the minimum diameter that can be considered for a given H/X is the one that leads to a height equivalent to the canister height.

The reduced diameter studies are discussed below for each loading pattern. Tables 6-31 and 6-32 list the radius, diameter, and height to diameter ratio for each of the five canister groups. Note that this information is provided for the IPB in Table 6-14.

Loading Patterns 1, 2, and 4

The results for these loading patterns are all similar, and are displayed in Tables 6-33, 6-34, and 6-36, and Figure 6-24 (a), (b), and (d). In all cases, the system reactivity drops sharply as the fissile region diameter is reduced from its maximum value, regardless of the value of H/X. These results confirm that the most reactive condition occurs when the fissile region diameter is maximized and equal to the diameter of the canister. Note: for Loading Pattern 4, only the diameter of the fissile region in the top Group 3 canister in Fuel compartment 1 and the Group 4 canister above the IPB's in the other four compartments are varied. These canisters were shown in the H/X study to dominate the reactivity of this system.

Loading Pattern 3

For Loading Pattern 3, only the radius of the fissile region in the intact Peach Bottom Assembly is reduced. The results in Table 6-35 and Figure 6-24 (c) show that the change in system reactivity is not statistically significant. This result is not surprising, since it has previously been shown that the IPB does not contribute to the reactivity of this loading.

### 6.4.2.4 Interstitial Water Studies

Having identified the most reactive contents, the next step is to identify the most reactive interstitial moderation and reflection conditions within the cask. These studies start with the case that produced the highest reactivity from the H/X studies. In order to evaluate the effects of preferential flooding of only certain parts of the cask, four separate parametric series are evaluated for each loading pattern. In the first parametric series, only the empty space inside the Oak Ridge Canister or Intact Peach Bottom Assembly is flooded. This empty space arises because optimal moderation occurs when the fissile mixture volume is less than the canister volume. In the second series, only the hollow spaces within the flux trap spacer are flooded. In the third series, all the open cask spaces except those in the canisters and the hollow region in the spacers are flooded. Finally, in the fourth series, all empty spaces in the cask are flooded. In all cases, the water density is varied from 0.1% of full density to 100% of full density.

The results for these studies are very similar for all four loading patterns, and are displayed in Figures 6-25 (a) – (d). Flooding of the empty space in the canister or IPB has either a small negative or a negligible impact on system reactivity. The same is true for flooding of the hollow region in the flux trap spacers. Flooding of the remainder of the cask has a strong negative impact on system reactivity, presumably because it makes the boron in the poison plates more effective.

In conclusion, water flooding of the cask does not increase reactivity of the cask system under any conditions.

### 6.4.2.5 Infinite Array Calculations

The normal condition array calculations differ from the single cask calculations in that the fissile material is assumed to be dry. This assumption can be made because the cask is loaded dry, and two containment vessels provide a leak-tight barrier against water ingress. Water ingress could only occur during an HAC event. Note that since the Transport Index based on criticality safety is 100 (N=0.5), array calculations are not necessary for the HAC (2*N = 1).

The infinite array model is simply generated from the single unit model by adding mirror reflectors on all surfaces. Note that the outermost region of the cask is specified as a hexprism to force generation of an infinite hexagonal array.

The fissile material is modeled as a carbon/fissile mixture. A parametric set of calculations is run to find the most reactive C/X ratio. The results of those calculations are shown in Figure 6-26 (a) – (d). These results demonstrate that the system reactivity is very low with only carbon moderation; the carbon-moderated infinite array reactivity is much less than that of the water-moderated single unit. The peak reactivity with carbon moderation occurs with the maximum amount of carbon in the canister. This is not surprising, since at this point the C/X ratio is still far below the optimal point, which occurs near 10,000.

### 6.4.2.6 Studies of Spacer Loading Errors

The calculations discussed in this section are not required by 10 CFR 71. However, it is felt they are necessary to demonstrate criticality safety for the Oak Ridge Container due to the unique use of axial spacers in the package. As discussed in Section 6.2.4, one of the two defenses that assure all spacers have been properly loaded into the sealed package is to verify the height of the canister stack in each fuel compartment before the Oak Ridge Container is closed. If the spacers have been properly loaded, the top of the canister stack will be within an inch of the top of the fuel compartment. If one or more spacers are missing, the top of the canister stack will be more than 16 *in.* from the top of the fuel compartment. If the latter situation is encountered, the fuel compartment must be reloaded. This assures that all spacers are present before the Oak Ridge Container is sealed and made ready for transport. To use this control, it is necessary to demonstrate that the package remains safely sub-critical when fully loaded with no spacers. Since the cask is loaded dry, the fuel is assumed to be dry in these calculations. Moderation is limited to that provided by the graphite present in the HTGR fuel assemblies. Note that these calculations also bound the dry normal condition, since the only difference between them and the dry normal condition is that the axial spacers are omitted.

The results of the calculations are presented in Figure 6-27 (a) – (d). For all of the loading patterns, reactivity of the dry cask is extremely low (the highest value of $k_{eff} + 2\sigma = 0.128$), even with optimal carbon moderation and no axial spacers. These calculations demonstrate that the cask can be safely loaded using the proposed procedure.

## 6.4.2.7 Sensitivity Studies

A series of calculations was run to test sensitivity of the calculated system reactivity to various cask parameters. The same calculations were performed for all four loading patterns with similar results, as presented in Tables 6-37 through 6-40. In these tables, the last column lists the difference between the calculated value of $k_{eff}$ for the entry in that row and the calculated value for the base (unperturbed) case, divided by the standard deviation. This value represents the difference in number of standard deviations, and is a good indicator of statistical significance. In general, if the difference between two results does not exceed 4 standard deviations, the two results can be considered statistically indistinguishable (they both represent the same value). Two results that differ by at least 6 standard deviations are considered statistically distinguishable (different values).

The first row in these tables repeats the result for the most reactive case found with optimal water moderation. All other cases in the table represent perturbations from this base case.

Poison Enclosure Steel Plates

The first calculation set tests the sensitivity of system reactivity to the thickness of the steel plates on the poison enclosure. Recall that these plates are specified as 16 and 22 Gauge, and were modeled with nominal thickness of 0.1510 and 0.0744 cm, respectively. Four calculations are performed, with the thickness of each plate increased by 10%, decreased by 10%, increased by 0.01 *in.*, and set to zero. The results for all four cases show reactivity differences less than 4 standard deviations from the base case, indicating the system reactivity remains statistically unchanged. However, the trend appears to show reactivity decreasing as the thickness of the plates decreases, presumably because some neutrons are reflected away from the boron poison plate by the steel shield. By this same logic, at some point one would expect system reactivity to increase with increasing thickness of the steel plates.

Drawing 3044-70-5 in Chapter 1, "Oak Ridge Container Poison Enclosure Details," specifies the poison enclosure steel plates are specified as 16 gauge (0.0595 *in.*) or 22 gauge (0.0293 *in.*). Typical tolerances for stainless steel sheet in these gages are ±.003 *in.* and ±.002 *in.* respectively which is within the 10% tolerance band evaluated. The calculations demonstrate that for steel plate thickness less than those specified, reactivity is either unchanged or decreased. The calculations also show that for steel plate thickness up to 0.010 inch greater than specified, system reactivity is unchanged.

Steel Shell and Lead Shield Thickness

The next two sets of calculations test sensitivity to the thickness of the inner and outer steel shells, and to the thickness of the lead shield. In the first set, the thickness of both the inner and outer steel shell is first increased by 10%, and then decreased by 10% from the nominal design values. In the second set, the thickness of the lead shield is first increased by 10% and then decreased by 10% of the nominal design value.

In all four cases, the reactivity change from the base case is less than four standard deviations, and therefore not statistically significant.

Drawing 1044-SAR-2 lists the following tolerances for the steel shells and lead shield:

Inner steel shell thickness = 1.12" ± 0.12"
Outer steel shell thickness = 1.50 ± 0.12"
Lead shield outer diameter = 27.12" + 0.25" – 0"

The tolerances of the two steel shells are equal to or less than 10%, which is within the calculated range. For the lead shield, the nominal, minimum, and maximum thickness are found by considering the nominal, minimum, and maximum thickness of the steel shells on either side, along with the requirement given above. The numbers work out to a nominal thickness of 3.44 *in.*, a maximum thickness of 3.68 *in.* (+ 7%), and a minimum thickness of 3.38 *in.* (- 2%). These permitted variations are well within the calculated range.

The sensitivity study evaluated variations in the thickness of the two steel shells and of the lead shield that were equal to or greater than the variations permitted by the specified tolerances, and demonstrate that system reactivity is unaffected.

<u>Boron Density and Poison Plate Thickness</u>

The next set of calculations investigates the sensitivity of the results to the density of boron in the poison enclosures and axial spacers. The density is incrementally reduced from the nominal modeled value of 0.03175 g/cm$^3$ (which is already 8.7% less than the concentration of $^{10}$B that the analysis could take credit for, as discussed in Section 6.3.2) all the way down to zero (no poison present). The results of this analysis are quite interesting, as can be seen in Figure 6-28. This figure plots the increase in reactivity, as measured by the number of standard deviations between the result and the base case, as the boron concentration is decreased. The curve for all four loading patterns is very similar, and appears to represent an exponential shape. The initial reductions in boron density result in little to no change in system reactivity, while later reductions (say from 30% to 10% of nominal modeled density) lead to large increases. Note that for all four loading patterns, the curve does not rise above the 4-$\sigma$ line until the boron density is decreased by more than 40% from the modeled value.

The observed pattern of reactivity increase with reduced boron density indicates that the nominal poison concentration and thickness are sufficient to decrease the thermal flux to zero inside the poison plates, such that the center of the plates are self-shielded. As the boron density is decreased, the amount of self shielding decreases, and the thermal neutron flux penetrates further into the poison plate, eventually making it to the other side, thus permitting thermal neutron interaction between canisters.

The minimum $^{10}$B concentration required during acceptance testing of the boron aluminum alloy is 0.0387 g/cm$^3$, while for the boron carbide aluminum metal matrix composite the $^{10}$B concentration must be at least 0.0465 b/cm$^3$.

Therefore, the sensitivity calculations demonstrate that the cask remains safely subcritical under optimal reactivity conditions even if only 49% (boron aluminum alloy) or 41% (boron carbide aluminum metal matrix composite) of the required minimum of $^{10}B$ is present.

In addition to boron density, it is necessary to investigate sensitivity to the thickness of the poison plates. Three calculations are run, with the thickness of the poison plates decreased to 90, 80, and 70 percent of their nominal modeled value (0.300 *in.*). The results for these cases show a statistically insignificant difference in all cases except Loading Pattern 2 at 70%. Drawing 3044-70-8 in Chapter 1, "Oak Ridge Container Details," specifies the thickness of poison plates as $0.305 \pm 0.005$ *in.* The sensitivity calculations show that system reactivity is not significantly affected if the thickness of all poison plates is as much as 20% lower than the permitted lower bound of 0.300 *in.*

Axial Positioning of Fuel in Canisters

The final calculation performed tests sensitivity of system reactivity to the axial positioning of fuel within the canisters for Loading Patterns 1 and 2. This sensitivity study is not applicable to Loading Patterns 3 and 4. In all previous calculations for Loading Patterns 1 and 2, the fissile mixture is centered within the canister. For these sensitivity calculations, the fissile mixture in the top canister is placed in the bottom of the canister, while that in the canister below it is placed at the top of the canister. This pattern is repeated for the two remaining canisters. This strategy minimizes the separation between the fissile mixtures in the top two canisters and the bottom two canisters in each fuel compartment. However, the results show a statistically insignificant change in reactivity as compared to the base case, which had the fissile mixture centered within each canister.

Plutonium Modeling

As discussed in Section 6.2, fissile plutonium is modeled by adding the mass of $^{241}Pu$ to the mass of $^{239}Pu$ in the model, while ignoring the fissionable isotope $^{240}Pu$, which acts as a neutron poison in thermal systems. This approach is recommended in ANSI ANS 8.15, provided the mass of $^{240}Pu$ is at least as great as that of $^{241}Pu$. One calculation is performed for each Loading Pattern to demonstrate that this approach is conservative. The most reactive case for each loading pattern is modified to model ALL of the permitted plutonium mass as $^{241}Pu$ ($^{241}Pu$ is more reactive than $^{239}Pu$ – a minimum critical mass of 244 grams for the former, versus 480 for the latter). An equal mass of $^{240}Pu$ is also added to the material model, since the $^{241}Pu$ mass cannot exceed the $^{240}Pu$ mass. These calculations are conservative because (1) they assume all of the fissile plutonium is $^{241}Pu$, while in reality it is typically less than 10%; and (2) they assume the $^{240}Pu$ mass is equal to the $^{241}Pu$ mass, while in reality it is always greater than the $^{241}Pu$ mass. The results in Tables 6-37, 6-39, and 6-40 show that system reactivity decreases for all three loading patterns when the plutonium is modeled in this manner. These calculations prove that the plutonium modeling methodology (modeling all fissile plutonium as $^{239}Pu$ and requiring that the amount of $^{240}Pu$ present be equal to or greater than the amount of $^{241}Pu$) is conservative.

## 6.4.3 Criticality Results

The results of all calculations are presented in this section, in both tabular and graphical form. The discussions of the cases evaluated and the results are presented in the previous Section 6.4.2.

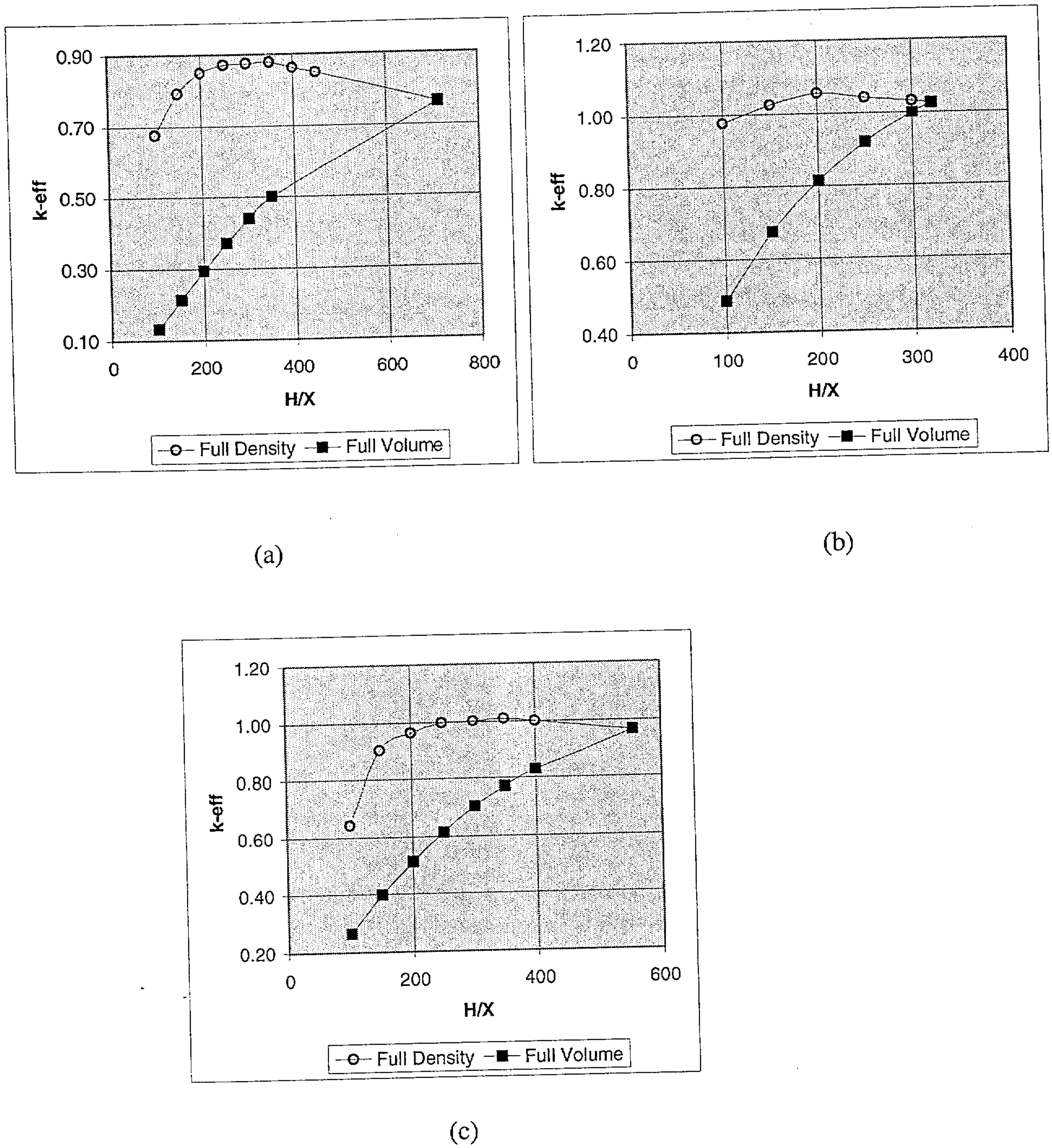
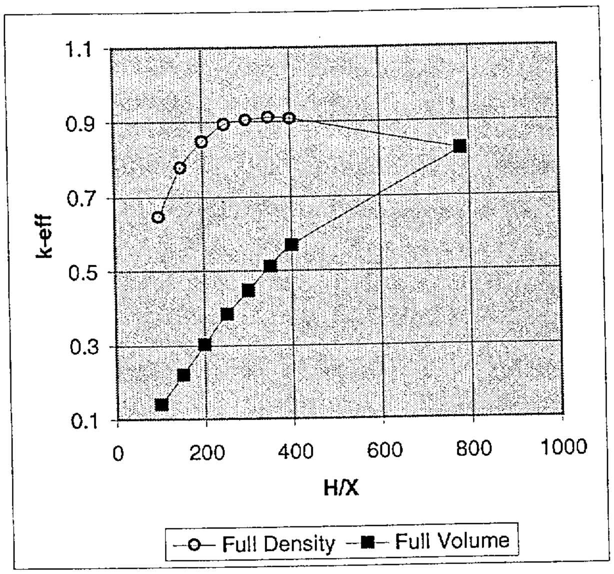
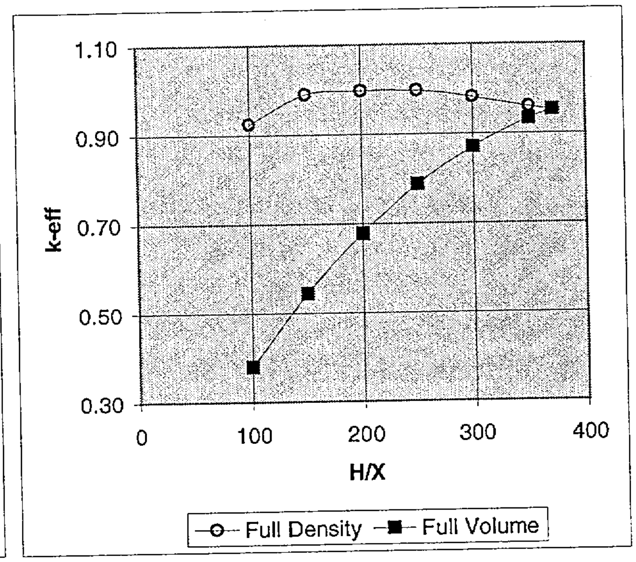



**Figure 6-21 Variation of the system multiplication factor as a function of H/X**
*Cask loaded with all (a) Group 1 canisters; (b) Group 2 canisters; (c) Group 3 canisters; (d) (on following page) Group 4 canisters; (e) (on following page) Group 5 canisters.*




(d)




(e)

**Figure 6-21 (continued) Variation of the system multiplication factor as a function of H/X**

Table 6-22 Optimal H/X Ratio for Loading Pattern 1

| | H/X Ratios | | | | |
|---|---|---|---|---|---|
| Case | FT's 2 - 5 | FT 1 | $k_{eff}$ | $\sigma$ | $k_{eff} + 2\sigma$ |
| ORCL1-9 | 712 | 320 | 0.8400 | 0.0025 | 0.845 |
| ORCL1-0 | 350 | 320 | 0.9042 | 0.0028 | 0.910 |
| ORCL1-1 | 300 | 300 | 0.9108 | 0.0029 | 0.917 |
| ORCL1-10 | 275 | 275 | 0.9107 | 0.0026 | 0.916 |
| ORCL1-11 | 250 | 250 | 0.9080 | 0.0030 | 0.914 |
| ORCL1-2 | 200 | 200 | 0.9005 | 0.0029 | 0.906 |
| ORCL1-3 | 175 | 175 | 0.8835 | 0.0029 | 0.889 |
| ORCL1-4 | 150 | 150 | 0.8557 | 0.0029 | 0.862 |
| ORCL1-5 | 125 | 125 | 0.8246 | 0.0029 | 0.830 |
| ORCL1-6 | 100 | 100 | 0.7785 | 0.0032 | 0.785 |
| ORCL1-7 | 30 | 30 | 0.4701 | 0.0025 | 0.475 |
| ORCL1-1a | 300 | 250 | 0.9159 | 0.0026 | 0.921 |
| ORCL1-1b | 300 | 200 | 0.9169 | 0.0031 | 0.923 |
| ORCL1-11a | 250 | 300 | 0.9035 | 0.0025 | 0.909 |
| ORCL1-11b | 250 | 200 | 0.9107 | 0.0029 | 0.917 |
| ORCL1-2a | 200 | 300 | 0.8845 | 0.0027 | 0.890 |
| ORCL1-2b | 200 | 250 | 0.8998 | 0.0028 | 0.905 |

Table 6-23 Optimal H/X Ratio for Loading Pattern 2

| | H/X Ratios | | | | |
|---|---|---|---|---|---|
| Case | FT's 2 - 5 | FT 1 | $k_{eff}$ | $\sigma$ | $k_{eff} + 2\sigma$ |
| ORCL3-1 | 712 | 371 | 0.8152 | 0.0023 | 0.820 |
| ORCL3-2 | 350 | 350 | 0.8923 | 0.0024 | 0.897 |
| ORCL3-3 | 300 | 300 | 0.8962 | 0.0027 | 0.902 |
| ORCL3-4 | 275 | 275 | 0.8975 | 0.0025 | 0.903 |
| ORCL3-5 | 250 | 250 | 0.8951 | 0.0034 | 0.902 |
| ORCL3-6 | 225 | 225 | 0.8978 | 0.0028 | 0.903 |
| ORCL3-7 | 200 | 200 | 0.8865 | 0.003 | 0.893 |
| ORCL3-8 | 175 | 175 | 0.8684 | 0.0030 | 0.874 |
| ORCL3-9 | 150 | 150 | 0.8459 | 0.0025 | 0.851 |
| ORCL3-10 | 125 | 125 | 0.8037 | 0.0027 | 0.809 |
| ORCL3-11 | 100 | 100 | 0.7529 | 0.003 | 0.759 |
| ORCL3-3a | 300 | 250 | 0.9011 | 0.0028 | 0.907 |
| ORCL3-3b | 300 | 200 | 0.9068 | 0.0026 | 0.912 |
| ORCL3-5a | 250 | 300 | 0.8945 | 0.0028 | 0.900 |
| ORCL3-5b | 250 | 200 | 0.9000 | 0.0030 | 0.906 |
| ORCL3-7a | 200 | 300 | 0.8757 | 0.0030 | 0.882 |
| ORCL3-7b | 200 | 250 | 0.8806 | 0.0029 | 0.886 |

## Table 6-24 Optimal H/X Ratio for Loading Pattern 3

| Case | H/X Ratios | | $k_{eff}$ | $\sigma$ | $k_{eff} + 2\sigma$ |
|---|---|---|---|---|---|
| | IPB | ORC | | | |
| ORCL4-1 | 3507 | 782 | 0.8200 | 0.0019 | 0.824 |
| ORCL4-1a | 3507 | 500 | 0.8852 | 0.0027 | 0.891 |
| ORCL4-1b | 3507 | 400 | 0.9032 | 0.0026 | 0.908 |
| ORCL4-1c | 3507 | 375 | 0.9044 | 0.0027 | 0.910 |
| ORCL4-2 | 3507 | 350 | 0.8995 | 0.0027 | 0.905 |
| ORCL4-2a | 3507 | 325 | 0.9025 | 0.0025 | 0.908 |
| ORCL4-3 | 3507 | 300 | 0.8895 | 0.0031 | 0.896 |
| ORCL4-4 | 3507 | 275 | 0.8850 | 0.0027 | 0.890 |
| ORCL4-5 | 3507 | 250 | 0.8730 | 0.0027 | 0.878 |
| ORCL4-6 | 3507 | 225 | 0.8518 | 0.0026 | 0.857 |
| ORCL4-7 | 3507 | 200 | 0.8326 | 0.0029 | 0.838 |
| ORCL4-8 | 3507 | 175 | 0.8012 | 0.0025 | 0.806 |
| ORCL4-9 | 3507 | 150 | 0.7608 | 0.0026 | 0.766 |
| ORCL4-10 | 3507 | 125 | 0.7051 | 0.0027 | 0.711 |
| ORCL4-1c1 | Not present | 375 | 0.8992 | 0.0027 | 0.905 |

## Table 6-25 Optimal H/X Ratio for Loading Pattern 4[5]

| Case | H/U | | $k_{eff}$ | $\sigma$ | $k_{eff} + 2\sigma$ |
|---|---|---|---|---|---|
| | Top Group 3 canister in FT 1 | Group 4 canister above IPB | | | |
| ORCL5-1 | 400 | 375 | 0.9178 | 0.0028 | 0.923 |
| ORCL5-1a | 350 | 375 | 0.9196 | 0.0027 | 0.925 |
| ORCL5-1b | 300 | 375 | 0.9211 | 0.0026 | 0.926 |
| ORCL5-1c | 250 | 375 | 0.9187 | 0.0026 | 0.924 |
| ORCL5-1d | 200 | 375 | 0.9112 | 0.0030 | 0.917 |
| ORCL5-1e | 150 | 375 | 0.8873 | 0.0028 | 0.893 |
| ORCL5-1f | 100 | 375 | 0.8645 | 0.0026 | 0.870 |
| ORCL5-1-1 | 400 | 400 | 0.9179 | 0.0034 | 0.925 |
| ORCL5-1a1 | 350 | 400 | 0.9201 | 0.0025 | 0.925 |
| ORCL5-1b1 | 300 | 400 | 0.9205 | 0.0026 | 0.926 |
| ORCL5-1c1 | 250 | 400 | 0.9191 | 0.0025 | 0.924 |
| ORCL5-1d1 | 200 | 400 | 0.9112 | 0.003 | 0.917 |
| ORCL5-1e1 | 150 | 400 | 0.8899 | 0.0029 | 0.896 |
| ORCL5-1f1 | 100 | 400 | 0.8589 | 0.0027 | 0.864 |
| ORCL5-1-2 | 400 | 350 | 0.9165 | 0.0024 | 0.921 |
| ORCL5-1a2 | 350 | 350 | 0.9178 | 0.0027 | 0.923 |
| ORCL5-1b2 | 300 | 350 | 0.9206 | 0.0028 | 0.926 |
| ORCL5-1c2 | 250 | 350 | 0.9193 | 0.0027 | 0.925 |
| ORCL5-1d2 | 200 | 350 | 0.9115 | 0.0026 | 0.917 |
| ORCL5-1e2 | 150 | 350 | 0.8949 | 0.0026 | 0.900 |
| ORCL5-1f2 | 100 | 350 | 0.8635 | 0.0022 | 0.868 |
| ORCL5-1-3 | 400 | 300 | 0.9097 | 0.0028 | 0.915 |
| ORCL5-1a3 | 350 | 300 | 0.9086 | 0.0025 | 0.914 |
| ORCL5-1b3 | 300 | 300 | 0.9140 | 0.0029 | 0.920 |
| ORCL5-1c3 | 250 | 300 | 0.9083 | 0.0026 | 0.914 |
| ORCL5-1d3 | 200 | 300 | 0.9064 | 0.0026 | 0.912 |
| ORCL5-1e3 | 150 | 300 | 0.8642 | 0.0026 | 0.869 |
| ORCL5-1f3 | 100 | 300 | 0.8192 | 0.0028 | 0.825 |

## Table 6-26 Optimal H/X Ratio for Loading Pattern 4- Middle Group 3[6]

| Case | H/U | $k_{eff}$ | $\sigma$ | Difference in $\sigma$'s |
|---|---|---|---|---|
| ORCL5-2 | 400 | 0.8555 | 0.0026 | - |
| ORCL5-2a | 350 | 0.8528 | 0.0024 | -1.0 |
| ORCL5-2b | 300 | 0.8481 | 0.0027 | -2.8 |
| ORCL5-2c | 250 | 0.8535 | 0.0026 | -0.8 |
| ORCL5-2d | 200 | 0.8512 | 0.0029 | -1.7 |
| ORCL5-2e | 150 | 0.8511 | 0.0026 | -1.7 |
| ORCL5-2f | 100 | 0.8570 | 0.0026 | 0.6 |

[5] Top Group 3 ORC in Fuel Tube 1, the other three ORC's in Fuel Tube 1 are modeled empty. Group 4 ORC above IPBs in Fuel Tubes 2-5. The IPB H/X = 3507 for all cases.
[6] Middle Group 3 ORC in Fuel Tube 1, the other three ORC's in Fuel Tube 1 are modeled empty. The Group 4 ORC's above the IPB are modeled with an H/X = 375 in all cases. The IPB's are modeled with an H/U=3507 in all cases. The last column lists the difference in reactivity between the first case and the subsequent cases.

## Table 6-27 Optimal H/X Ratio for Loading Pattern 4- Middle Group 4

| Case | H/U | $k_{eff}$ | σ | Difference in σ's |
|---|---|---|---|---|
| ORCL5-3 | 400 | 0.8497 | 0.0025 | |
| ORCL5-3a | 350 | 0.8538 | 0.0027 | -0.7 |
| ORCL5-3b | 300 | 0.8517 | 0.0025 | -1.5 |
| ORCL5-3c | 250 | 0.8522 | 0.0026 | -1.3 |
| ORCL5-3d | 200 | 0.8509 | 0.0026 | -1.8 |
| ORCL5-3e | 150 | 0.8498 | 0.0028 | -2.2 |
| ORCL5-3f | 100 | 0.8534 | 0.0028 | -0.8 |

## Table 6-28 Optimal H/X Ratio for Loading Pattern 4- Bottom Group 4

| Case | H/U | $k_{eff}$ | σ | Difference in σ's |
|---|---|---|---|---|
| ORCL5-4 | 400 | 0.8477 | 0.0030 | |
| ORCL5-4a | 350 | 0.8535 | 0.0026 | -0.8 |
| ORCL5-4b | 300 | 0.8544 | 0.0025 | -0.4 |
| ORCL5-4c | 250 | 0.8525 | 0.0028 | -1.2 |
| ORCL5-4d | 200 | 0.8560 | 0.0025 | 0.2 |
| ORCL5-4e | 150 | 0.8478 | 0.0027 | -3.0 |
| ORCL5-4f | 100 | 0.8531 | 0.0029 | -0.9 |

## Table 6-29 Optimal H/X Ratio for Loading Pattern 4 IPB[7]

| Case | H/U | $k_{eff}$ | σ | Difference in σ's |
|---|---|---|---|---|
| ORCL5-5 | 3507 | 0.9223 | 0.0029 | |
| ORCL5-5a | 2500 | 0.9248 | 0.0036 | 0.86 |
| ORCL5-5b | 1500 | 0.9225 | 0.003 | 0.07 |
| ORCL5-5c | 300 | 0.9241 | 0.0025 | 0.62 |
| ORCL5-5d | 200 | 0.9206 | 0.0026 | -0.59 |
| ORCL5-5e | 150 | 0.9263 | 0.0025 | 1.38 |
| ORCL5-5f | 100 | 0.9206 | 0.0026 | -0.59 |

## Table 6-30 Containment System Closely Reflected by 12-In. of Water

| Case | Loading Pattern | $k_{eff}$ | σ | $k_{eff} + 2σ$ |
|---|---|---|---|---|
| ORCL1-100 | 1 | 0.8205 | 0.0029 | 0.826 |
| ORCL3-100 | 2 | 0.8214 | 0.0026 | 0.827 |
| ORCL4-100 | 3 | 0.8174 | 0.0028 | 0.823 |
| ORCL5-100 | 4 | 0.8331 | 0.0026 | 0.838 |

[7] For these calculations, the H/U for all four ORC's in Fuel Tube 1 is 300, while that in the Group 4 ORC above the IPB is 375.

## Table 6-31 Parameters for Reduced Diameter Studies Canister Groups 1 – 3

| Group 1 Canister | | | | Group 2 Canister | | | |
|---|---|---|---|---|---|---|---|
| H/X | R (cm) | H (cm) | h/D | H/X | R (cm) | H (cm) | h/D |
| 300 | 6.50 | 41.39 | 3.2 | 300 | 6.63 | 88.18 | 6.7 |
| 300 | 6.00 | 48.58 | 4.0 | 250 | 6.50 | 76.52 | 5.9 |
| 300 | 5.50 | 57.82 | 5.3 | 250 | 6.06 | 88.04 | 7.3 |
| 300 | 5.00 | 69.96 | 7.0 | 200 | 6.50 | 61.30 | 4.7 |
| 300 | 4.50 | 86.37 | 9.6 | 200 | 6.00 | 71.94 | 6.0 |
| 250 | 6.50 | 34.53 | 2.7 | 200 | 5.50 | 85.62 | 7.8 |
| 250 | 6.00 | 40.52 | 3.4 | Group 3 Canister | | | |
| 250 | 5.50 | 48.22 | 4.4 | H/X | R (cm) | H (cm) | h/D |
| 250 | 5.00 | 58.35 | 5.8 | 400 | 6.50 | 70.57 | 5.4 |
| 250 | 4.50 | 72.04 | 8.0 | 400 | 6.00 | 82.82 | 6.9 |
| 250 | 4.07 | 88.06 | 10.8 | 400 | 5.82 | 88.02 | 7.6 |
| 200 | 6.50 | 27.66 | 2.1 | 350 | 6.50 | 61.78 | 4.8 |
| 200 | 6.00 | 32.46 | 2.7 | 350 | 6.00 | 72.50 | 6.0 |
| 200 | 5.50 | 38.63 | 3.5 | 350 | 5.5 | 86.282 | 7.84 |
| 200 | 5.00 | 46.74 | 4.7 | 350 | 5.44 | 88.196 | 8.11 |
| 200 | 4.50 | 57.71 | 6.4 | 300 | 6.5 | 52.985 | 4.08 |
| 200 | 4.00 | 73.04 | 9.1 | 300 | 6 | 62.184 | 5.18 |
| 200 | 3.64 | 88.20 | 12.1 | 300 | 5.5 | 74.004 | 6.73 |
| | | | | 300 | 5.04 | 88.129 | 8.74 |

## Table 6-32 Parameters for Reduced Diameter Studies Canister Groups 4 and 5

| Group 4 Canister | | | | Group 5 Canister | | | |
|---|---|---|---|---|---|---|---|
| H/X | R (cm) | H (cm) | h/D | H/X | R (cm) | H (cm) | h/D |
| 400 | 6.50 | 50.17 | 3.9 | 300 | 6.50 | 79.30 | 6.1 |
| 400 | 6.00 | 58.89 | 4.9 | 300 | 6.17 | 88.01 | 7.1 |
| 400 | 5.50 | 70.08 | 6.4 | 250 | 6.50 | 66.15 | 5.1 |
| 400 | 4.91 | 87.93 | 9.0 | 250 | 6.00 | 77.63 | 6.5 |
| 350 | 6.50 | 43.92 | 3.4 | 250 | 5.63 | 88.17 | 7.8 |
| 350 | 6.00 | 51.55 | 4.3 | 200 | 6.50 | 52.99 | 4.1 |
| 350 | 5.50 | 61.35 | 5.6 | 200 | 6.00 | 62.19 | 5.2 |
| 350 | 5.00 | 74.23 | 7.4 | 200 | 5.50 | 74.01 | 6.7 |
| 350 | 4.59 | 88.09 | 9.6 | 200 | 5.04 | 88.14 | 8.7 |
| 300 | 6.50 | 37.67 | 2.9 | 200 | 4.50 | 110.56 | 12.3 |
| 300 | 6.00 | 44.21 | 3.7 | | | | |
| 300 | 5.50 | 52.62 | 4.8 | | | | |
| 300 | 5.00 | 63.67 | 6.4 | | | | |
| 300 | 4.50 | 78.60 | 8.7 | | | | |
| 300 | 4.25 | 88.12 | 10.4 | | | | |
| 200 | 4.50 | 52.52 | 5.8 | | | | |
| 200 | 4.00 | 66.47 | 8.3 | | | | |

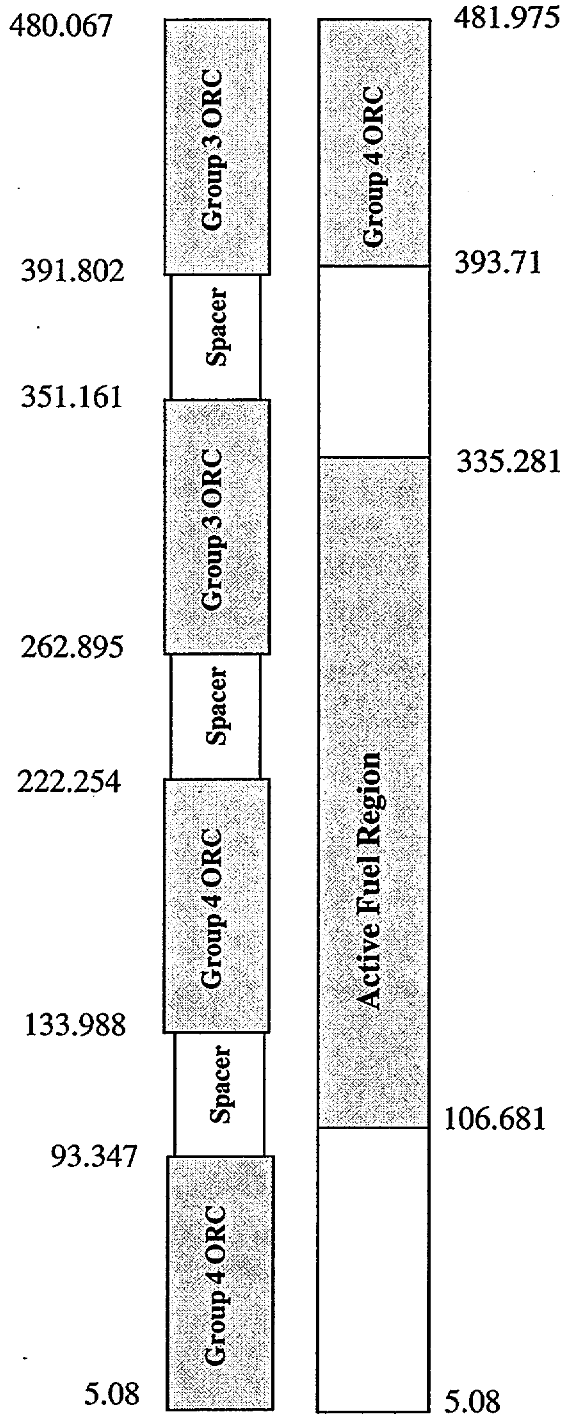
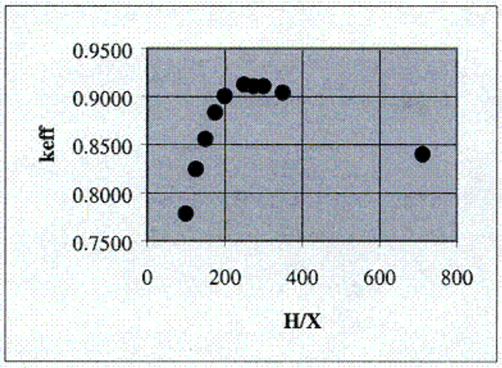
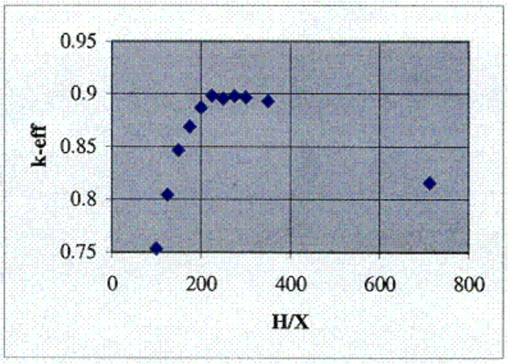


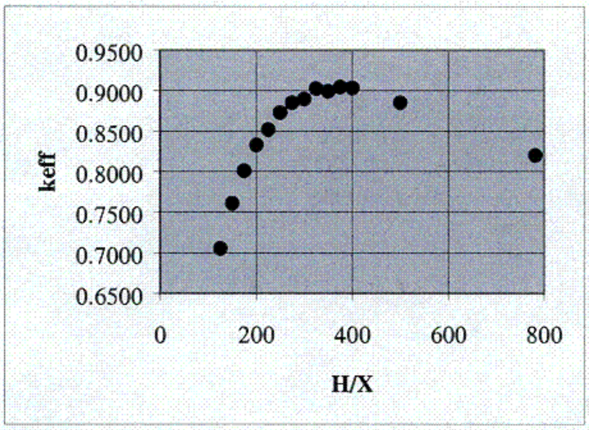

**Figure 6-22 Elevation view of IPB fuel compartment with other fuel compartment.**
*Compartment 1 with two group 3 and two group 4 canisters, Recall that in the model, the fissile mixture within an canister may occupy a height less than the height of the canister, depending on the H/U modeled. In contrast, the axial length and positioning of the fissile mixture in the IPB is fixed. Dimensions in cm.*



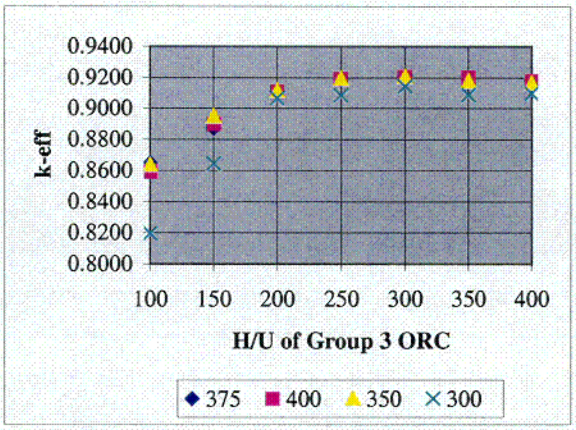

(a)




(b)




(c)




(d)

**Figure 6-23 System reactivity with H/X ratio**
*Loading Patterns 1 – 4, (a – d), respectively*



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## Table 6-33 Smaller Fissile Region Diameter Study - Loading Pattern 1

| Case | Radius (cm) | | $k_{eff}$ | σ | $k_{eff} + 2\sigma$ |
|---|---|---|---|---|---|
| | Group 1 ORC | Group 2 ORC | | | |
| **H/X=300** | | | | | |
| ORCL1-1 | 6.847 | 6.847 | 0.9108 | 0.0029 | 0.917 |
| ORCL1-60 | 6.50 | 6.63 | 0.8821 | 0.0024 | 0.887 |
| ORCL1-61 | 6.00 | 6.63 | 0.8578 | 0.0027 | 0.863 |
| ORCL1-62 | 5.50 | 6.63 | 0.8260 | 0.0028 | 0.832 |
| ORCL1-63 | 5.00 | 6.63 | 0.7993 | 0.0025 | 0.804 |
| ORCL1-64 | 4.50 | 6.63 | 0.7734 | 0.0027 | 0.779 |
| **H/X=250** | | | | | |
| ORCL1-11 | 6.847 | 6.847 | 0.9126 | 0.0027 | 0.918 |
| ORCL1-65 | 6.50 | 6.50 | 0.8815 | 0.0025 | 0.887 |
| ORCL1-66 | 6.00 | 6.06 | 0.8324 | 0.0028 | 0.838 |
| ORCL1-67 | 5.50 | 6.06 | 0.8021 | 0.0028 | 0.808 |
| ORCL1-68 | 5.00 | 6.06 | 0.7716 | 0.0025 | 0.777 |
| ORCL1-69 | 4.50 | 6.06 | 0.7388 | 0.0026 | 0.744 |
| ORCL1-70 | 4.07 | 6.06 | 0.7131 | 0.0026 | 0.718 |
| **H/X=200** | | | | | |
| ORCL1-2 | 6.847 | 6.847 | 0.9005 | 0.0029 | 0.906 |
| ORCL1-71 | 6.50 | 6.5 | 0.8660 | 0.0027 | 0.871 |
| ORCL1-72 | 6.00 | 6.0 | 0.8258 | 0.0032 | 0.832 |
| ORCL1-73 | 5.50 | 5.5 | 0.7707 | 0.0029 | 0.777 |
| ORCL1-74 | 5.00 | 5.5 | 0.742 | 0.0033 | 0.749 |
| ORCL1-75 | 4.50 | 5.5 | 0.7054 | 0.0027 | 0.711 |
| ORCL1-76 | 4.00 | 5.5 | 0.6665 | 0.0029 | 0.672 |
| ORCL1-77 | 3.64 | 5.5 | 0.6497 | 0.0027 | 0.655 |

Table 6-34 Fissile Region Diameter Study – Loading Pattern 2

| Case | Radius | | $k_{eff}$ | $\sigma$ | $k_{eff} + 2\sigma$ |
|---|---|---|---|---|---|
| | Group 1 | Group 5 | | | |
| **H/X=300** | | | | | |
| ORCL3-3 | 6.85 | 6.85 | 0.8962 | 0.0027 | 0.902 |
| ORCL3-60 | 6.50 | 6.50 | 0.8666 | 0.0027 | 0.872 |
| ORCL3-61 | 6.00 | 6.17 | 0.8208 | 0.0024 | 0.826 |
| ORCL3-62 | 5.50 | 6.17 | 0.7839 | 0.0024 | 0.789 |
| ORCL3-63 | 5.00 | 6.17 | 0.7506 | 0.0024 | 0.755 |
| ORCL3-64 | 4.50 | 6.17 | 0.7101 | 0.0023 | 0.715 |
| **H/X=250** | | | | | |
| ORCL3-5 | 6.85 | 6.85 | 0.8951 | 0.0034 | 0.902 |
| ORCL3-65 | 6.50 | 6.50 | 0.8673 | 0.0029 | 0.873 |
| ORCL3-66 | 6.00 | 6.00 | 0.8202 | 0.0027 | 0.826 |
| ORCL3-67 | 5.50 | 5.63 | 0.7656 | 0.0025 | 0.771 |
| ORCL3-68 | 5.00 | 5.63 | 0.7300 | 0.0022 | 0.734 |
| ORCL3-69 | 4.50 | 5.63 | 0.6914 | 0.0024 | 0.697 |
| ORCL3-70 | 4.07 | 5.63 | 0.6550 | 0.0025 | 0.660 |
| **H/X=200** | | | | | |
| ORCL3-7 | 6.85 | 6.85 | 0.8865 | 0.0030 | 0.893 |
| ORCL3-71 | 6.50 | 6.50 | 0.8567 | 0.0028 | 0.862 |
| ORCL3-72 | 6.00 | 6.00 | 0.8162 | 0.0025 | 0.8212 |
| ORCL3-73 | 5.50 | 5.50 | 0.7616 | 0.0028 | 0.7672 |
| ORCL3-74 | 5.00 | 5.04 | 0.7043 | 0.0026 | 0.7095 |
| ORCL3-75 | 4.50 | 5.04 | 0.6591 | 0.0022 | 0.6635 |
| ORCL3-76 | 4.07 | 5.04 | 0.6182 | 0.0023 | 0.6228 |

## Table 6-35 Smaller Fissile Region Diameter Study – Loading Pattern 3

| Case | Intact Peach Bottom H/X | Intact Peach Bottom Radius | Group 4 Canister H/X | $k_{eff}$ | $\sigma$ | $k_{eff} + 2\sigma$ | $\Delta\sigma$[8] |
|---|---|---|---|---|---|---|---|
| ORCL4-2 | 3507 | 6.847 | 350 | 0.8983 | 0.0029 | 0.904 | |
| ORCL4-11a | 2500 | 5.781 | | 0.9035 | 0.0026 | 0.909 | 1.8 |
| ORCL4-11b | 1500 | 4.479 | | 0.9026 | 0.0026 | 0.908 | 1.5 |
| ORCL4-11c | 300 | 2.007 | | 0.9030 | 0.0029 | 0.909 | 1.6 |
| ORCL4-11j | 200 | 1.640 | | 0.9033 | 0.0028 | 0.909 | 1.7 |
| ORCL4-11k | 100 | 1.164 | | 0.9014 | 0.0027 | 0.907 | 1.1 |
| ORCL4-3 | 3507 | 6.847 | 300 | 0.8895 | 0.0031 | 0.896 | |
| ORCL4-11d | 2500 | 5.781 | | 0.8952 | 0.0028 | 0.901 | 1.8 |
| ORCL4-11e | 1500 | 4.479 | | 0.8931 | 0.0026 | 0.898 | 1.2 |
| ORCL4-11f | 300 | 2.007 | | 0.8911 | 0.0032 | 0.898 | 0.5 |
| ORCL4-11l | 200 | 1.640 | | 0.8963 | 0.0029 | 0.902 | 2.2 |
| ORCL4-11m | 100 | 1.164 | | 0.8901 | 0.0027 | 0.896 | 0.2 |
| ORCL4-4 | 3507 | 6.847 | 275 | 0.8841 | 0.0027 | 0.890 | |
| ORCL4-11g | 2500 | 5.781 | | 0.8818 | 0.0027 | 0.887 | -0.9 |
| ORCL4-11h | 1500 | 4.479 | | 0.8874 | 0.0028 | 0.893 | 1.2 |
| ORCL4-11n | 200 | 1.640 | | 0.8856 | 0.0028 | 0.891 | 0.6 |
| ORCL4-11o | 100 | 1.164 | | 0.8879 | 0.0030 | 0.894 | 1.4 |
| ORCL4-11i | 300 | 2.007 | | 0.8821 | 0.0025 | 0.887 | -0.7 |

[8] This column is the difference between the calculated value of $k_{eff}$ for the radius indicated and that calculated at the full radius of 6.847 cm, divided by the standard deviation. In all cases the differences are less than 2 standard deviations, which demonstrates that the results are statistically indistinguishable.

## Table 6-36 Smaller Fissile Region Diameter Study –Loading Pattern 4

| Case | Radius | | $k_{eff}$ | $\sigma$ | $k_{eff} + 2\sigma$ |
|---|---|---|---|---|---|
| | Top Group 3 Canister | Group 4 Canister Above IPB | | | |
| **H/X=400** | | | | | |
| ORCL5-6 | 6.85 | 6.85 | 0.9290 | 0.0028 | 0.935 |
| ORCL5-6a | 6.50 | 6.50 | 0.8942 | 0.0027 | 0.900 |
| ORCL5-6b | 6.00 | 6.00 | 0.8440 | 0.0024 | 0.849 |
| ORCL5-6c | 5.82 | 5.50 | 0.7943 | 0.0024 | 0.799 |
| ORCL5-6d | 5.82 | 4.91 | 0.7498 | 0.0024 | 0.755 |
| **H/X=350** | | | | | |
| ORCL5-7 | 6.85 | 6.85 | 0.9018 | 0.0025 | 0.907 |
| ORCL5-7a | 6.50 | 6.50 | 0.8784 | 0.0026 | 0.884 |
| ORCL5-7b | 6.00 | 6.00 | 0.8235 | 0.0028 | 0.829 |
| ORCL5-7c | 5.50 | 5.50 | 0.7581 | 0.0028 | 0.764 |
| ORCL5-7d | 5.44 | 5.00 | 0.7238 | 0.0026 | 0.729 |
| ORCL5-7e | 5.44 | 4.59 | 0.6843 | 0.0024 | 0.689 |
| **H/X=300** | | | | | |
| ORCL5-8 | 6.85 | 6.85 | 0.8878 | 0.0024 | 0.893 |
| ORCL5-8a | 6.50 | 6.50 | 0.8607 | 0.0025 | 0.866 |
| ORCL5-8b | 6.00 | 6.00 | 0.8150 | 0.0027 | 0.820 |
| ORCL5-8c | 5.50 | 5.50 | 0.7572 | 0.0026 | 0.762 |
| ORCL5-8d | 5.04 | 5.00 | 0.6906 | 0.0025 | 0.696 |
| ORCL5-8e | 5.04 | 4.50 | 0.6918 | 0.0031 | 0.698 |
| ORCL5-8f | 5.04 | 4.25 | 0.6888 | 0.0027 | 0.694 |

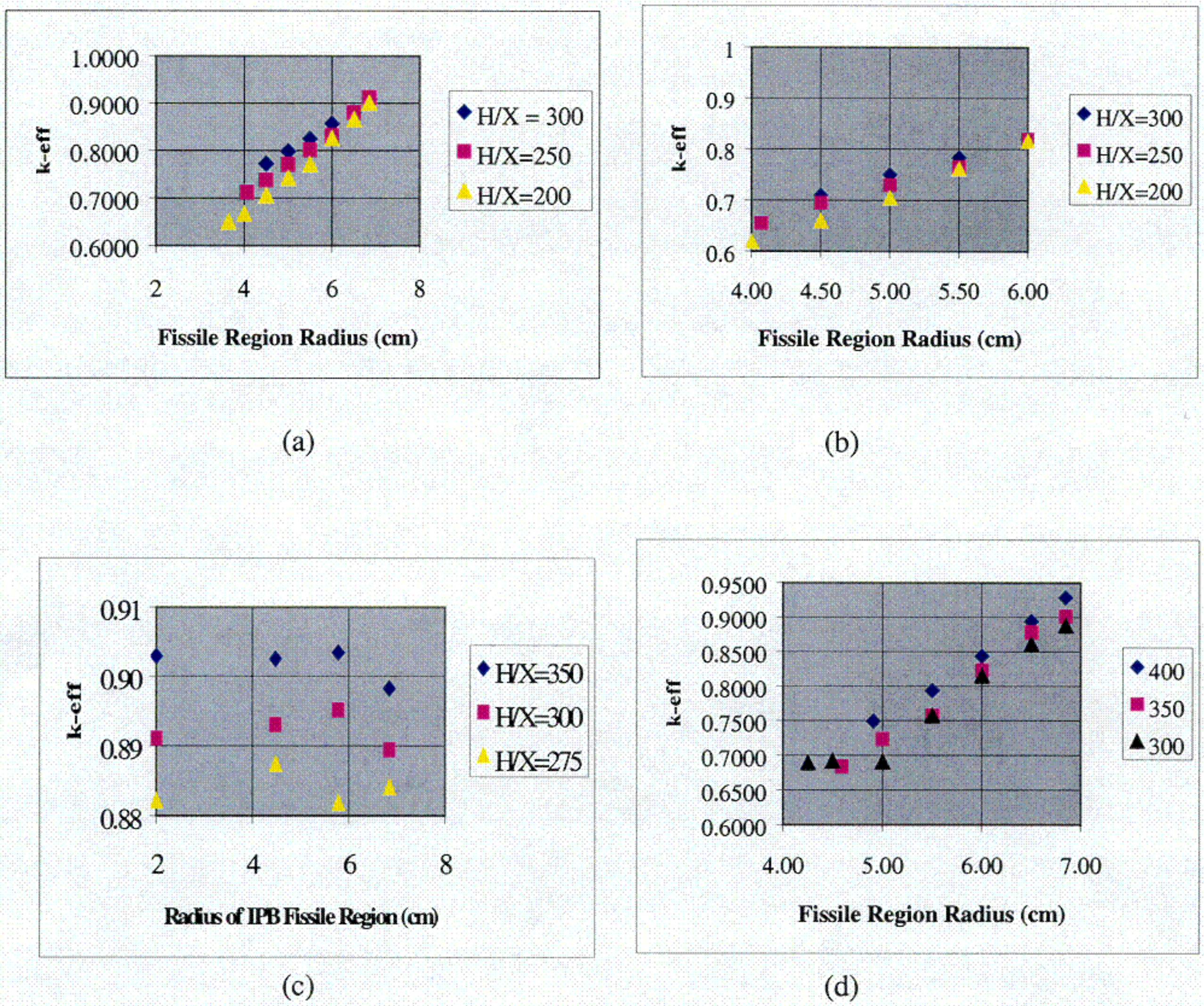


**Figure 6-24 System reactivity with reduced fissile region diameter.**
*Loading Patterns 1 – 4 in (a – d), respectively. Note: the H/X ratios in (c) are for the group 4 ORC.*



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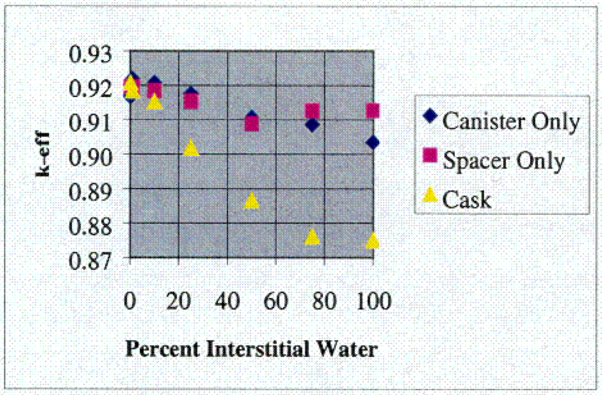
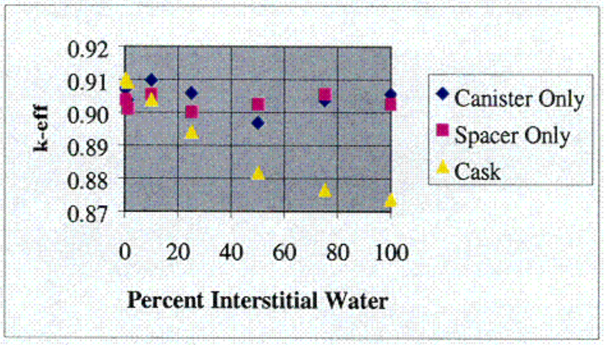
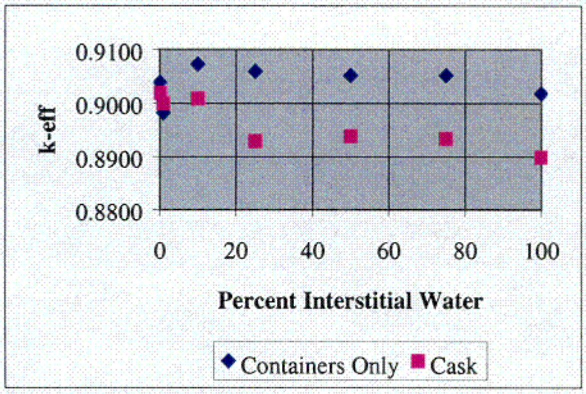


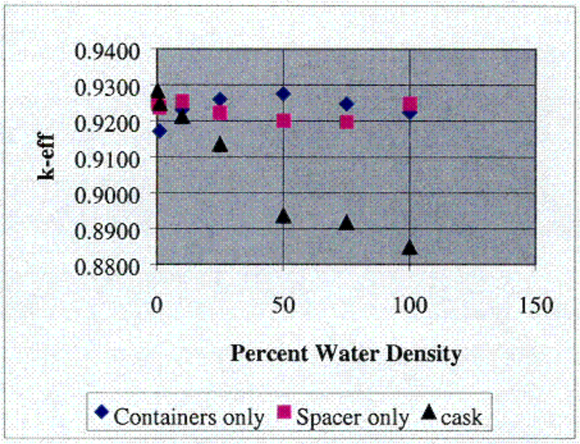

(a)




(b)




(c)

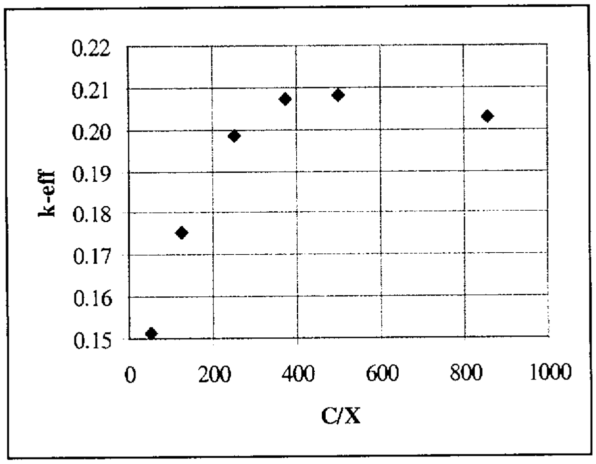



(d)

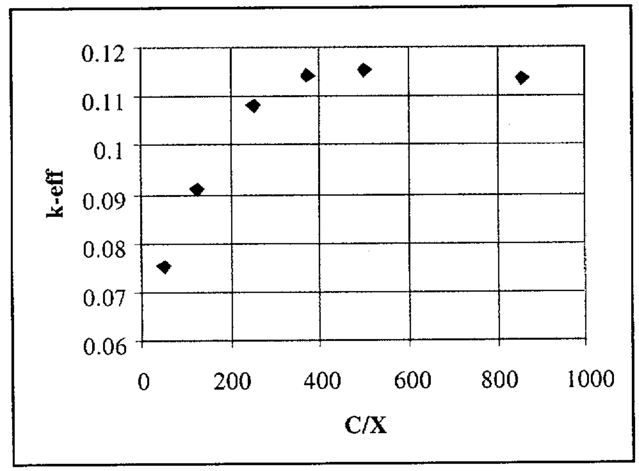
**Figure 6-25 System reactivity with interstitial water concentration.**
*Three data sets are presented on each graph. The first is for water flooding of only the space in the canister not filled by the fissile mixture. The second is for water flooding of only the hollow regions of the flux trap spacer. The final set is for water flooding of the entire cask except the hollow regions of the spacer and the void region of the canisters. Data are shown for Loading Patterns 1 – 4 in (a – d), respectively.*



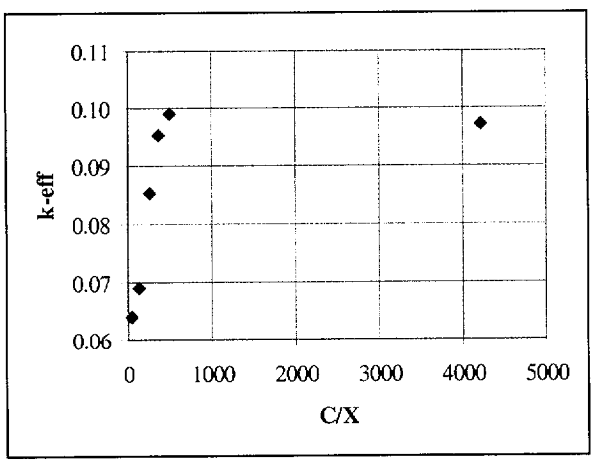
C07



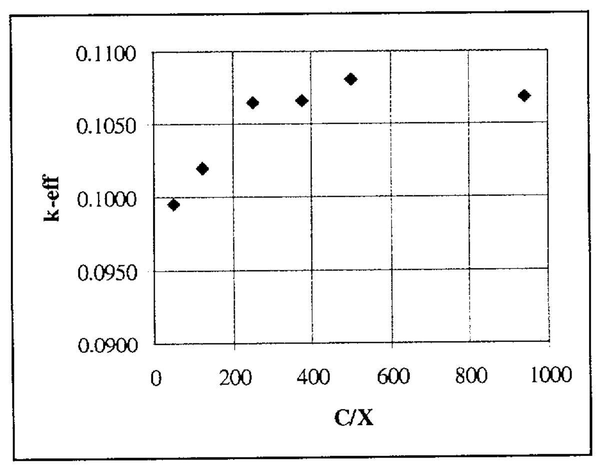

(a)




(b)




(c)




(d)

**Figure 6-26 System reactivity with C/X ratio for an infinite array.**
*Normal condition casks. For the NCT array, the casks are assumed to be dry, so fuel moderation is only from the carbon present in HTGR assemblies. Data are shown for Loading Patterns 1 – 4 in (a – d), respectively.*

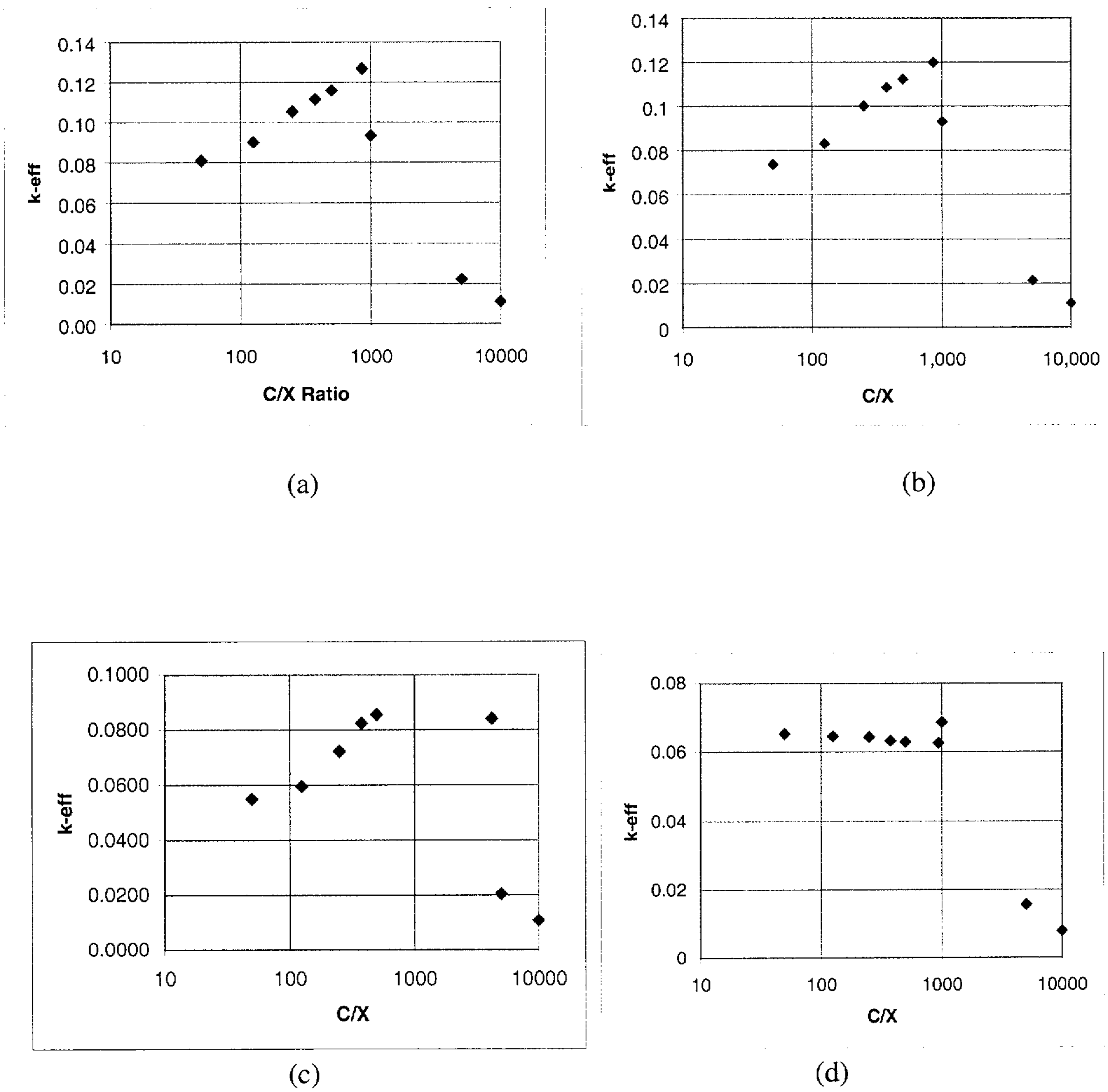



**Figure 6-27 System reactivity with C/X ratio for a dry cask with no axial spacers.**
*Tthe casks are assumed to be dry, so fuel moderation is only from the carbon present in HTGR assemblies. Data are shown for Loading Patterns 1 – 4 in (a – d), respectively.*

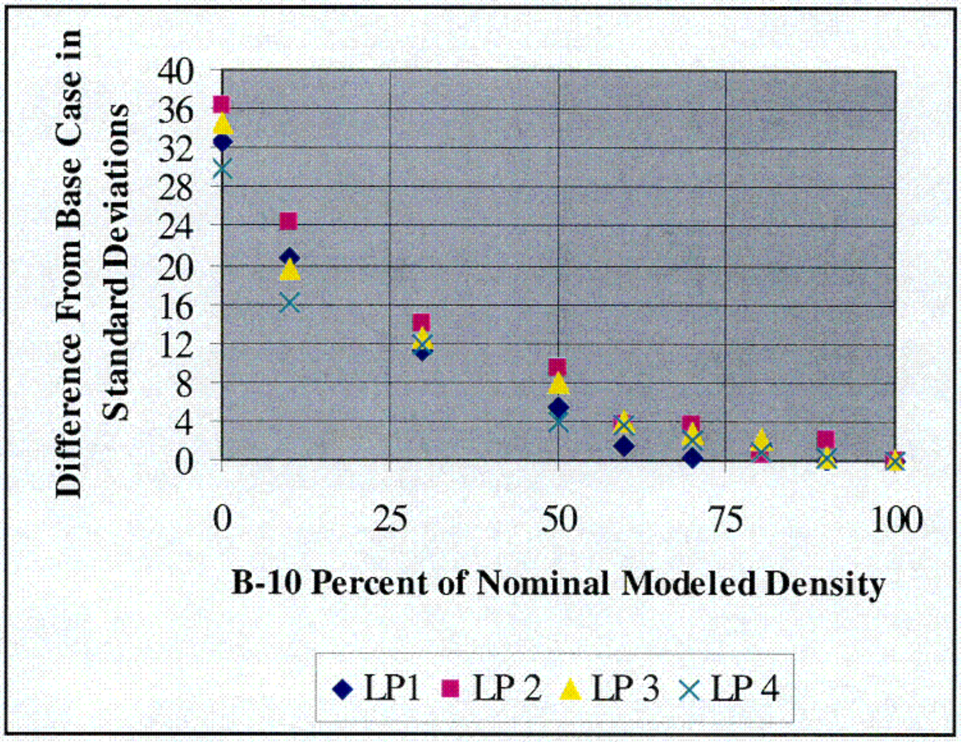



**Figure 6-28 Reactivity vs boron concentration in the poison plates.**
*Posion plates in both the enclosures and the axial spacers is decreased, as measured in the number of standard deviations from the base case.*



C08

## Table 6-37 Sensitivity Studies - Loading Pattern 1

| Description | Case | $k_{eff}$ | σ | $\frac{\sigma-\sigma_{base}}{\sigma}$ |
|---|---|---|---|---|
| **Base Case** | ORCL1-1a | 0.9209 | 0.0028 | - |
| **Poison Enclosure Steel** | | | | |
| Thickness=+10% | ORCL1-80 | 0.9204 | 0.0026 | -0.2 |
| Thickness=+0.01 in. | ORCL1-80a | 0.9241 | 0.0026 | 1.1 |
| Thickness=-10% | ORCL1-81 | 0.9218 | 0.0028 | 0.3 |
| Thickness=0 | ORCL1-81a | 0.9096 | 0.0031 | -4.0 |
| **Inner and Outer Steel Shells** | | | | |
| Thickness=+10% | ORCL1-82 | 0.9223 | 0.0006 | 0.5 |
| Thickness=-10% | ORCL1-83 | 0.9147 | 0.0031 | -2.2 |
| **Lead Shield** | | | | |
| Thickness=+10% | ORCL1-84 | 0.9170 | 0.0029 | -1.4 |
| Thickness=-10% | ORCL1-85 | 0.9152 | 0.0032 | -2.0 |
| **B-10 in Poison Enclosures and Axial Spacers** | | | | |
| Density=90% | ORCL1-86 | 0.9207 | 0.0032 | -0.1 |
| Density =80% | ORCL1-87 | 0.9248 | 0.0030 | 1.4 |
| Density =70% | ORCL1-88 | 0.9215 | 0.0026 | 0.2 |
| Density =60% | ORCL1-89 | 0.9250 | 0.0026 | 1.5 |
| Density =50% | ORCL1-89a | 0.9362 | 0.0027 | 5.5 |
| Density =30% | ORCL1-89b | 0.9524 | 0.0025 | 11.3 |
| Density =10% | ORCL1-89c | 0.9794 | 0.0025 | 20.9 |
| Density =0 | ORCL1-89d | 1.0125 | 0.0027 | 32.7 |
| Thickness=-10% | ORCL1-89ee | 0.9207 | 0.0027 | -0.1 |
| Thickness =-20% | ORCL1-89ff | 0.9187 | 0.0028 | -0.8 |
| Thickness =-30% | ORCL1-89gg | 0.9261 | 0.0027 | 1.9 |
| **Fuel at top and bottom of adjacent canisters** | ORCL1-1aa | 0.9206 | 0.0028 | -0.1 |
| **Fissile Plutonium Modeled as Pu-241** | ORCL1-200 | 0.885 | 0.0028 | -10.8 |

## Table 6-38 Sensitivity Studies - Loading Pattern 2

| Description | Case | $k_{eff}$ | σ | $\frac{\sigma-\sigma_{base}}{\sigma}$ |
|---|---|---|---|---|
| **Base Case** | ORCL3-3b | 0.9068 | 0.0026 | - |
| **Poison Enclosure Steel** | | | | |
| Thickness=+10% | ORCL3-80 | 0.9049 | 0.003 | -0.7 |
| Thickness=+0.01 in. | ORCL3-80a | 0.9052 | 0.0029 | -0.6 |
| Thickness=-10% | ORCL3-81 | 0.9125 | 0.01 | 2.2 |
| Thickness=0 | ORCL3-81a | 0.8973 | 0.005 | -3.7 |
| **Inner and Outer Steel Shells** | | | | |
| Thickness=+10% | ORCL3-82 | 0.9065 | 0.0025 | -0.1 |
| Thickness=-10% | ORCL3-83 | 0.9051 | 0.0025 | -0.7 |
| **Lead Shield** | | | | |
| Thickness=+10% | ORCL3-84 | 0.9083 | 0.0024 | 0.6 |
| Thickness=-10% | ORCL3-85 | 0.9019 | 0.0028 | -1.9 |
| **B-10 in Poison Enclosures and Axial Spacers** | | | | |
| Density=90% | ORCL3-86 | 0.9127 | 0.0028 | 2.3 |
| Density =80% | ORCL3-87 | 0.9082 | 0.0028 | 0.5 |
| Density =70% | ORCL3-88 | 0.9165 | 0.0027 | 3.7 |
| Density =60% | ORCL3-89 | 0.9163 | 0.0024 | 3.7 |
| Density =50% | ORCL3-89a | 0.9314 | 0.0028 | 9.5 |
| Density =30% | ORCL3-89b | 0.9435 | 0.0026 | 14.1 |
| Density =10% | ORCL3-89c | 0.9702 | 0.0025 | 24.4 |
| Density =0 | ORCL3-89d | 1.0009 | 0.0027 | 36.2 |
| Thickness=-10% | ORCL3-89e | 0.9056 | 0.0027 | -0.5 |
| Thickness =-20% | ORCL3-89f | 0.9166 | 0.0027 | 3.8 |
| Thickness =-30% | ORCL3-89g | 0.927 | 0.0027 | 7.8 |
| **Fuel at top and bottom of adjacent canisters** | ORCL3-3bb | 0.9168 | 0.0027 | 3.8 |

## Table 6-39 Sensitivity Studies - Loading Pattern 3

| Description | Case | $k_{eff}$ | $\sigma$ | $\frac{\sigma - \sigma_{base}}{\sigma}$ |
|---|---|---|---|---|
| **Base Case** | ORCL4-1c | 0.9044 | 0.0027 | - |
| **Poison Enclosure Steel** | | | | |
| Thickness=+10% | ORCL4-80 | 0.9053 | 0.0027 | 0.3 |
| Thickness=+0.01 in. | ORCL4-80a | 0.9038 | 0.0029 | -0.2 |
| Thickness=-10% | ORCL4-81 | 0.8997 | 0.0027 | -1.7 |
| Thickness=0 | ORCL4-81a | 0.894 | 0.0026 | -3.9 |
| **Inner and Outer Steel Shells** | | | | |
| Thickness=+10% | ORCL4-82 | 0.9027 | 0.0026 | -0.6 |
| Thickness=-10% | ORCL4-83 | 0.8989 | 0.0024 | -2.0 |
| **Lead Shield** | | | | |
| Thickness=+10% | ORCL4-84 | 0.9064 | 0.0025 | 0.7 |
| Thickness=-10% | ORCL4-85 | 0.8989 | 0.0026 | -2.0 |
| **B-10 in Poison Enclosures and Axial Spacers** | | | | |
| Density=90% | ORCL4-86 | 0.9054 | 0.0027 | 0.4 |
| Density =80% | ORCL4-87 | 0.9099 | 0.0024 | 2.0 |
| Density =70% | ORCL4-88 | 0.9115 | 0.0025 | 2.6 |
| Density =60% | ORCL4-89 | 0.9148 | 0.0025 | 3.9 |
| Density =50% | ORCL4-89a | 0.9255 | 0.0026 | 7.8 |
| Density =30% | ORCL4-89b | 0.9380 | 0.0024 | 12.4 |
| Density =10% | ORCL4-89c | 0.9573 | 0.0025 | 19.6 |
| Density =0 | ORCL4-89d | 0.9972 | 0.0026 | 34.4 |
| Thickness=-10% | ORCL4-89e | 0.8991 | 0.0024 | -2.0 |
| Thickness =-20% | ORCL4-89f | 0.9059 | 0.0027 | 0.6 |
| Thickness =-30% | ORCL4-89g | 0.9158 | 0.0024 | 4.2 |
| **Fissile Plutonium Modeled as Pu-241** | ORCL4-200 | 0.7922 | 0.0023 | -39.9 |

## Table 6-40 Sensitivity Studies - Loading Pattern 4

| Description | Case | $k_{eff}$ | σ | $\frac{\sigma-\sigma_{base}}{\sigma}$ |
|---|---|---|---|---|
| **Base Case** | ORCL5-5 | 0.9261 | 0.0027 | - |
| **Poison Enclosure Steel** | | | | |
| Thickness=+10% | ORCL5-80 | 0.9231 | 0.0029 | -1.1 |
| Thickness=+0.01 in. | ORCL5-80a | 0.9249 | 0.0028 | -0.4 |
| Thickness=-10% | ORCL5-81 | 0.9211 | 0.0034 | -1.9 |
| Thickness=0 | ORCL5-81a | 0.9179 | 0.0027 | -3.0 |
| **Inner and Outer Steel Shells** | | | | |
| Thickness=+10% | ORCL5-82 | 0.9276 | 0.0028 | 0.6 |
| Thickness=-10% | ORCL5-83 | 0.9219 | 0.0028 | -1.6 |
| **Lead Shield** | | | | |
| Thickness=+10% | ORCL5-84 | 0.9268 | 0.0030 | 0.3 |
| Thickness=-10% | ORCL5-85 | 0.9187 | 0.0028 | -2.7 |
| **B-10 in Poison Enclosures and Axial Spacers** | | | | |
| Density=90% | ORCL5-86 | 0.9240 | 0.0026 | -0.8 |
| Density =80% | ORCL5-87 | 0.9312 | 0.0025 | 1.9 |
| Density =70% | ORCL5-88 | 0.9375 | 0.0027 | 4.2 |
| Density =60% | ORCL5-89 | 0.9398 | 0.0024 | 5.1 |
| Density =50% | ORCL5-89a | 0.9422 | 0.0031 | 6.0 |
| Density =30% | ORCL5-89b | 0.9602 | 0.0026 | 12.6 |
| Density =10% | ORCL5-89c | 0.9867 | 0.0025 | 22.4 |
| Density =0 | ORCL5-89d | 1.0241 | 0.0024 | 36.3 |
| Thickness=-10% | ORCL5-89ee | 0.9258 | 0.0026 | -0.1 |
| Thickness =-20% | ORCL5-89ff | 0.9263 | 0.0027 | 0.1 |
| Thickness =-30% | ORCL5-89gg | 0.9282 | 0.0027 | 0.8 |
| **Fissile Plutonium Modeled as Pu-241** | ORCL5-200 | 0.7963 | 0.022 | -48.1 |

## 6.5 Critical Benchmark Experiments

Validation of the SCALE 27-group cross section set used in conjunction with the CSAS6 calculational sequence has been performed by modeling appropriate benchmark experiments. All benchmark experiments were taken from the International Handbook of Evaluated Criticality Benchmark Experiments[5]. This source was chosen because: (1) All experiments in the Handbook have been thoroughly evaluated, using current criteria and standards, with extensive peer review; and (2) The Handbook includes a large number of quality benchmark experiments performed both in the U.S. and internationally, including numerous Russian experiments conducted with various configurations of boron-containing poison rods. The validation cases were run on the same computer that the criticality calculations were run on.

### 6.5.1 Benchmark Experiments and Applicability

Benchmark experiments with features similar to those in the cask model are chosen. The important parameters of the cask model that need to be covered by the benchmark experiments include highly enriched uranium and mixed uranium/plutonium solution systems, arrays of fissile cylinders, and natural boron poison plates. The ideal situation would be to model benchmark experiments that utilized the exact geometry and materials of the cask model. Of course, if such experiments existed, calculations wouldn't be necessary. Therefore, numerous benchmark experiments, each of which models one or more of the important parameters of the cask model, are selected. These experiments can be broadly divided into four groups: highly enriched uranium systems in simple geometry, arrays of cylinders containing HEU solution, cylinders of HEU solution with $B_4C$ poison rods, mixed uranium/plutonium systems in simple cylindrical geometry, and mixed uranium/plutonium systems in annular geometry, with a boron-poisoned concrete insert. These experiments test all of the important parameters of the cask that influence criticality safety, and therefore form a comprehensive validation for the system. A brief discussion of the various experiments is provided in Section 6.5.2 and in the tables of Section 6.5.3.

### 6.5.2 Details of Benchmark Calculations

A brief description of the benchmark experiments is given in this section. The purpose of this section is to demonstrate to the reader that the benchmark experiments chosen are appropriate and sufficient. Further details for each experiment are readily available in Reference 5.

#### 6.5.2.1 Uranium Solution Systems

The experiments modeled can be divided into three groups: (1) isolated cylinders or spheres of uranium oxyfluoride; (2) arrays of cylinders of uranyl nitrate; and (3) isolated cylinders of uranyl nitrate with boron carbide poison rods.

Simple Spheres and Cylinders of Uranium Solution

The sphere experiments are identified in Reference 5 as HEU-SOL-THERM-009, -010, -011, -012, and –013. All of these experiments were performed at the Oak Ridge National Laboratory in the 1950's. The experiments utilize spheres of differing sizes (6.4, 9.7, 17, 91, and 174 liters). All of the spheres except the largest were reflected with an effectively infinite thickness of water. Four different critical states were reported for the 6.4-liter, 9.7-liter, and 174-liter spheres. These different critical states were achieved by varying solution density, solution temperature, or (in the case of the 174-liter sphere) boric acid concentration. A single critical state is reported for the 91-liter sphere, and two different measurements of essentially the same critical state for the 17-liter sphere. These 15 sphere experiments span a wide range of uranium concentrations (20.12 to 699 g/L) and H/U values (36 to 1375).

A group of experiments using unreflected cylinders of uranyl nitrate was also performed at the Oak Ridge National Laboratory. These experiments are referred to in Reference 5 as HEU-SOL-THERM-001. These 10 experiments utilized uranyl nitrate solutions with uranium concentration varying from 54.89 to 357.7 g/L, H/U ratios from 64 to 466, and height to diameter ratios from 0.4 to 1.2. Together with the sphere experiments discussed in the previous paragraph, these 10 cylinder experiments provide a good basis for a generalized uranium solution validation.

Arrays of Uranium Solution Cylinders

Two sets of experiments represent this group. They are identified in Reference 5 as HEU-SOL-THERM-007 and –008. The first set includes 17 experiments performed at the Rocky Flats Plant in the 1970's. Aluminum cylinders on a 12-inch lattice pitch were arranged in 4 x 4, 2 x 2, 2 x 3, and 2 x 4 planar arrays. The array was reflected on all sides, top, and bottom by approximately 10 in. of concrete. Uranyl nitrate solution was introduced into the array via ½-inch pipes connected to the bottom of each cylinder. Uranium concentration was varied from 67 to 370 g/L, and the H/U values ranged from 65 to 406. For a particular array size and uranium concentration, the critical state was achieved by adding fissile solution until the critical height was determined. The height to diameter ratios for the critical systems range from 0.8 to 6.5.

The second experiment set (HEU-SOL-THERM-008) includes an additional 14 experiments performed at the Rocky Flats Plant using the same array. The difference with this set is that the reflector is Plexiglas, approximately 8 in. in thickness. For this set of experiments, the uranium concentration was 60 or 356 g/L, and the H/U values were 69 or 454. The height to diameter ratio of the cylinders in the resulting critical configurations varied from 0.9 to 5.2.

Combined, these two experiment sets make a total of 31 benchmark experiments that test the ability of the code/cross section set to properly model interacting moderated elements in arrays, as well as reflection of those arrays.

Isolated Cylinders with $B_4C$ Poison Rods

The experiments in this set are identified in Reference 5 as HEU-SOL-THERM-027, -028, -029. –030, -031, -035, and -036. All of these experiments were performed in Russia in the 1960's.

The fissile material in all of these experiments was uranyl nitrate enriched to approximately 89% $^{235}U$. Although the details varied widely, the general concept for all of these experiments was as follows. One or more boron carbide poison rods was inserted into large cylindrical or square tanks. Uranyl nitrate solution was then added to the tank until the critical height was determined. The tanks were either bare or water-reflected. The poison rods were stainless steel tubes filled with boron carbide powder at a density of 1.25 g/cm$^3$. A number of different rod sizes were used, with inner diameters of 1.4, 1.7, 2.6, 2.7, 4.5, and 5.0 cm. A large variety of rod configurations were investigated, including a single rod in the center of the tank, 3, 4, and 6 rod configurations, and configurations with very large numbers of rods (up to 451) in both square and hexagonal lattices. The uranium concentration in these experiments was between 37.5 and 289 g/L, and the H/U ratios varied between 91 and 767. The height to diameter ratios for the critical states varied between 0.08 and 3.3. This extensive experimental set includes 54 experiments that thoroughly test the code/cross section capability to properly model the effects of solid boron poison elements on the reactivity of thermal uranium solution systems.

### 6.5.2.2 Mixed Uranium/Plutonium Solution Systems

These experiments utilize a solution meant to mimic that from a reprocessing facility preparing MOX fuel for commercial applications. The uranium therefore is enriched to light water reactor levels, and the plutonium includes 239, 240, 241, and 242. These experiments were performed at Pacific Northwest Laboratory in the 1980's as part of a collaborative effort between DOE and the Power Reactor and Nuclear Fuel Development Corporation (PNC) of Japan.

#### Simple Cylindrical Systems

The experiments in this category are referred to in Reference 5 as MIX-SOL-THERM-002 and – 004. The former reports three experiments performed in "large" cylindrical geometry: a tank with diameter 68.68-cm. The tank was reflected by water. Both the plutonium and uranium concentration were relatively low, approximately 12 g/L. MIX-SOL-THERM-004 reports experiments performed in "small" cylindrical geometry: a 39.39-cm tank. The tank had either no reflector or a water reflector. The plutonium concentration in these experiments varied from approximately 40 to 173 g/L.

#### Annular Systems

These experiments were more complicated than those reported in the previous subsection, in that they utilized an annular tank with an annular concrete insert. The insert was concrete poisoned to differing levels with $B_4C$. In some cases, a partially filled bottle was placed inside the concrete insert, creating a two-region system. These two fissile volumes were not connected, and in fact they contained differing fissile solutions, and were filled to differing heights at the critical state. These experiments therefore demonstrate the ability of the code/cross section set to model mixed uranium/plutonium thermal solution systems, the ability to handle interaction between regions, and the ability to account for a poison material placed between those systems. Therefore, this set by itself covers many of the important parameters for the cask system.

## 6.5.3 Results of Benchmark Calculations

The benchmark calculations were run on the same computer used for the criticality calculations. The results of the benchmark calculations are presented in Tables 6-41 through 6-57. All KENO VI results were compared to those reported in the Handbook from KENO V.a calculations, and the two results were found to be within two standard deviations in all cases. This adds confidence that the KENO VI input files were set up correctly.

An Upper Subcritical Limit (USL) has been determined by combining all 118 benchmark experiments, calculating a confidence band, and applying an administrative margin. The Upper Subcritical Limit provides a high degree of confidence that a given system is subcritical if a criticality calculation based on the system yields a multiplication factor below the USL. The USLSTATS computer program(6) was used for the calculation. This program calculates the USL using two different approaches. The first approach is to find a confidence band with the desired confidence of fit, and then apply an administrative margin. The second approach is to find a single-sided uniform-width closed-interval tolerance level. In this second approach, the margin is calculated as a statistical parameter, and is almost always less than the 5% value generally used for an administrative margin. For this reason, the first approach is almost always more conservative. It is the approach used here to set the USL.

The independent parameter to which the $k_{eff}$ values were matched is the Average Energy Group causing fission, or AEG. This parameter is widely used because it is intricately linked to the neutron energy spectrum, and is affected by both moderation and reflection conditions (as opposed to the H/U ratio, for instance, which is linked only to the moderation level).

The following statistical parameters were selected for the input:

Proportion of population falling above lower tolerance level: 0.995
Confidence on that proportion: 0.95
Confidence on linear regression fit: 0.95
Administrative margin: 0.05

The results of the ULSTATS calculation are:

$\chi$ = 0.9839 (upper limit is 9.49). This result demonstrates that the data does in fact constitute a normal distribution, which is necessary for the statistical analysis to be applicable.

USL = 0.9417 (20.73 <= AEG <= 24.98)

The minimum margin of subcriticality is 0.0097, far less than the 0.05 administrative margin used.

The results of the validation calculations and the ULSTATS analysis are plotted in Figure 6-29. Only one of the 118 calculational results fall below the lower confidence band. Over its range, the data is well distributed between the upper and lower bounds of the confidence interval.

Based on these results, an Upper Subcritical Limit of 0.942 is established for the cask calculations in this chapter. This USL is based on a 95% confidence interval with a 5% administrative margin, and is adequate to establish high confidence that any system falling within the area of applicability of the validation and which yields a calculated value of $k_{eff}$ below this USL is in fact subcritical.

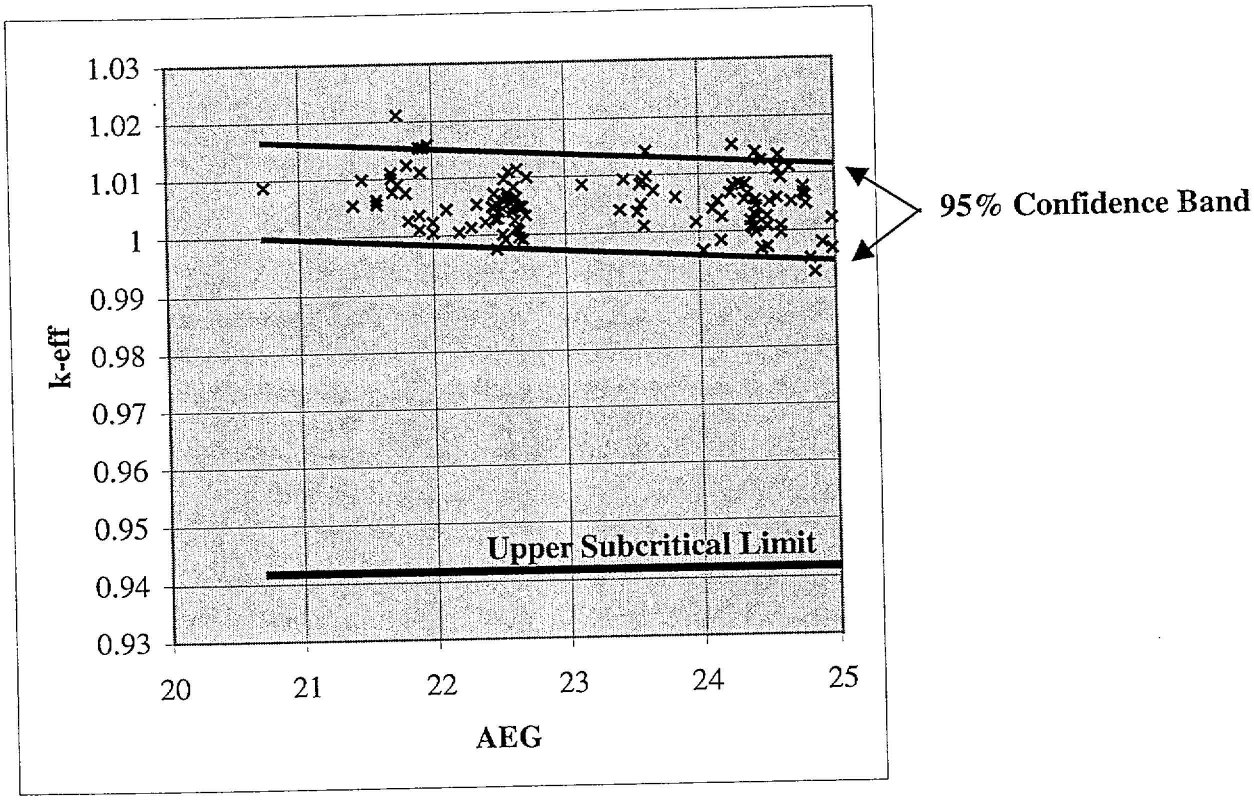



**Figure 6-29 Plot of results of all 118 validation calculations,**
*with the 95% confidence band and the Upper Subcritical Limit identified.*

## Table 6-41 Experiments HEU-SOL-THERM-001
**Unreflected Single Cylinders of Highly Enriched Uranyl Nitrate**

| Case | U (g/L) | Excess $HNO_3$ (mols/L) | Soln Height (cm) | Tank Diameter (cm) | H/U | h/D | $k_{eff}$ | σ | AEG |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 145.68 | 0.294 | 31.2 | 27.92 | 169 | 1.1 | 1.0049 | 0.0021 | 23.57 |
| 2 | 346.73 | 0.542 | 28.93 | 27.92 | 66 | 1.0 | 0.9970 | 0.0021 | 24.46 |
| 3 | 142.92 | 0.283 | 33.55 | 28.01 | 173 | 1.2 | 1.0141 | 0.0022 | 23.61 |
| 4 | 357.71 | 0.549 | 30.91 | 28.01 | 64 | 1.1 | 1.0056 | 0.0023 | 21.58 |
| 5 | 54.89 | 0.105 | 39.48 | 33.01 | 466 | 1.2 | 1.0058 | 0.0022 | 24.57 |
| 6 | 59.65 | 0.114 | 36.67 | 33.01 | 428 | 1.1 | 1.0051 | 0.0019 | 24.52 |
| 7 | 137.4 | 0.287 | 23.96 | 33.01 | 180 | 0.7 | 1.0073 | 0.0012 | 23.66 |
| 8 | 145.68 | 0.294 | 23.67 | 33.01 | 169 | 0.7 | 1.0089 | 0.0021 | 23.58 |
| 9 | 357.71 | 0.549 | 22.53 | 33.01 | 64 | 0.7 | 1.0064 | 0.0019 | 21.58 |
| 10 | 63.95 | 0.111 | 20.48 | 50.69 | 398 | 0.4 | 1.0100 | 0.0022 | 21.69 |

## Table 6-42 Experiments HEU-SOL-THERM-007
## Planar Arrays of Uranyl Nitrate Cylinders Reflected By Concrete

| Case | U (g/L) | Array Size | Soln Height (cm) | Soln Diameter (cm) | H/U | h/D | $k_{eff}$ | σ | AEG |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 67.28 | 4 x 4 | 28.63 | 21.12 | 406 | 1.4 | 1.0138 | 0.0012 | 24.42 |
| 2 | 369.96 | 4 x 4 | 17.24 | 21.12 | 65 | 0.8 | 1.0211 | 0.0015 | 21.74 |
| 3 | 67.28 | 4 x 4 | 27.15 | 21.12 | 406 | 1.3 | 1.0124 | 0.0014 | 24.46 |
| 4 | 364.11 | 4 x 4 | 17.13 | 21.12 | 67 | 0.8 | 1.0153 | 0.0016 | 21.93 |
| 5 | 76.09 | 2 x 2 | 60.7 | 21.12 | 358 | 2.9 | 1.0056 | 0.0012 | 24.33 |
| 6 | 360.37 | 2 x 2 | 29.49 | 21.12 | 67 | 1.4 | 1.0077 | 0.0017 | 21.70 |
| 7 | 76.09 | 2 x 2 | 62.34 | 21.12 | 358 | 3.0 | | | |
| 8 | 364.11 | 2 x 2 | 31.11 | 21.12 | 67 | 1.5 | 1.0090 | 0.0016 | 21.74 |
| 9 | 80.72 | 2 x 2 | 57.88 | 21.12 | 337 | 2.7 | 1.0083 | 0.0016 | 24.30 |
| 10 | 83.49 | 4 x 4 | 57.34 | 16.12 | 325 | 3.6 | 1.0150 | 0.0014 | 24.25 |
| 11 | 360.37 | 4 x 4 | 32.32 | 16.12 | 67 | 2.0 | 1.0124 | 0.0015 | 21.81 |
| 12 | 83.49 | 4 x 4 | 51.21 | 16.12 | 325 | 3.2 | | | |
| 13 | 359.55 | 4 x 4 | 31.82 | 16.12 | 68 | 2.0 | 1.0158 | 0.0015 | 21.97 |
| 14 | 359.55 | 2 x 4 | 51.45 | 16.12 | 68 | 3.2 | 1.0112 | 0.0014 | 21.91 |
| 15 | 359.55 | 2 x 3 | 65.49 | 16.12 | 68 | 4.1 | 1.0153 | 0.0014 | 21.90 |
| 16 | 359.55 | 2 x 2 | 101.45 | 16.12 | 68 | 6.3 | | | |
| 17 | 359.55 | 2 x 2 | 104.04 | 16.12 | 68 | 6.5 | | | |

## Table 6-43 Experiments HEU-SOL-THERM-008
## Planar Arrays of Uranyl Nitrate Cylinders Reflected By Plexiglass

| Case | U (g/L) | Array Size | Soln Height (cm) | Soln Diameter (cm) | H/U | h/D | $k_{eff}$ | σ | AEG |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 60.32 | 4 x 4 | 34.82 | 21.12 | 454 | 1.6 | 0.9973 | 0.0014 | 2.45E+01 |
| 2 | 355.94 | 4 x 4 | 19.27 | 21.12 | 69 | 0.9 | 1.0012 | 0.0014 | 2.19E+01 |
| 3 | 60.32 | 4 x 4 | 31.76 | 21.12 | 454 | 1.5 | 1.0009 | 0.0013 | 2.46E+01 |
| 4 | 355.94 | 4 x 4 | 18.82 | 21.12 | 69 | 0.9 | 1.0046 | 0.0014 | 2.21E+01 |
| 5 | 60.32 | 2 x 2 | 110.2 | 21.12 | 454 | 5.2 | 1.0008 | 0.0015 | 2.45E+01 |
| 6 | 355.94 | 2 x 2 | 31.93 | 21.12 | 69 | 1.5 | 1.0075 | 0.0015 | 2.18E+01 |
| 7 | 60.32 | 2 x 2 | 102.29 | 21.12 | 454 | 4.8 | 1.0011 | 0.0013 | 2.45E+01 |
| 8 | 355.94 | 2 x 2 | 33.2 | 21.12 | 69 | 1.6 | 1.0036 | 0.0016 | 2.19E+01 |
| 9 | 60.32 | 4 x 4 | 105.85 | 21.12 | 454 | 5.0 | 1.0026 | 0.0014 | 2.45E+01 |
| 10 | 355.94 | 4 x 4 | 38.1 | 16.12 | 69 | 2.4 | 1.0005 | 0.0014 | 2.20E+01 |
| 11 | 60.32 | 4 x 4 | 78.4 | 16.12 | 454 | 4.9 | 0.9997 | 0.0013 | 2.46E+01 |
| 12 | 355.94 | 4 x 4 | 35.56 | 16.12 | 69 | 2.2 | 1.0006 | 0.0014 | 2.22E+01 |
| 13 | 355.94 | 2 x 3 | 95.2 | 16.12 | 69 | 5.9 | 1.0024 | 0.0015 | 2.20E+01 |

## Table 6-44 Experiments HEU-SOL-THERM-009
**Water-Reflected 6.4-Liter Sphere of Uranium Oxyflouride**

| Case | U (g/L) | Radius (cm) | H/U | $k_{eff}$ | σ | AEG |
|---|---|---|---|---|---|---|
| 1 | 696 | 11.52 | 36 | 1.0088 | 0.0020 | 20.73 |
| 2 | 543 | 11.47* | 47 | 1.0099 | 0.0021 | 21.47 |
| 3 | 349 | 11.52 | 76 | 1.0097 | 0.0020 | 22.54 |
| 4 | 213 | 11.84 | 127 | 1.0041 | 0.0020 | 23.41 |

## Table 6-45 Experiments HEU-SOL-THERM-010
**Water-Reflected 9.7-Liter Sphere of Uranium Oxyflouride**

| Case | U (g/L) | Radius (cm) | H/U | Temp (°C) | $k_{eff}$ | σ | AEG |
|---|---|---|---|---|---|---|---|
| 1 | 102.1 | 13.21 | 270 | 27.5 | 1.0081 | 0.0019 | 24.25 |
| 2 | 103.8 | 13.22 | 264 | 39.5 | 1.0067 | 0.0020 | 24.23 |
| 3 | 109.4 | 13.24 | 246 | 74.0 | 1.0026 | 0.0020 | 24.17 |
| 4 | 111.5 | 13.24 | 239 | 85.5 | 1.0054 | 0.0022 | 24.14 |

## Table 6-46 Experiments HEU-SOL-THERM-011
**Water-Reflected 17-Liter Sphere of Uranium Oxyflouride**

| Case | U (g/L) | Radius (cm) | H/U | $k_{eff}$ | σ | AEG |
|---|---|---|---|---|---|---|
| 1 | 53 | 15.957 | 523 | 1.0110 | 0.0024 | 24.67 |
| 2 | 52 | 15.957 | 533 | 1.0051 | 0.0018 | 24.68 |

## Table 6-47 Experiments HEU-SOL-THERM-012
**Water-Reflected 91-Liter Sphere of Uranium Oxyflouride**

| Case | U (g/L) | Radius (cm) | H/U | $k_{eff}$ | σ | AEG |
|---|---|---|---|---|---|---|
| 1 | 20.5 | 27.95 | 1272 | 1.0021 | 0.0015 | 24.98 |

## Table 6-48 Experiments HEU-SOL-THERM-013
**Unreflected 171-Liter Sphere of Uranium Oxyflouride**

| Case | U (g/L) | Radius (cm) | H/U | Benchmark Model $k_{eff}$ | $k_{eff}$ | σ | AEG |
|---|---|---|---|---|---|---|---|
| 1 | 20.12 | 34.6 | 1375 | 1.0012 | 0.9969 | 0.0018 | 24.98 |
| 2 | 23.53 | 34.6 | 1173 | 1.0007 | 0.9979 | 0.0015 | 24.91 |
| 3 | 26.77 | 34.6 | 1030 | 1.0009 | 0.9928 | 0.0018 | 24.85 |
| 4 | 28.45 | 34.6 | 971 | 1.0003 | 0.9953 | 0.0015 | 24.82 |

Table 6-49 Experiments HEU-SOL-THERM-028

**Water-Reflected Cylinders of Uranyl Nitrate With a 5-cm Diameter $B_4C$ Poison Rod**

| Case | U (g/L) | Tank Diameter (cm) | Critical Height (cm) | H/U | h/D | $k_{eff}$ | σ | AEG |
|---|---|---|---|---|---|---|---|---|
| 1 | 76 | 28.07 | 26.9862 | 375 | 1.0 | 1.0026 | 0.0009 | 24.43 |
| 2 | 76 | 28.07 | 56.2107 | 375 | 2.0 | 1.0008 | 0.0010 | 24.41 |
| 3 | 76 | 30.06 | 24.3769 | 375 | 0.8 | 1.0055 | 0.0010 | 24.42 |
| 4 | 76 | 30.06 | 39.3696 | 375 | 1.3 | 1.0009 | 0.0009 | 24.41 |
| 5 | 76 | 31.93 | 22.2296 | 375 | 0.7 | 0.9999 | 0.0009 | 24.42 |
| 6 | 76 | 31.93 | 32.0284 | 375 | 1.0 | 1.0029 | 0.0009 | 24.41 |
| 7 | 76 | 40.07 | 18.3182 | 375 | 0.5 | 1.0045 | 0.0010 | 24.42 |
| 8 | 76 | 40.07 | 21.4641 | 375 | 0.5 | 1.0005 | 0.0009 | 24.40 |
| 9 | 276 | 22.04 | 25.9491 | 91 | 1.2 | 1.0034 | 0.0011 | 22.70 |
| 10 | 276 | 22.04 | 73.7830 | 91 | 3.3 | 0.9991 | 0.0010 | 22.68 |
| 11 | 276 | 24.05 | 22.2332 | 91 | 0.9 | 1.0048 | 0.0011 | 22.68 |
| 12 | 276 | 24.05 | 38.3307 | 91 | 1.6 | 1.0007 | 0.0011 | 22.65 |
| 13 | 276 | 28.07 | 18.0985 | 91 | 0.6 | 1.0049 | 0.0011 | 22.66 |
| 14 | 276 | 28.07 | 24.1385 | 91 | 0.9 | 1.0065 | 0.0010 | 22.63 |
| 15 | 276 | 31.93 | 16.3600 | 91 | 0.5 | 1.0113 | 0.0011 | 22.64 |
| 16 | 276 | 31.93 | 19.6303 | 91 | 0.6 | 1.0082 | 0.0011 | 22.61 |
| 17 | 276 | 40.07 | 13.7981 | 91 | 0.3 | 1.0025 | 0.0011 | 22.62 |
| 18 | 276 | 40.07 | 15.3084 | 91 | 0.4 | 1.0040 | 0.0010 | 22.60 |

Table 6-50 Experiments HEU-SOL-THERM-029

**Water-Reflected Cylinders of Uranyl Nitrate (286 g U/L; H/U=91) With a Cluster of Seven 2.6-cm Diameter $B_4C$ Poison Rods**

| Case | Poison Rod Pitch (cm) | Tank Diameter (cm) | Critical Height (cm) | h/D | $k_{eff}$ | σ | AEG |
|---|---|---|---|---|---|---|---|
| 1 | - | 40.07 | 14.4325 | 0.4 | 1.0064 | 0.0011 | 22.56 |
| 2 | 6.0 | 40.07 | 23.6039 | 0.6 | 1.0109 | 0.0014 | 22.58 |
| 3 | 7.0 | 40.07 | 25.9271 | 0.6 | 0.9992 | 0.0015 | 22.55 |
| 4 | 10.5 | 40.07 | 32.4321 | 0.8 | 0.9976 | 0.0016 | 22.48 |
| 5 | 12.3 | 40.07 | 29.2725 | 0.7 | 1.0048 | 0.0015 | 22.46 |
| 6 | 14.0 | 40.07 | 24.4403 | 0.6 | 1.0072 | 0.0015 | 22.46 |
| 7 | 16.0 | 40.07 | 20.6302 | 0.5 | 1.0028 | 0.0015 | 22.47 |

## Table 6-51 Experiments HEU-SOL-THERM-030
**Water-Reflected Cylinders of Uranyl Nitrate With a Cluster of 3, 4, or 6 5-cm Diameter $B_4C$ Poison Rods**

| Case | U (g/L) | Number of Poison Rods | Critical Height (cm) | H/U | h/D | $k_{eff}$ | σ | AEG |
|---|---|---|---|---|---|---|---|---|
| 1 | 76 | - | 18.7147 | 375 | 0.5 | 1.0031 | 0.0010 | 24.41 |
| 2 | 76 | 3 | 27.6702 | 375 | 0.7 | 1.0019 | 0.0011 | 24.38 |
| 3 | 76 | 4 | 36.3524 | 375 | 0.9 | 1.0008 | 0.0012 | 24.38 |
| 4 | 289 | - | 14.3532 | 91 | 0.4 | 1.0072 | 0.0011 | 22.56 |
| 5 | 289 | 3 | 17.5160 | 91 | 0.4 | | | |
| 6 | 289 | 4 | 20.0804 | 91 | 0.5 | 1.0046 | 0.0012 | 22.53 |
| 7 | 289 | 6 | 26.3942 | 91 | 0.7 | 1.0028 | 0.0014 | 22.49 |

## Table 6-52 Experiments HEU-SOL-THERM-031
**Water-Reflected Cylinders of Uranyl Nitrate (289 g U/L, H/U=91) With a Cluster of 18 or 36 1.7-cm and 1.4-cm Diameter $B_4C$ Poison Rods**

| Case | Poison Rods | | Critical Height (cm) | h/D | $k_{eff}$ | σ | AEG |
|---|---|---|---|---|---|---|---|
| | Number | Pitch (cm) | | | | | |
| 1 | 18 | 4 | 20.7726 | 0.5 | 1.0041 | 0.0022 | 22.50 |
| 2 | 36 | 4 | 37.9165 | 0.9 | 1.0023 | 0.0025 | 22.40 |
| 3 | 18 | 6 | 21.9405 | 0.5 | 1.0049 | 0.0018 | 22.45 |
| 4 | 36 | 6 | 31.2768 | 0.8 | 1.0013 | 0.0028 | 22.29 |

## Table 6-53 Experiments HEU-SOL-THERM-035
**Water-Reflected Cylinders of Uranyl Nitrate With a Cluster of 18, 19, or 61 4.5-cm Diameter $B_4C$ Poison Rods in a Hexagonal Lattice**

| Case | U (g/L) | Poison Rods | | Critical Height (cm) | H/U | h/D | $k_{eff}$ | σ | AEG |
|---|---|---|---|---|---|---|---|---|---|
| | | Number | Pitch (cm) | | | | | | |
| 1 | 37.51 | - | | 20.3439 | 767 | 0.5 | 1.0047 | 0.0009 | 24.79 |
| 2 | 37.51 | 19 | 7.6 | 24.7831 | 767 | 0.6 | 1.0077 | 0.0009 | 24.77 |
| 3 | 37.51 | 18 | 7.6 | 24.4979 | 767 | 0.6 | 1.0066 | 0.0008 | 24.77 |
| 4 | 37.51 | 19 | 7.6 | 23.1260 | 767 | 0.6 | 1.0061 | 0.0011 | 24.78 |
| 5 | 74.87 | - | 7.6 | 15.0826 | 379 | 0.4 | 1.0066 | 0.0010 | 24.36 |
| 6 | 74.87 | 19 | 10.6 | 17.5148 | 379 | 0.4 | 1.0082 | 0.0010 | 24.34 |
| 7 | 152.3 | - | | 11.8906 | 181 | 0.3 | 1.0097 | 0.0011 | 23.61 |
| 8 | 152.3 | 19 | 10.6 | 14.4216 | 181 | 0.4 | 1.0037 | 0.0010 | 23.54 |

## Table 6-54 Experiments HEU-SOL-THERM-036

**Unreflected Cylinders of Uranyl Nitrate (93 g U/L, H/U=302) With a Cluster of 1.4-cm Diameter $B_4C$ Poison Rods in a Square Lattice**

| Case | Poison Rods | | Critical Height (cm) | $k_{eff}$ | σ | AEG |
|---|---|---|---|---|---|---|
| | Number | Pitch | | | | |
| 1 | - | - | 15.8156 | 0.9985 | 0.0010 | 24.16 |
| 2 | 36 | 12 | 21.0562 | 1.0040 | 0.0011 | 24.10 |
| 3 | 64 | 9 | 33.499 | 0.9968 | 0.0010 | 24.03 |
| 4 | 81 | 8 | 72.2768 | 1.0017 | 0.0010 | 23.98 |

## Table 6-55 Experiments MIX-SOL-THERM-001

**Mixed Uranium/Plutonium Nitrate Solutions in Annular Geometry, With Boron-Poisoned Concrete Inserts**

| Case | U (g/L) | U (g/L) | Insert | Bottle[9] | Critical Height (cm) | $k_{eff}$ | σ | AEG |
|---|---|---|---|---|---|---|---|---|
| a087 | 365.20 | 102.19 | 2% $B_4C$ concrete annulus | none | 48.55 | 1.0012 | 0.0016 | 22.63 |
| a087s | 364.88 | 102.69 | 2% $B_4C$ concrete annulus | none | 48.99 | 1.0050 | 0.0014 | 22.61 |
| a91 | 363.66 | 103.37 | 0% $B_4C$ concrete annulus | 2 | 27.67 | 0.9995 | 0.0016 | 22.65 |
| a92 | 373.33 | 106.30 | 1% $B_4C$ concrete annulus | 2 | 37.19 | 1.0001 | 0.0015 | 22.53 |
| a93 | 379.55 | 107.91 | 6% $B_4C$ concrete annulus | 2 | 51.1 | 1.0054 | 0.0014 | 22.48 |
| a94 | 380.41 | 108.27 | Void | 2 | 32.86 | 1.0059 | 0.0016 | 22.54 |
| a95 | 6.50 | 195.61 | 2% $B_4C$ concrete annulus | 3 | 27.51 | 1.011 | 0.0016 | 21.69 |
| a96 | 3.80 | 110.13 | 2% $B_4C$ concrete annulus | 3 | 25.69 | 1.0099 | 0.0016 | 22.71 |
| a97 | 2.30 | 58.30 | 2% $B_4C$ concrete annulus | 3 | 28.94 | 1.0092 | 0.0016 | 23.44 |
| a98 | 247.33 | 72.74 | 2% $B_4C$ concrete annulus | 2 | 39.58 | 1.0085 | 0.0017 | 23.13 |
| a108 | 161.72 | 47.08 | 2% $B_4C$ concrete annulus | 2 | 45.09 | 1.0012 | 0.0015 | 23.59 |

[9] A bottle of mixed uranium/plutonium nitrate solution was present inside the concrete insert in some of the experiments. Bottle number 2 had solution to a height of 59.4 cm, while number 3 had solution to a height of 36.8 cm. Bottle 2 had uranium and plutonium concentrations of 363.30 and 103.36 g/cm$^3$, respectively, while bottle 3 had uranium and plutonium concentrations of 5.10 and 194.92 g/cm$^3$, respectively.

## Table 6-56 Experiments MIX-SOL-THERM-002

**Mixed Uranium/Plutonium Nitrate Solutions in Large Cylindrical Geometry (68.68-cm Diameter) With a Water Reflector**

| Case | U (g/L) | Pu (g/L) | Critical Height (cm) | h/D | $k_{eff}$ | σ | AEG |
|---|---|---|---|---|---|---|---|
| 58 | 11.05 | 11.88 | 76.8 | 1.12 | 1.0133 | 0.0011 | 24.59 |
| 59 | 10.78 | 11.73 | 83.14 | 1.21 | 1.0093 | 0.0012 | 24.60 |
| 61 | 41.04 | 12.19 | 81.72 | 1.19 | 1.0107 | 0.0013 | 24.57 |

## Table 6-57 Experiments MIX-SOL-THERM-004

**Mixed Uranium/Plutonium Nitrate Solutions in Small Cylindrical Geometry (39.39-cm Diameter) With, Water, Concrete, or No Reflector**

| Case | U (g/L | Pu (g/L) | Critical Height (cm) | Reflector | h/D | $k_{eff}$ | σ | AEG |
|---|---|---|---|---|---|---|---|---|
| D25665 | 63.38 | 41.69 | 44.46 | bare | 1.13 | 1.006 | 0.0004 | 23.83 |
| D19669 | 174.67 | 119.04 | 25.26 | water | 0.64 | 1.0082 | 0.0017 | 22.61 |
| D20670 | 174.53 | 118.9 | 41.08 | bare | 1.04 | 1.0054 | 0.0004 | 22.33 |
| D15677 | 262.79 | 172.56 | 57.97 | bare | 1.47 | 1.0055 | 0.0005 | 21.40 |
| D16678 | 262.55 | 172.83 | 28.93 | water | 0.73 | 1.0027 | 0.0019 | 21.82 |

## 6.6 References

1. Dyer, F.F., R.P. Wichner, W.J. Martin, L.L. Fairchild, R.J. Kedl, and H.J. de Nordwall, *Postirradiation Examination of Peach Bottom HTGR Driver Fuel Element E06-01*, ORNL-5126, April 1976.

2. C.A. Baldwin, R.N. Morris, *Peach Bottom Reactor – Core 2 Materials Available at ORNL for Retrieval and Test Specimen Preparation,* May 1998.

3. SCALE 4.4, Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluation for Workstations and Personal Computers, Oak Ridge National Laboratory (RSIC CCC-545).

4. W. R. Stratton, *Criticality Data and Factors Affecting Criticality of Single Homogeneous Units*, Los Alamos Scientific Laboratory report LA-3612 (September 1967).

5. International Handbook of Evaluated Criticality Safety Benchmark Experiments, NEA Nuclear Science Committee, Organization for Economic Co-Operation and Development, NEA/NSC/DOC(95)03/I.

6. Lichtenwalter, J.J., Bowman, S.M., DeHart, M.D., Hopper, C.M., *Criticality Benchmark Guide for Light-Water-Reactor Fuel in Transportation and Storage Packages*, NUREG/CR-6361 (ORNL/TM-13211), U.S. Nuclear Regulatory Commission, March 1997.

7. Lichtenwalter, Jerry, *Hetrogenous Reactivity Effects in Medium and High Enriched Uranium Metal-Water Systems*, paper presented at the ANS NCSD Topical meeting on Criticality Safety Challenges of the Next Decade, Chelan, Washington, September 12-17, 1997.

## 6.7 Appendix

### Selected KENOVI Input Files

### Loading Pattern 1

### Case ORCL1-1a

```
=csas26              parm=size=3000000
Loading Pattern 1
'four group 2 ORC's in fuel tube 1
'four group 1 ORC's in fuel tubes 2 - 5
27GROUPNDF4                     INFHOMMEDIUM
ss304           1  1.0 293 END
'POISON
B-10            2  DEN=0.03175 END
'group 1: H/X=300
URANIUM         8  DEN=0.0865   1.0   293   92235 100 end
H2O             8  DEN=0.9937   1.0   293   end
'group 2:  H/X=250
URANIUM         3  DEN=0.0852   1.0   293   92235 100 end
PLUTONIUMALP    3  DEN=0.0188   1.0   293   94239 100 end
H2O             3  DEN=0.9918   1.0   293   end
H2O             4  1.0 293 END
PB              5  1.0 293.0 END
AL              6  1.0  293.  END
H2O             7  1.0e-20 293 END
END COMP
MORE DATA dab=300 end
read parameters
NB8=300 TME=5000 GEN=300 NPG=400 RUN=yes
end parameters
READ GEOM

unit 2
com='flux trap spacer'
cylinder 1  6.35  40.64 0
cylinder 2  5.08  39.68 34.93
cylinder 3  5.95  33.03 32.95
cylinder 4  5.95  32.51 2.67
cylinder 5  5.95  2.03 1.27
media 1 1   1 -2 -3 -4 -5
media 2 1   3
media 2 1   5
media 0 1   2
media 0 1   4
boundary 1

unit 3
com='ORC, group 1, centered'
cylinder 1  6.8469  62.79 25.48
cylinder 2  6.847   88.265 0
media 8 1    1
media 7 1    2 -1
boundary 2

unit 6
com='FTs 2 - 5'
cylinder 11 6.725   5.08 0    origin z=0.00001
cylinder 1  6.847   88.265 0  origin z=5.081
cylinder 2  6.350   40.64 0   origin z=93.347
cylinder 3  6.847   88.265 0  origin z=133.988
cylinder 4  6.350   40.64 0   origin z=222.254
cylinder 5  6.847   88.265 0  origin z=262.895
cylinder 6  6.350   40.64 0   origin z=351.161
```

```
cylinder 7  6.847  88.265 0  origin z=391.802
cylinder 10 6.847  480.069 0 origin z=0
cylinder 12 7.065  480.070 0 origin z=0
media 1 1  12 -10
media 0 1  10 -11 -7 -6 -5 -4 -3 -2 -1
media 1 1  11 -1
hole  3  1           origin z=5.081
hole  2  2 -1 -3     origin z=93.347
hole  3  3           origin z=133.988
hole  2  4 -3 -5     origin z=222.254
hole  3  5           origin z=262.895
hole  2  6 -5 -7     origin z=351.161
hole  3  7           origin z=391.802
boundary 12

'***************************************************************************

unit 11
com='ORC group 2 centered'
cylinder 1  6.847  78.61 9.65
cylinder 2  6.847  88.265 0
media 3 1   1
media 7 1   2 -1
boundary 2

unit 14
com='FT 1'
cylinder 11 6.725  5.08 0    origin z=0.00001
cylinder 1  6.847  88.265 0  origin z=5.081
cylinder 2  6.350  40.64 0   origin z=93.347
cylinder 3  6.847  88.265 0  origin z=133.988
cylinder 4  6.350  40.64 0   origin z=222.254
cylinder 5  6.847  88.265 0  origin z=262.895
cylinder 6  6.350  40.64 0   origin z=351.161
cylinder 7  6.847  88.265 0  origin z=391.802
cylinder 10 6.847  480.069 0 origin z=0
cylinder 12 7.065  480.070 0 origin z=0
media 1 1  12 -10
media 0 1  10 -11 -7 -6 -5 -4 -3 -2 -1
media 1 1  11 -1
hole 11  1           origin z=5.081
hole  2  2 -1 -3     origin z=93.347
hole 11  3           origin z=133.988
hole  2  4 -3 -5     origin z=222.254
hole 11  5           origin z=262.895
hole  2  6 -5 -7     origin z=351.161
hole 11  7           origin z=391.802
boundary 12

unit 21
com='one complete axial layer - layer 1 (bottom)'
'***one piece of pentagonal poison enclosure - top center****
cuboid 1 8.191 0.110 0 -0.151 482.2217 0
origin x= 0 y= 0 rotate a1=  0
wedge  2 0.110 0 -0.151  482.2217
origin x= 8.192 y= 0 rotate a1=  0
wedge  3 -0.110 0 -0.151  482.2217
origin x= 0.109 y= 0 rotate a1=  0
cuboid 4 1.348 0 0 -0.151 482.2217 0
origin x= 8.191 y= -0.151 rotate a1=  -126
cuboid 5 7.395 0.902 -1.091 -1.242 482.2217 0
origin x= 0 y= 0 rotate a1=  0
cuboid 6 0 -1.348 0 -0.151 482.2217 0
origin x= 0.110 y= -0.151 rotate a1= 126
cuboid 7 7.393 0.908 -0.211 -0.973 482.2217 0
origin x= 0 y= 0 rotate a1=  0
wedge  8 0.554 0 -0.762  482.2217
origin x= 7.394 y= -0.211 rotate a1=  0
wedge  9 -0.554 0 -0.762  482.2217
origin x= 0.907 y= -0.211 rotate a1=  0
media 1 1  1                -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
```

```
media 1 1  2               -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  3               -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  4 -1 -5         -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  6 -1 -5         -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  5               -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  7               -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  8               -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  9               -130 -131 -132 -133 -134 -135 -136 -137 -138 -139

'***one piece of pentagonal poison enclosure - top right****

cuboid 21 8.191 0.110 0 -0.151 482.2217 0
origin x= 8.311 y= 0.000 rotate a1=  -72
wedge 22 0.110 0 -0.151  482.2217
origin x= 10.842 y= -7.791 rotate a1=  -72
wedge 23 -0.110 0 -0.151  482.2217
origin x= 8.344 y= -0.103 rotate a1=  -72
cuboid 24 1.348 0 0 -0.151 482.2217 0
origin x= 10.698 y= -7.837 rotate a1=  -198
cuboid 25 7.395 0.902 -1.091 -1.242 482.2217 0
origin x= 8.311 y= 0.000 rotate a1=  -72
cuboid 26 0 -1.348 0 -0.151 482.2217 0
origin x= 8.201 y= -0.151 rotate a1= 54
cuboid 27 7.393 0.908 -0.211 -0.973 482.2217 0
origin x= 8.311 y= 0.000 rotate a1=  -72
wedge 28 0.554 0 -0.762  482.2217
origin x= 10.395 y= -7.097 rotate a1=  -72
wedge 29 -0.554 0 -0.762  482.2217
origin x= 8.391 y= -0.928 rotate a1=  -72
media 1 1  21              -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  22              -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  23              -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  24 -21 -25      -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  26 -21 -25      -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  25              -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  27              -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  28              -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  29              -130 -131 -132 -133 -134 -135 -136 -137 -138 -139

'***one piece of pentagonal poison enclosure - top left****

cuboid 31 8.191 0.110 0 -0.151 482.2217 0
origin x= -2.568 y= -7.904 rotate a1=  -288
wedge 32 0.110 0 -0.151  482.2217
origin x= -0.037 y= -0.113 rotate a1=  -288
wedge 33 -0.110 0 -0.151  482.2217
origin x= -2.535 y= -7.800 rotate a1=  -288
cuboid 34 1.348 0 0 -0.151 482.2217 0
origin x= 0.107 y= -0.161 rotate a1=  -414
cuboid 35 7.395 0.902 -1.091 -1.242 482.2217 0
origin x= -2.568 y= -7.904 rotate a1=  -288
cuboid 36 0 -1.348 0 -0.151 482.2217 0
origin x= -2.390 y= -7.846 rotate a1=  -162
cuboid 37 7.393 0.908 -0.211 -0.973 482.2217 0
origin x= -2.568 y= -7.904 rotate a1=  -288
wedge 38 0.554 0 -0.762  482.2217
origin x= -0.083 y= -0.937 rotate a1=  -288
wedge 39 -0.554 0 -0.762  482.2217
origin x= -2.088 y= -7.106 rotate a1=  -288
media 1 1  31              -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  32              -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  33              -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  34 -31 -35      -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  36 -31 -35      -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  35              -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  37              -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  38              -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  39              -130 -131 -132 -133 -134 -135 -136 -137 -138 -139

'***one piece of pentagonal poison enclosure - bottom left****
```

```
cuboid 41 8.191 0.110 0 -0.151 482.2217 0
origin x= 4.155 y= -12.789 rotate a1=  -216
wedge 42 0.110 0 -0.151  482.2217
origin x= -2.472 y= -7.974 rotate a1=  -216
wedge 43 -0.110 0 -0.151  482.2217
origin x= 4.067 y= -12.725 rotate a1=  -216
cuboid 44 1.348 0 0 -0.151 482.2217 0
origin x= -2.382 y= -7.852 rotate a1=  -342
cuboid 45 7.395 0.902 -1.091 -1.242 482.2217 0
origin x= 4.155 y= -12.789 rotate a1=  -216
cuboid 46 0 -1.348 0 -0.151 482.2217 0
origin x= 4.155 y= -12.602 rotate a1=  -90
cuboid 47 7.393 0.908 -0.211 -0.973 482.2217 0
origin x= 4.155 y= -12.789 rotate a1=  -216
wedge 48 0.554 0 -0.762  482.2217
origin x= -1.703 y= -8.273 rotate a1=  -216
wedge 49 -0.554 0 -0.762  482.2217
origin x= 3.545 y= -12.085 rotate a1=  -216
media 1 1  41                -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  42                -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  43                -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  44 -41 -45        -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  46 -41 -45        -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  45                -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  47                -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  48                -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  49                -130 -131 -132 -133 -134 -135 -136 -137 -138 -139

'***one piece of pentagonal poison enclosure - bottom right****

cuboid 51 8.191 0.110 0 -0.151 482.2217 0
origin x= 10.879 y= -7.904 rotate a1=  -144
wedge 52 0.110 0 -0.151  482.2217
origin x= 4.251 y= -12.719 rotate a1=  -144
wedge 53 -0.110 0 -0.151  482.2217
origin x= 10.791 y= -7.968 rotate a1=  -144
cuboid 54 1.348 0 0 -0.151 482.2217 0
origin x= 4.163 y= -12.596 rotate a1=  -270
cuboid 55 7.395 0.902 -1.091 -1.242 482.2217 0
origin x= 10.879 y= -7.904 rotate a1=  -144
cuboid 56 0 -1.348 0 -0.151 482.2217 0
origin x= 10.701 y= -7.846 rotate a1=  -18
cuboid 57 7.393 0.908 -0.211 -0.973 482.2217 0
origin x= 10.879 y= -7.904 rotate a1=  -144
wedge 58 0.554 0 -0.762  482.2217
origin x= 4.773 y= -12.080 rotate a1=  -144
wedge 59 -0.554 0 -0.762  482.2217
origin x= 10.021 y= -8.267 rotate a1=  -144
media 1 1  51                -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  52                -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  53                -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  54 -51 -55        -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  56 -51 -55        -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  55                -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  57                -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  58                -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  59                -130 -131 -132 -133 -134 -135 -136 -137 -138 -139

'***radial arm poison enclosure - center bottom***

cuboid 61 5.588 0.151 0.444 -0.444 482.2217 0
origin x= 4.155 y= -12.799 rotate a1= -90
cuboid 62 5.588 0.000 0.595 -0.595 482.2217 0
origin x= 4.155 y= -12.799 rotate a1= -90
cuboid 63 9.144 5.588 0.444 -0.444 482.2217 0
origin x= 4.155 y= -12.799 rotate a1= -90
cuboid 64 9.144 5.588 0.518 -0.518 482.2217 0
origin x= 4.155 y= -12.799 rotate a1= -90
cuboid 65 10.568 9.144 0.444 -0.444 482.2217 0
origin x= 4.155 y= -12.799 rotate a1= -90
cuboid 66 10.719 9.144 0.595 -0.595 482.2217 0
```

```
origin x= 4.155 y= -12.799 rotate a1= -90
cuboid 67 10.464 0.255 0.381 -0.381 482.2217 0
origin x= 4.155 y= -12.799 rotate a1= -90
media 1 1  62 -61 -63 -67 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  64 -62 -63     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  66 -64 -65 -67 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  67             -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  61 -63 -67     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  63 -65 -67     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  65 -67         -130 -131 -132 -133 -134 -135 -136 -137 -138 -139

'***radial arm poison enclosure - bottom right***

cuboid 71 5.588 0.151 0.444 -0.444 482.2217 0
origin x= 10.889 y= -7.914 rotate a1= -18
cuboid 72 5.588 0.000 0.595 -0.595 482.2217 0
origin x= 10.889 y= -7.914 rotate a1= -18
cuboid 73 9.144 5.588 0.444 -0.444 482.2217 0
origin x= 10.889 y= -7.914 rotate a1= -18
cuboid 74 9.144 5.588 0.518 -0.518 482.2217 0
origin x= 10.889 y= -7.914 rotate a1= -18
cuboid 75 10.568 9.144 0.444 -0.444 482.2217 0
origin x= 10.889 y= -7.914 rotate a1= -18
cuboid 76 10.719 9.144 0.595 -0.595 482.2217 0
origin x= 10.889 y= -7.914 rotate a1= -18
cuboid 77 10.312 0.104 0.381 -0.381 482.2217 0
origin x= 10.889 y= -7.914 rotate a1= -18
media 1 1  72 -71 -73 -77 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  74 -72 -73     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  76 -74 -75 -77 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  77             -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  71 -73 -77     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  73 -75 -77     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  75 -77         -130 -131 -132 -133 -134 -135 -136 -137 -138 -139

'***radial arm poison enclosure - bottom left***

cuboid 81 5.588 0.151 0.444 -0.444 482.2217 0
origin x= -2.578 y= -7.914 rotate a1= -162
cuboid 82 5.588 0.000 0.595 -0.595 482.2217 0
origin x= -2.578 y= -7.914 rotate a1= -162
cuboid 83 9.144 5.588 0.444 -0.444 482.2217 0
origin x= -2.578 y= -7.914 rotate a1= -162
cuboid 84 9.144 5.588 0.518 -0.518 482.2217 0
origin x= -2.578 y= -7.914 rotate a1= -162
cuboid 85 10.568 9.144 0.444 -0.444 482.2217 0
origin x= -2.578 y= -7.914 rotate a1= -162
cuboid 86 10.719 9.144 0.595 -0.595 482.2217 0
origin x= -2.578 y= -7.914 rotate a1= -162
cuboid 87 10.312 0.104 0.381 -0.381 482.2217 0
origin x= -2.578 y= -7.914 rotate a1= -162
media 1 1  82 -81 -83 -87 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  84 -82 -83     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  86 -84 -85 -87 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  87             -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  81 -83 -87     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  83 -85 -87     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  85 -87         -130 -131 -132 -133 -134 -135 -136 -137 -138 -139

'***radial arm poison enclosure - top left***

cuboid 91 5.588 0.151 0.444 -0.444 482.2217 0
origin x= 0.010 y= 0.010 rotate a1= 126
cuboid 92 5.588 0.000 0.595 -0.595 482.2217 0
origin x= 0.010 y= 0.010 rotate a1= 126
cuboid 93 9.144 5.588 0.444 -0.444 482.2217 0
origin x= 0.010 y= 0.010 rotate a1= 126
cuboid 94 9.144 5.588 0.518 -0.518 482.2217 0
origin x= 0.010 y= 0.010 rotate a1= 126
cuboid 95 10.568 9.144 0.444 -0.444 482.2217 0
origin x= 0.010 y= 0.010 rotate a1= 126
```

```
cuboid 96 10.719 9.144 0.595 -0.595 482.2217 0
origin x= 0.010 y= 0.010 rotate a1= 126
cuboid 97 10.312 0.104 0.381 -0.381 482.2217 0
origin x= 0.010 y= 0.010 rotate a1= 126
media 1 1  92 -91 -93 -97 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  94 -92 -93     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  96 -94 -95 -97 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  97             -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  91 -93 -97     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  93 -95 -97     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  95 -97         -130 -131 -132 -133 -134 -135 -136 -137 -138 -139

'***radial arm poison enclosure - top right***

cuboid 101 5.588 0.151 0.444 -0.444 482.2217 0
origin x= 8.321 y= 0.010 rotate a1= 54
cuboid 102 5.588 0.000 0.595 -0.595 482.2217 0
origin x= 8.321 y= 0.010 rotate a1= 54
cuboid 103 9.144 5.588 0.444 -0.444 482.2217 0
origin x= 8.321 y= 0.010 rotate a1= 54
cuboid 104 9.144 5.588 0.518 -0.518 482.2217 0
origin x= 8.321 y= 0.010 rotate a1= 54
cuboid 105 10.568 9.144 0.444 -0.444 482.2217 0
origin x= 8.321 y= 0.010 rotate a1= 54
cuboid 106 10.719 9.144 0.595 -0.595 482.2217 0
origin x= 8.321 y= 0.010 rotate a1= 54
cuboid 107 10.312 0.104 0.381 -0.381 482.2217 0
origin x= 8.321 y= 0.010 rotate a1= 54

media 1 1  102 -101 -103 -107 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  104 -102 -103      -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  106 -104 -105 -107 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  107                -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  101 -103 -107      -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  103 -105 -107      -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  105 -107           -130 -131 -132 -133 -134 -135 -136 -137 -138 -139

'***insert fuel compartments***

cylinder 120    7.065   480.070 0    origin x=4.15 y=7.638
hole 6  120                          origin x=4.15 y=7.638
cylinder 121    7.065   480.070 0    origin x=16.736 y=-1.481
hole 14  121                         origin x=16.736 y=-1.481
cylinder 122    7.065   480.070 0    origin x=11.928 y=-16.376
hole 6  122                          origin x=11.928 y=-16.376
cylinder 123    7.065   480.070 0    origin x=-3.628 y=-16.376
hole 6  123                         origin x=-3.628 y=-16.376
cylinder 124    7.065   480.070 0    origin x=-8.436 y=-1.481
hole 6  124                          origin x=-8.436 y=-1.481

'***bottom plate***
cylinder   130    20.841  5.1181 0       origin x=4.15 y=-5.57 z=0
cylinder   140    20.841  4.445  0.001   origin x=4.15 y=-5.57 z=0
media 0 1  130 -140 -120 -121 -122 -123 -124
media 1 1  140      -120 -121 -122 -123 -124

'***middle plate***
cylinder   131    20.841  3.2512 0       origin x=4.15 y=-5.57 z=54.953
cylinder   141    20.841  2.5781 0.6731  origin x=4.15 y=-5.57 z=54.953
media 0 1  131 -141 -120 -121 -122 -123 -124
media 1 1  141      -120 -121 -122 -123 -124

'***middle plate***
cylinder   132    20.841  3.2512 0      origin x=4.15 y=-5.57 z=108.039
cylinder   142    20.841  2.5781 0.6731 origin x=4.15 y=-5.57 z=108.039
media 0 1  132 -142 -120 -121 -122 -123 -124
media 1 1  142      -120 -121 -122 -123 -124

'***middle plate***
cylinder   133    20.841  3.2512 0       origin x=4.15 y=-5.57 z=161.125
cylinder   143    20.841  2.5781 0.6731  origin x=4.15 y=-5.57 z=161.125
```

```
media 0 1  133 -143 -120 -121 -122 -123 -124
media 1 1  143      -120 -121 -122 -123 -124

'***middle plate***
cylinder   134    20.841  3.2512 0       origin x=4.15 y=-5.57 z=214.211
cylinder   144    20.841  2.5781 0.6731  origin x=4.15 y=-5.57 z=214.211
media 0 1  134 -144 -120 -121 -122 -123 -124
media 1 1  144      -120 -121 -122 -123 -124

'***middle plate***
cylinder   135    20.841  3.2512 0       origin x=4.15 y=-5.57 z=267.297
cylinder   145    20.841  2.5781 0.6731  origin x=4.15 y=-5.57 z=267.297
media 0 1  135 -145 -120 -121 -122 -123 -124
media 1 1  145      -120 -121 -122 -123 -124

'***middle plate***
cylinder   136    20.841  3.2512 0       origin x=4.15 y=-5.57 z=320.383
cylinder   146    20.841  2.5781 0.6731  origin x=4.15 y=-5.57 z=320.383
media 0 1  136 -146 -120 -121 -122 -123 -124
media 1 1  146      -120 -121 -122 -123 -124

'***middle plate***
cylinder   137    20.841  3.2512 0       origin x=4.15 y=-5.57 z=373.469
cylinder   147    20.841  2.5781 0.6731  origin x=4.15 y=-5.57 z=373.469
media 0 1  137 -147 -120 -121 -122 -123 -124
media 1 1  147      -120 -121 -122 -123 -124

'***middle plate***
cylinder   138    20.841  3.2512 0       origin x=4.15 y=-5.57 z=426.555
cylinder   148    20.841  2.5781 0.6731  origin x=4.15 y=-5.57 z=426.555
media 0 1  138 -148 -120 -121 -122 -123 -124
media 1 1  148      -120 -121 -122 -123 -124

'***top plate
cylinder   139    20.841  2.5781 0       origin x=4.15 y=-5.57 z=479.641
cylinder   149    20.841  2.5780 0.6731  origin x=4.15 y=-5.57 z=479.641
media 0 1  139 -149 -120 -121 -122 -123 -124
media 1 1  149      -120 -121 -122 -123 -124

'***Inside of Oak Ridge Container***
cylinder 200   21.0566  482.60 -0.00001   origin x=4.15 y=-5.57
media 0 1  200 -1 -2 -3 -4 -5 -6 -7 -8 -9 -21 -22 -23 -24 -25 -26 -27 -28 -29
-31 -32 -33 -34 -35 -36 -37 -38 -39 -41 -42 -43 -44 -45 -46 -47 -48 -49
-51 -52 -53 -54 -55 -56 -57 -58 -59 -61 -62 -63 -64 -65 -66 -67 -71 -72 -73
-74 -75 -76 -77 -81 -82 -83 -84 -85 -86 -87 -91 -92 -93 -94 -95 -96 -97 -101
-102 -103 -104 -105 -106 -107 -120 -121 -122 -123 -124 -130 -131 -132 -133
-134 -135 -136 -137 -138 -139

'***outside of Oak Ridge container (including bottom and top plug)***
cylinder  201   21.400    500.38  -2.54   origin x=4.15 y=-5.57
cylinder  202   21.755    500.38  -2.54   origin x=4.15 y=-5.57
cylinder  203   22.555    500.38  -2.54   origin x=4.15 y=-5.57
media 1 1  201 -200
media 0 1  202 -201
media 6 1  203 -202
boundary 203

'***************************************************************************

global
unit 30
com='TN-FSV Cask with Oak Ridge Container'
cylinder 2    39.218    508.788 502.438 origin x=4.15 y=-5.57
cylinder 3    39.218    -9.374 -23.344  origin x=4.15 y=-5.57
cylinder 4    22.859    -2.542 -9.373   origin x=4.15 y=-5.57
cylinder 5    22.555    500.38  -2.54   origin x=4.15 y=-5.57
cylinder 6    22.860    502.437 -2.541   origin x=4.15 y=-5.57
cylinder 7    25.705    502.4371 -9.3731   origin x=4.15 y=-5.57
cylinder 8    34.442    502.4372 -9.3732   origin x=4.15 y=-5.57
cylinder 9    38.252    502.4373 -9.3733   origin x=4.15 y=-5.57
cylinder 10   38.583    502.4374 -9.3734   origin x=4.15 y=-5.57
```

```
cylinder 11  39.218   502.4375 -9.3735   origin x=4.15 y=-5.57
cylinder 12  69.698   532.917 -33.02  origin x=4.15 y=-5.57
hole 21      5
media 1 1    2
media 1 1    3
media 6 1    4
media 0 1    6 -5
media 1 1    7 -6 -4
media 5 1    8 -7
media 1 1    9 -8
media 0 1    10 -9
media 1 1    11 -10
media 4 1    12 -2 -3 -11
boundary 12

end geom
 end data
end
```

## Loading Pattern 2

## Case ORCL-3-3b

```
=csas26              parm=size=3000000
Loading Pattern 2
'four group 5 ORC's in fuel tube 1
'four group 1 ORC's in fuel tubes 2 - 5
27GROUPNDF4                    INFHOMMEDIUM
ss304            1  1.0 293 END
'POISON
B-10             2  DEN=0.03175 END
'group 1: H/X=300
URANIUM          8  DEN=0.0865  1.0   293   92235 100 end
H2O              8  DEN=0.9937  1.0   293   end
'group 5:  H/X=200
URANIUM          3  DEN=0.1294  1.0   293   92235 100 end
H2O              3  DEN=0.9914  1.0   293   end
H2O              4  1.0 293 END
PB               5  1.0 293.0 END
AL               6  1.0  293.  END
H2O              7  1.0e-20 293 END
END COMP
MORE DATA dab=300 end
read parameters
NB8=300 TME=5000 GEN=300 NPG=400 RUN=yes
end parameters
READ GEOM

unit 2
com='flux trap spacer'
cylinder 1  6.35   40.64 0
cylinder 2  5.08   39.68 34.93
cylinder 3  5.95   33.03 32.95
cylinder 4  5.95   32.51 2.67
cylinder 5  5.95   2.03 1.27
media 1 1   1 -2 -3 -4 -5
media 2 1   3
media 2 1   5
media 0 1   2
media 0 1   4
boundary 1

unit 3
com='ORC, group 1, centered'
cylinder 1  6.8469  62.79 25.48
cylinder 2  6.847   88.265 0
media 8 1    1
media 7 1    2 -1
```

```
boundary 2

unit 6
com='FTs 1, 3, 5; centered'
cylinder 11 6.725  5.08 0    origin z=0.00001
cylinder 1  6.847  88.265 0  origin z=5.081
cylinder 2  6.350  40.64 0   origin z=93.347
cylinder 3  6.847  88.265 0  origin z=133.988
cylinder 4  6.350  40.64 0   origin z=222.254
cylinder 5  6.847  88.265 0  origin z=262.895
cylinder 6  6.350  40.64 0   origin z=351.161
cylinder 7  6.847  88.265 0  origin z=391.802
cylinder 10 6.847  480.069 0 origin z=0
cylinder 12 7.065  480.070 0 origin z=0
media 1 1  12 -10
media 0 1  10 -11 -7 -6 -5 -4 -3 -2 -1
media 1 1  11 -1
hole  3  1           origin z=5.081
hole  2  2 -1 -3     origin z=93.347
hole  3  3           origin z=133.988
hole  2  4 -3 -5     origin z=222.254
hole  3  5           origin z=262.895
hole  2  6 -5 -7     origin z=351.161
hole  3  7           origin z=391.802
boundary 12

'***************************************************************************

unit 11
com='ORC group 5 centered'
cylinder 1  6.847  68.01 20.26
cylinder 2  6.847  88.265 0
media 3 1   1
media 7 1   2 -1
boundary 2

unit 14
com='FT 2, centered'
cylinder 11 6.725  5.08 0    origin z=0.00001
cylinder 1  6.847  88.265 0  origin z=5.081
cylinder 2  6.350  40.64 0   origin z=93.347
cylinder 3  6.847  88.265 0  origin z=133.988
cylinder 4  6.350  40.64 0   origin z=222.254
cylinder 5  6.847  88.265 0  origin z=262.895
cylinder 6  6.350  40.64 0   origin z=351.161
cylinder 7  6.847  88.265 0  origin z=391.802
cylinder 10 6.847  480.069 0 origin z=0
cylinder 12 7.065  480.070 0 origin z=0
media 1 1  12 -10
media 0 1  10 -11 -7 -6 -5 -4 -3 -2 -1
media 1 1  11 -1
hole 11  1           origin z=5.081
hole  2  2 -1 -3     origin z=93.347
hole 11  3           origin z=133.988
hole  2  4 -3 -5     origin z=222.254
hole 11  5           origin z=262.895
hole  2  6 -5 -7     origin z=351.161
hole 11  7    -      origin z=391.802
boundary 12

unit 21
com='one complete axial layer - layer 1 (bottom)'
'***one piece of pentagonal poison enclosure - top center****
cuboid 1 8.191 0.110 0 -0.151 482.2217 0
origin x= 0 y= 0 rotate a1=  0
wedge  2 0.110 0 -0.151  482.2217
origin x= 8.192 y= 0 rotate a1=  0
wedge  3 -0.110 0 -0.151  482.2217
origin x= 0.109 y= 0 rotate a1=  0
cuboid 4 1.348 0 0 -0.151 482.2217 0
origin x= 8.191 y= -0.151 rotate a1=  -126
```

```
cuboid 5 7.395 0.902 -1.091 -1.242 482.2217 0
origin x= 0 y= 0 rotate a1=  0
cuboid 6 0 -1.348 0 -0.151 482.2217 0
origin x= 0.110 y= -0.151 rotate a1= 126
cuboid 7 7.393 0.908 -0.211 -0.973 482.2217 0
origin x= 0 y= 0 rotate a1=  0
wedge  8 0.554 0 -0.762  482.2217
origin x= 7.394 y= -0.211 rotate a1=  0
wedge  9 -0.554 0 -0.762  482.2217
origin x= 0.907 y= -0.211 rotate a1=  0
media 1 1  1              -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  2              -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  3              -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  4 -1 -5        -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  6 -1 -5        -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  5              -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  7              -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  8              -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  9              -130 -131 -132 -133 -134 -135 -136 -137 -138 -139

'***one piece of pentagonal poison enclosure - top right****

cuboid 21 8.191 0.110 0 -0.151 482.2217 0
origin x= 8.311 y= 0.000 rotate a1=  -72
wedge 22 0.110 0 -0.151  482.2217
origin x= 10.842 y= -7.791 rotate a1=  -72
wedge 23 -0.110 0 -0.151  482.2217
origin x= 8.344 y= -0.103 rotate a1=  -72
cuboid 24 1.348 0 0 -0.151 482.2217 0
origin x= 10.698 y= -7.837 rotate a1=  -198
cuboid 25 7.395 0.902 -1.091 -1.242 482.2217 0
origin x= 8.311 y= 0.000 rotate a1=  -72
cuboid 26 0 -1.348 0 -0.151 482.2217 0
origin x= 8.201 y= -0.151 rotate a1= 54
cuboid 27 7.393 0.908 -0.211 -0.973 482.2217 0
origin x= 8.311 y= 0.000 rotate a1=  -72
wedge 28 0.554 0 -0.762  482.2217
origin x= 10.395 y= -7.097 rotate a1=  -72
wedge 29 -0.554 0 -0.762  482.2217
origin x= 8.391 y= -0.928 rotate a1=  -72
media 1 1  21             -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  22             -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  23             -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  24 -21 -25     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  26 -21 -25     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  25             -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  27             -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  28             -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  29             -130 -131 -132 -133 -134 -135 -136 -137 -138 -139

'***one piece of pentagonal poison enclosure - top left****

cuboid 31 8.191 0.110 0 -0.151 482.2217 0
origin x= -2.568 y= -7.904 rotate a1=  -288
wedge 32 0.110 0 -0.151  482.2217
origin x= -0.037 y= -0.113 rotate a1=  -288
wedge 33 -0.110 0 -0.151  482.2217
origin x= -2.535 y= -7.800 rotate a1=  -288
cuboid 34 1.348 0 0 -0.151 482.2217 0
origin x= 0.107 y= -0.161 rotate a1=  -414
cuboid 35 7.395 0.902 -1.091 -1.242 482.2217 0
origin x= -2.568 y= -7.904 rotate a1=  -288
cuboid 36 0 -1.348 0 -0.151 482.2217 0
origin x= -2.390 y= -7.846 rotate a1=  -162
cuboid 37 7.393 0.908 -0.211 -0.973 482.2217 0
origin x= -2.568 y= -7.904 rotate a1=  -288
wedge 38 0.554 0 -0.762  482.2217
origin x= -0.083 y= -0.937 rotate a1=  -288
wedge 39 -0.554 0 -0.762  482.2217
origin x= -2.088 y= -7.106 rotate a1=  -288
media 1 1  31             -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
```

```
media 1 1  32                   -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  33                   -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  34 -31 -35           -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  36 -31 -35           -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  35                   -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  37                   -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  38                   -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  39                   -130 -131 -132 -133 -134 -135 -136 -137 -138 -139

'***one piece of pentagonal poison enclosure - bottom left****

cuboid 41 8.191 0.110 0 -0.151 482.2217 0
origin x= 4.155 y= -12.789 rotate a1=  -216
wedge 42 0.110 0 -0.151  482.2217
origin x= -2.472 y= -7.974 rotate a1=  -216
wedge 43 -0.110 0 -0.151  482.2217
origin x= 4.067 y= -12.725 rotate a1=  -216
cuboid 44 1.348 0 0 -0.151 482.2217 0
origin x= -2.382 y= -7.852 rotate a1=  -342
cuboid 45 7.395 0.902 -1.091 -1.242 482.2217 0
origin x= 4.155 y= -12.789 rotate a1=  -216
cuboid 46 0 -1.348 0 -0.151 482.2217 0
origin x= 4.155 y= -12.602 rotate a1=  -90
cuboid 47 7.393 0.908 -0.211 -0.973 482.2217 0
origin x= 4.155 y= -12.789 rotate a1=  -216
wedge 48 0.554 0 -0.762  482.2217
origin x= -1.703 y= -8.273 rotate a1=  -216
wedge 49 -0.554 0 -0.762  482.2217
origin x= 3.545 y= -12.085 rotate a1=  -216
media 1 1  41                   -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  42                   -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  43                   -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  44 -41 -45           -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  46 -41 -45           -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  45                   -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  47                   -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  48                   -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  49                   -130 -131 -132 -133 -134 -135 -136 -137 -138 -139

'***one piece of pentagonal poison enclosure - bottom right****

cuboid 51 8.191 0.110 0 -0.151 482.2217 0
origin x= 10.879 y= -7.904 rotate a1=  -144
wedge 52 0.110 0 -0.151  482.2217
origin x= 4.251 y= -12.719 rotate a1=  -144
wedge 53 -0.110 0 -0.151  482.2217
origin x= 10.791 y= -7.968 rotate a1=  -144
cuboid 54 1.348 0 0 -0.151 482.2217 0
origin x= 4.163 y= -12.596 rotate a1=  -270
cuboid 55 7.395 0.902 -1.091 -1.242 482.2217 0
origin x= 10.879 y= -7.904 rotate a1=  -144
cuboid 56 0 -1.348 0 -0.151 482.2217 0
origin x= 10.701 y= -7.846 rotate a1=  -18
cuboid 57 7.393 0.908 -0.211 -0.973 482.2217 0
origin x= 10.879 y= -7.904 rotate a1=  -144
wedge 58 0.554 0 -0.762  482.2217
origin x= 4.773 y= -12.080 rotate a1=  -144
wedge 59 -0.554 0 -0.762  482.2217
origin x= 10.021 y= -8.267 rotate a1=  -144
media 1 1  51                   -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  52                   -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  53                   -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  54 -51 -55           -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  56 -51 -55           -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  55                   -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  57                   -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  58                   -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  59                   -130 -131 -132 -133 -134 -135 -136 -137 -138 -139

'***radial arm poison enclosure - center bottom***
```

```
cuboid 61 5.588 0.151 0.444 -0.444 482.2217 0
origin x= 4.155 y= -12.799 rotate a1= -90
cuboid 62 5.588 0.000 0.595 -0.595 482.2217 0
origin x= 4.155 y= -12.799 rotate a1= -90
cuboid 63 9.144 5.588 0.444 -0.444 482.2217 0
origin x= 4.155 y= -12.799 rotate a1= -90
cuboid 64 9.144 5.588 0.518 -0.518 482.2217 0
origin x= 4.155 y= -12.799 rotate a1= -90
cuboid 65 10.568 9.144 0.444 -0.444 482.2217 0
origin x= 4.155 y= -12.799 rotate a1= -90
cuboid 66 10.719 9.144 0.595 -0.595 482.2217 0
origin x= 4.155 y= -12.799 rotate a1= -90
cuboid 67 10.464 0.255 0.381 -0.381 482.2217 0
origin x= 4.155 y= -12.799 rotate a1= -90
media 1 1  62 -61 -63 -67 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  64 -62 -63     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  66 -64 -65 -67 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  67             -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  61 -63 -67     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  63 -65 -67     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  65 -67         -130 -131 -132 -133 -134 -135 -136 -137 -138 -139

'***radial arm poison enclosure - bottom right***

cuboid 71 5.588 0.151 0.444 -0.444 482.2217 0
origin x= 10.889 y= -7.914 rotate a1= -18
cuboid 72 5.588 0.000 0.595 -0.595 482.2217 0
origin x= 10.889 y= -7.914 rotate a1= -18
cuboid 73 9.144 5.588 0.444 -0.444 482.2217 0
origin x= 10.889 y= -7.914 rotate a1= -18
cuboid 74 9.144 5.588 0.518 -0.518 482.2217 0
origin x= 10.889 y= -7.914 rotate a1= -18
cuboid 75 10.568 9.144 0.444 -0.444 482.2217 0
origin x= 10.889 y= -7.914 rotate a1= -18
cuboid 76 10.719 9.144 0.595 -0.595 482.2217 0
origin x= 10.889 y= -7.914 rotate a1= -18
cuboid 77 10.312 0.104 0.381 -0.381 482.2217 0
origin x= 10.889 y= -7.914 rotate a1= -18
media 1 1  72 -71 -73 -77 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  74 -72 -73     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  76 -74 -75 -77 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  77             -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  71 -73 -77     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  73 -75 -77     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  75 -77         -130 -131 -132 -133 -134 -135 -136 -137 -138 -139

'***radial arm poison enclosure - bottom left***

cuboid 81 5.588 0.151 0.444 -0.444 482.2217 0
origin x= -2.578 y= -7.914 rotate a1= -162
cuboid 82 5.588 0.000 0.595 -0.595 482.2217 0
origin x= -2.578 y= -7.914 rotate a1= -162
cuboid 83 9.144 5.588 0.444 -0.444 482.2217 0
origin x= -2.578 y= -7.914 rotate a1= -162
cuboid 84 9.144 5.588 0.518 -0.518 482.2217 0
origin x= -2.578 y= -7.914 rotate a1= -162
cuboid 85 10.568 9.144 0.444 -0.444 482.2217 0
origin x= -2.578 y= -7.914 rotate a1= -162
cuboid 86 10.719 9.144 0.595 -0.595 482.2217 0
origin x= -2.578 y= -7.914 rotate a1= -162
cuboid 87 10.312 0.104 0.381 -0.381 482.2217 0
origin x= -2.578 y= -7.914 rotate a1= -162
media 1 1  82 -81 -83 -87 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  84 -82 -83     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  86 -84 -85 -87 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  87             -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  81 -83 -87     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  83 -85 -87     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  85 -87         -130 -131 -132 -133 -134 -135 -136 -137 -138 -139

'***radial arm poison enclosure - top left***
```

```
cuboid 91 5.588 0.151 0.444 -0.444 482.2217 0
origin x= 0.010 y= 0.010 rotate a1= 126
cuboid 92 5.588 0.000 0.595 -0.595 482.2217 0
origin x= 0.010 y= 0.010 rotate a1= 126
cuboid 93 9.144 5.588 0.444 -0.444 482.2217 0
origin x= 0.010 y= 0.010 rotate a1= 126
cuboid 94 9.144 5.588 0.518 -0.518 482.2217 0
origin x= 0.010 y= 0.010 rotate a1= 126
cuboid 95 10.568 9.144 0.444 -0.444 482.2217 0
origin x= 0.010 y= 0.010 rotate a1= 126
cuboid 96 10.719 9.144 0.595 -0.595 482.2217 0
origin x= 0.010 y= 0.010 rotate a1= 126
cuboid 97 10.312 0.104 0.381 -0.381 482.2217 0
origin x= 0.010 y= 0.010 rotate a1= 126
media 1 1  92 -91 -93 -97 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  94 -92 -93     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  96 -94 -95 -97 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  97             -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  91 -93 -97     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  93 -95 -97     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  95 -97         -130 -131 -132 -133 -134 -135 -136 -137 -138 -139

'***radial arm poison enclosure - top right***

cuboid 101 5.588 0.151 0.444 -0.444 482.2217 0
origin x= 8.321 y= 0.010 rotate a1= 54
cuboid 102 5.588 0.000 0.595 -0.595 482.2217 0
origin x= 8.321 y= 0.010 rotate a1= 54
cuboid 103 9.144 5.588 0.444 -0.444 482.2217 0
origin x= 8.321 y= 0.010 rotate a1= 54
cuboid 104 9.144 5.588 0.518 -0.518 482.2217 0
origin x= 8.321 y= 0.010 rotate a1= 54
cuboid 105 10.568 9.144 0.444 -0.444 482.2217 0
origin x= 8.321 y= 0.010 rotate a1= 54
cuboid 106 10.719 9.144 0.595 -0.595 482.2217 0
origin x= 8.321 y= 0.010 rotate a1= 54
cuboid 107 10.312 0.104 0.381 -0.381 482.2217 0
origin x= 8.321 y= 0.010 rotate a1= 54

media 1 1  102 -101 -103 -107 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  104 -102 -103      -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  106 -104 -105 -107 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  107                -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  101 -103 -107      -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  103 -105 -107      -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  105 -107           -130 -131 -132 -133 -134 -135 -136 -137 -138 -139

'***insert fuel compartments***

cylinder 120    7.065  480.070 0  origin x=4.15 y=7.638
hole 6  120                       origin x=4.15 y=7.638
cylinder 121    7.065  480.070 0  origin x=16.736 y=-1.481
hole 14  121                      origin x=16.736 y=-1.481
cylinder 122    7.065  480.070 0  origin x=11.928 y=-16.376
hole 6  122                       origin x=11.928 y=-16.376
cylinder 123    7.065  480.070 0  origin x=-3.628 y=-16.376
hole 6  123                       origin x=-3.628 y=-16.376
cylinder 124    7.065  480.070 0  origin x=-8.436 y=-1.481
hole 6  124                       origin x=-8.436 y=-1.481

'***bottom plate***
cylinder   130    20.841  5.1181 0      origin x=4.15 y=-5.57 z=0
cylinder   140    20.841  4.445  0.001  origin x=4.15 y=-5.57 z=0
media 0 1  130 -140 -120 -121 -122 -123 -124
media 1 1  140      -120 -121 -122 -123 -124

'***middle plate***
cylinder   131    20.841  3.2512 0      origin x=4.15 y=-5.57 z=54.953
cylinder   141    20.841  2.5781 0.6731 origin x=4.15 y=-5.57 z=54.953
media 0 1  131 -141 -120 -121 -122 -123 -124
```

```
media 1 1  141      -120 -121 -122 -123 -124

'***middle plate***
cylinder   132    20.841  3.2512 0      origin x=4.15 y=-5.57 z=108.039
cylinder   142    20.841  2.5781 0.6731 origin x=4.15 y=-5.57 z=108.039
media 0 1  132 -142 -120 -121 -122 -123 -124
media 1 1  142      -120 -121 -122 -123 -124

'***middle plate***
cylinder   133    20.841  3.2512 0       origin x=4.15 y=-5.57 z=161.125
cylinder   143    20.841  2.5781 0.6731  origin x=4.15 y=-5.57 z=161.125
media 0 1  133 -143 -120 -121 -122 -123 -124
media 1 1  143      -120 -121 -122 -123 -124

'***middle plate***
cylinder   134    20.841  3.2512 0       origin x=4.15 y=-5.57 z=214.211
cylinder   144    20.841  2.5781 0.6731  origin x=4.15 y=-5.57 z=214.211
media 0 1  134 -144 -120 -121 -122 -123 -124
media 1 1  144      -120 -121 -122 -123 -124

'***middle plate***
cylinder   135    20.841  3.2512 0       origin x=4.15 y=-5.57 z=267.297
cylinder   145    20.841  2.5781 0.6731  origin x=4.15 y=-5.57 z=267.297
media 0 1  135 -145 -120 -121 -122 -123 -124
media 1 1  145      -120 -121 -122 -123 -124

'***middle plate***
cylinder   136    20.841  3.2512 0       origin x=4.15 y=-5.57 z=320.383
cylinder   146    20.841  2.5781 0.6731  origin x=4.15 y=-5.57 z=320.383
media 0 1  136 -146 -120 -121 -122 -123 -124
media 1 1  146      -120 -121 -122 -123 -124

'***middle plate***
cylinder   137    20.841  3.2512 0       origin x=4.15 y=-5.57 z=373.469
cylinder   147    20.841  2.5781 0.6731  origin x=4.15 y=-5.57 z=373.469
media 0 1  137 -147 -120 -121 -122 -123 -124
media 1 1  147      -120 -121 -122 -123 -124

'***middle plate***
cylinder   138    20.841  3.2512 0       origin x=4.15 y=-5.57 z=426.555
cylinder   148    20.841  2.5781 0.6731  origin x=4.15 y=-5.57 z=426.555
media 0 1  138 -148 -120 -121 -122 -123 -124
media 1 1  148      -120 -121 -122 -123 -124

'***top plate
cylinder   139    20.841  2.5781 0       origin x=4.15 y=-5.57 z=479.641
cylinder   149    20.841  2.5780 0.6731  origin x=4.15 y=-5.57 z=479.641
media 0 1  139 -149 -120 -121 -122 -123 -124
media 1 1  149      -120 -121 -122 -123 -124

'***Inside of Oak Ridge Container***
cylinder 200   21.0566  482.60 -0.00001   origin x=4.15 y=-5.57
media 0 1  200 -1 -2 -3 -4 -5 -6 -7 -8 -9 -21 -22 -23 -24 -25 -26 -27 -28 -29
-31 -32 -33 -34 -35 -36 -37 -38 -39 -41 -42 -43 -44 -45 -46 -47 -48 -49
-51 -52 -53 -54 -55 -56 -57 -58 -59 -61 -62 -63 -64 -65 -66 -67 -71 -72 -73
-74 -75 -76 -77 -81 -82 -83 -84 -85 -86 -87 -91 -92 -93 -94 -95 -96 -97 -101
-102 -103 -104 -105 -106 -107 -120 -121 -122 -123 -124 -130 -131 -132 -133
-134 -135 -136 -137 -138 -139

'***outside of Oak Ridge container (including bottom and top plug)***
cylinder  201   21.400    500.38  -2.54   origin x=4.15 y=-5.57
cylinder  202   21.755    500.38  -2.54   origin x=4.15 y=-5.57
cylinder  203   22.555    500.38  -2.54   origin x=4.15 y=-5.57
media 1 1  201 -200
media 0 1  202 -201
media 6 1  203 -202
boundary 203

'***************************************************************************

global
```

```
unit 30
com='TN-FSV Cask with Oak Ridge Container'
cylinder 2   39.218    508.788 502.438 origin x=4.15 y=-5.57
cylinder 3   39.218    -9.374 -23.344  origin x=4.15 y=-5.57
cylinder 4   22.859    -2.542 -9.373   origin x=4.15 y=-5.57
cylinder 5   22.555    500.38  -2.54   origin x=4.15 y=-5.57
cylinder 6   22.860    502.437 -2.541   origin x=4.15 y=-5.57
cylinder 7   25.705    502.4371 -9.3731   origin x=4.15 y=-5.57
cylinder 8   34.442    502.4372 -9.3732   origin x=4.15 y=-5.57
cylinder 9   38.252    502.4373 -9.3733   origin x=4.15 y=-5.57
cylinder 10  38.583    502.4374 -9.3734   origin x=4.15 y=-5.57
cylinder 11  39.218    502.4375 -9.3735   origin x=4.15 y=-5.57
cylinder 12  69.698    532.917 -33.02  origin x=4.15 y=-5.57
hole 21      5
media 1 1    2
media 1 1    3
media 6 1    4
media 0 1    6 -5
media 1 1    7 -6 -4
media 5 1    8 -7
media 1 1    9 -8
media 0 1    10 -9
media 1 1    11 -10
media 4 1    12 -2 -3 -11
boundary 12

end geom
 end data
end
```

## Loading Pattern 3

## Case ORCL4-26

```
=csas26              parm=size=3000000
Loading Pattern 3
'interstitial water in canisters only
'One group 4 ORC and one IPB in all FT's      27
GROUPNDF4                  INFHOMMEDIUM
ss304          1  1.0 293 END

'POISON
B-10           2  DEN=0.03175 END
'group 4: H/X=375
URANIUM        8  DEN=0.0440  1.0  293  92235 100 end
PLUTONIUMALP   8  DEN=0.0256  1.0  293  94239 100 end
H2O            8  DEN=0.9946  1.0  293  end
'IPB:  H/X=3507
URANIUM        9  DEN=0.0074  1.0  293  92235 100 end
H2O            9  DEN=0.9978  1.0  293  end
H2O            4  1.0 293 END
PB             5  1.0 293.0 END
AL             6  1.0  293.  END
H2O            7  1.0 293 END
H2O           10  1.0e-20 293 END
H2O           11  1.0e-20 293 END
END COMP
MORE DATA dab=300 end
read parameters
NB8=300 TME=5000 GEN=300 NPG=400 RUN=yes
end parameters
READ GEOM

unit 6
com='ORC, group 4, bottom'
cylinder 1  6.8469  42.40 0.001
cylinder 2  6.847   88.265 0
media 8 1    1
```

```
media 7 1    2 -1
boundary 2

unit 7
com='Peach Bottom Assembly'
cylinder 1 6.847  330.20 101.60
cylinder 2 6.847  388.62 0
media  9 1   1
media  7 1   2 -1
boundary 2

unit 10
com='Fuel Tube - 1 IPB & 1 group 4 ORC'
cylinder 11 6.725  5.08 0    origin z=0.000001
cylinder 1  6.847  388.62 0  origin z=5.081
cylinder 2  6.847 88.265 0   origin z=393.71
cylinder 10 6.847  481.967 0 origin z=0
cylinder 12 7.065  481.967 0 origin z=0
media 1 1 12 -10
media 11 1 10 -11 -2 -1
media 1 1 11 -1
hole 7  1            origin z=5.081
hole 6  2 -1         origin z=393.71
boundary 12

'**************************************************************************

unit 21
com='one complete axial layer - layer 1 (bottom)'
'***one piece of pentagonal poison enclosure - top center****
cuboid 1 8.191 0.110 0 -0.151 482.2217 0
origin x= 0 y= 0 rotate a1=  0
wedge  2 0.110 0 -0.151  482.2217
origin x= 8.192 y= 0 rotate a1=  0
wedge  3 -0.110 0 -0.151  482.2217
origin x= 0.109 y= 0 rotate a1=  0
cuboid 4 1.348 0 0 -0.151 482.2217 0
origin x= 8.191 y= -0.151 rotate a1=  -126
cuboid 5 7.395 0.902 -1.091 -1.242 482.2217 0
origin x= 0 y= 0 rotate a1=  0
cuboid 6 0 -1.348 0 -0.151 482.2217 0
origin x= 0.110 y= -0.151 rotate a1= 126
cuboid 7 7.393 0.908 -0.211 -0.973 482.2217 0
origin x= 0 y= 0 rotate a1=  0
wedge  8 0.554 0 -0.762  482.2217
origin x= 7.394 y= -0.211 rotate a1=  0
wedge  9 -0.554 0 -0.762  482.2217
origin x= 0.907 y= -0.211 rotate a1=  0
media 1 1  1            -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  2            -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  3            -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  4 -1 -5      -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  6 -1 -5      -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  5            -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  7            -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  8            -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  9            -130 -131 -132 -133 -134 -135 -136 -137 -138 -139

'***one piece of pentagonal poison enclosure - top right****

cuboid 21 8.191 0.110 0 -0.151 482.2217 0
origin x= 8.311 y= 0.000 rotate a1=  -72
wedge 22 0.110 0 -0.151  482.2217
origin x= 10.842 y= -7.791 rotate a1=  -72
wedge 23 -0.110 0 -0.151  482.2217
origin x= 8.344 y= -0.103 rotate a1=  -72
cuboid 24 1.348 0 0 -0.151 482.2217 0
origin x= 10.698 y= -7.837 rotate a1=  -198
cuboid 25 7.395 0.902 -1.091 -1.242 482.2217 0
origin x= 8.311 y= 0.000 rotate a1=  -72
cuboid 26 0 -1.348 0 -0.151 482.2217 0
```

```
origin x= 8.201 y= -0.151 rotate a1= 54
cuboid 27 7.393 0.908 -0.211 -0.973 482.2217 0
origin x= 8.311 y= 0.000 rotate a1=  -72
wedge 28 0.554 0 -0.762  482.2217
origin x= 10.395 y= -7.097 rotate a1=  -72
wedge 29 -0.554 0 -0.762  482.2217
origin x= 8.391 y= -0.928 rotate a1=  -72
media 1 1  21                 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  22                 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  23                 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  24 -21 -25         -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  26 -21 -25         -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  25                 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  27                 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  28                 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  29                 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139

'***one piece of pentagonal poison enclosure - top left****

cuboid 31 8.191 0.110 0 -0.151 482.2217 0
origin x= -2.568 y= -7.904 rotate a1=  -288
wedge 32 0.110 0 -0.151  482.2217
origin x= -0.037 y= -0.113 rotate a1=  -288
wedge 33 -0.110 0 -0.151  482.2217
origin x= -2.535 y= -7.800 rotate a1=  -288
cuboid 34 1.348 0 0 -0.151 482.2217 0
origin x= 0.107 y= -0.161 rotate a1=  -414
cuboid 35 7.395 0.902 -1.091 -1.242 482.2217 0
origin x= -2.568 y= -7.904 rotate a1=  -288
cuboid 36 0 -1.348 0 -0.151 482.2217 0
origin x= -2.390 y= -7.846 rotate a1=  -162
cuboid 37 7.393 0.908 -0.211 -0.973 482.2217 0
origin x= -2.568 y= -7.904 rotate a1=  -288
wedge 38 0.554 0 -0.762  482.2217
origin x= -0.083 y= -0.937 rotate a1=  -288
wedge 39 -0.554 0 -0.762  482.2217
origin x= -2.088 y= -7.106 rotate a1=  -288
media 1 1  31                 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  32                 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  33                 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  34 -31 -35         -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  36 -31 -35         -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  35                 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  37                 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  38                 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  39                 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139

'***one piece of pentagonal poison enclosure - bottom left****

cuboid 41 8.191 0.110 0 -0.151 482.2217 0
origin x= 4.155 y= -12.789 rotate a1=  -216
wedge 42 0.110 0 -0.151  482.2217
origin x= -2.472 y= -7.974 rotate a1=  -216
wedge 43 -0.110 0 -0.151  482.2217
origin x= 4.067 y= -12.725 rotate a1=  -216
cuboid 44 1.348 0 0 -0.151 482.2217 0
origin x= -2.382 y= -7.852 rotate a1=  -342
cuboid 45 7.395 0.902 -1.091 -1.242 482.2217 0
origin x= 4.155 y= -12.789 rotate a1=  -216
cuboid 46 0 -1.348 0 -0.151 482.2217 0
origin x= 4.155 y= -12.602 rotate a1=  -90
cuboid 47 7.393 0.908 -0.211 -0.973 482.2217 0
origin x= 4.155 y= -12.789 rotate a1=  -216
wedge 48 0.554 0 -0.762  482.2217
origin x= -1.703 y= -8.273 rotate a1=  -216
wedge 49 -0.554 0 -0.762  482.2217
origin x= 3.545 y= -12.085 rotate a1=  -216
media 1 1  41                 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  42                 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  43                 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  44 -41 -45         -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
```

```
media 1 1  46 -41 -45         -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  45                 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  47                 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  48                 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  49                 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139

'***one piece of pentagonal poison enclosure - bottom right****

cuboid 51 8.191 0.110 0 -0.151 482.2217 0
origin x= 10.879 y= -7.904 rotate a1=  -144
wedge 52 0.110 0 -0.151  482.2217
origin x= 4.251 y= -12.719 rotate a1=  -144
wedge 53 -0.110 0 -0.151  482.2217
origin x= 10.791 y= -7.968 rotate a1=  -144
cuboid 54 1.348 0 0 -0.151 482.2217 0
origin x= 4.163 y= -12.596 rotate a1=  -270
cuboid 55 7.395 0.902 -1.091 -1.242 482.2217 0
origin x= 10.879 y= -7.904 rotate a1=  -144
cuboid 56 0 -1.348 0 -0.151 482.2217 0
origin x= 10.701 y= -7.846 rotate a1=  -18
cuboid 57 7.393 0.908 -0.211 -0.973 482.2217 0
origin x= 10.879 y= -7.904 rotate a1=  -144
wedge 58 0.554 0 -0.762  482.2217
origin x= 4.773 y= -12.080 rotate a1=  -144
wedge 59 -0.554 0 -0.762  482.2217
origin x= 10.021 y= -8.267 rotate a1=  -144
media 1 1  51                 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  52                 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  53                 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  54 -51 -55         -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  56 -51 -55         -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  55                 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  57                 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  58                 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  59                 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139

'***radial arm poison enclosure - center bottom***

cuboid 61 5.588 0.151 0.444 -0.444 482.2217 0
origin x= 4.155 y= -12.799 rotate a1= -90
cuboid 62 5.588 0.000 0.595 -0.595 482.2217 0
origin x= 4.155 y= -12.799 rotate a1= -90
cuboid 63 9.144 5.588 0.444 -0.444 482.2217 0
origin x= 4.155 y= -12.799 rotate a1= -90
cuboid 64 9.144 5.588 0.518 -0.518 482.2217 0
origin x= 4.155 y= -12.799 rotate a1= -90
cuboid 65 10.568 9.144 0.444 -0.444 482.2217 0
origin x= 4.155 y= -12.799 rotate a1= -90
cuboid 66 10.719 9.144 0.595 -0.595 482.2217 0
origin x= 4.155 y= -12.799 rotate a1= -90
cuboid 67 10.464 0.255 0.381 -0.381 482.2217 0
origin x= 4.155 y= -12.799 rotate a1= -90
media 1 1  62 -61 -63 -67 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  64 -62 -63     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  66 -64 -65 -67 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  67             -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  61 -63 -67     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  63 -65 -67     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  65 -67         -130 -131 -132 -133 -134 -135 -136 -137 -138 -139

'***radial arm poison enclosure - bottom right***

cuboid 71 5.588 0.151 0.444 -0.444 482.2217 0
origin x= 10.889 y= -7.914 rotate a1= -18
cuboid 72 5.588 0.000 0.595 -0.595 482.2217 0
origin x= 10.889 y= -7.914 rotate a1= -18
cuboid 73 9.144 5.588 0.444 -0.444 482.2217 0
origin x= 10.889 y= -7.914 rotate a1= -18
cuboid 74 9.144 5.588 0.518 -0.518 482.2217 0
origin x= 10.889 y= -7.914 rotate a1= -18
cuboid 75 10.568 9.144 0.444 -0.444 482.2217 0
```

```
origin x= 10.889 y= -7.914 rotate a1= -18
cuboid 76 10.719 9.144 0.595 -0.595 482.2217 0
origin x= 10.889 y= -7.914 rotate a1= -18
cuboid 77 10.312 0.104 0.381 -0.381 482.2217 0
origin x= 10.889 y= -7.914 rotate a1= -18
media 1 1  72 -71 -73 -77 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  74 -72 -73     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  76 -74 -75 -77 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  77             -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  71 -73 -77     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  73 -75 -77     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  75 -77         -130 -131 -132 -133 -134 -135 -136 -137 -138 -139

'***radial arm poison enclosure - bottom left***

cuboid 81 5.588 0.151 0.444 -0.444 482.2217 0
origin x= -2.578 y= -7.914 rotate a1= -162
cuboid 82 5.588 0.000 0.595 -0.595 482.2217 0
origin x= -2.578 y= -7.914 rotate a1= -162
cuboid 83 9.144 5.588 0.444 -0.444 482.2217 0
origin x= -2.578 y= -7.914 rotate a1= -162
cuboid 84 9.144 5.588 0.518 -0.518 482.2217 0
origin x= -2.578 y= -7.914 rotate a1= -162
cuboid 85 10.568 9.144 0.444 -0.444 482.2217 0
origin x= -2.578 y= -7.914 rotate a1= -162
cuboid 86 10.719 9.144 0.595 -0.595 482.2217 0
origin x= -2.578 y= -7.914 rotate a1= -162
cuboid 87 10.312 0.104 0.381 -0.381 482.2217 0
origin x= -2.578 y= -7.914 rotate a1= -162
media 1 1  82 -81 -83 -87 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  84 -82 -83     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  86 -84 -85 -87 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  87             -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  81 -83 -87     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  83 -85 -87     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  85 -87         -130 -131 -132 -133 -134 -135 -136 -137 -138 -139

'***radial arm poison enclosure - top left***

cuboid 91 5.588 0.151 0.444 -0.444 482.2217 0
origin x= 0.010 y= 0.010 rotate a1= 126
cuboid 92 5.588 0.000 0.595 -0.595 482.2217 0
origin x= 0.010 y= 0.010 rotate a1= 126
cuboid 93 9.144 5.588 0.444 -0.444 482.2217 0
origin x= 0.010 y= 0.010 rotate a1= 126
cuboid 94 9.144 5.588 0.518 -0.518 482.2217 0
origin x= 0.010 y= 0.010 rotate a1= 126
cuboid 95 10.568 9.144 0.444 -0.444 482.2217 0
origin x= 0.010 y= 0.010 rotate a1= 126
cuboid 96 10.719 9.144 0.595 -0.595 482.2217 0
origin x= 0.010 y= 0.010 rotate a1= 126
cuboid 97 10.312 0.104 0.381 -0.381 482.2217 0
origin x= 0.010 y= 0.010 rotate a1= 126
media 1 1  92 -91 -93 -97 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  94 -92 -93     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  96 -94 -95 -97 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  97             -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  91 -93 -97     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  93 -95 -97     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  95 -97         -130 -131 -132 -133 -134 -135 -136 -137 -138 -139

'***radial arm poison enclosure - top right***

cuboid 101 5.588 0.151 0.444 -0.444 482.2217 0
origin x= 8.321 y= 0.010 rotate a1= 54
cuboid 102 5.588 0.000 0.595 -0.595 482.2217 0
origin x= 8.321 y= 0.010 rotate a1= 54
cuboid 103 9.144 5.588 0.444 -0.444 482.2217 0
origin x= 8.321 y= 0.010 rotate a1= 54
cuboid 104 9.144 5.588 0.518 -0.518 482.2217 0
origin x= 8.321 y= 0.010 rotate a1= 54
```

```
cuboid 105 10.568 9.144 0.444 -0.444 482.2217 0
origin x= 8.321 y= 0.010 rotate a1= 54
cuboid 106 10.719 9.144 0.595 -0.595 482.2217 0
origin x= 8.321 y= 0.010 rotate a1= 54
cuboid 107 10.312 0.104 0.381 -0.381 482.2217 0
origin x= 8.321 y= 0.010 rotate a1= 54

media 1 1  102 -101 -103 -107 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  104 -102 -103      -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  106 -104 -105 -107 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  107                -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  101 -103 -107      -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  103 -105 -107      -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  105 -107           -130 -131 -132 -133 -134 -135 -136 -137 -138 -139

'***insert fuel compartments***

cylinder 120   7.065  481.967 0  origin x=4.15 y=7.638
hole 10  120                      origin x=4.15 y=7.638
cylinder 121   7.065  481.967 0  origin x=16.736 y=-1.481
hole 10  121                     origin x=16.736 y=-1.481
cylinder 122   7.065  481.967 0  origin x=11.928 y=-16.376
hole 10  122                      origin x=11.928 y=-16.376
cylinder 123   7.065  481.967 0  origin x=-3.628 y=-16.376
hole 10  123                     origin x=-3.628 y=-16.376
cylinder 124   7.065  481.967 0  origin x=-8.436 y=-1.481
hole 10  124                      origin x=-8.436 y=-1.481

'***bottom plate***
cylinder   130    20.841  5.1181 0       origin x=4.15 y=-5.57 z=0
cylinder   140    20.841  4.445  0.001   origin x=4.15 y=-5.57 z=0
media 11 1  130 -140 -120 -121 -122 -123 -124
media 1 1  140      -120 -121 -122 -123 -124

'***middle plate***
cylinder   131    20.841  3.2512 0       origin x=4.15 y=-5.57 z=54.953
cylinder   141    20.841  2.5781 0.6731  origin x=4.15 y=-5.57 z=54.953
media 11 1  131 -141 -120 -121 -122 -123 -124
media 1 1  141      -120 -121 -122 -123 -124

'***middle plate***
cylinder   132    20.841  3.2512 0      origin x=4.15 y=-5.57 z=108.039
cylinder   142    20.841  2.5781 0.6731 origin x=4.15 y=-5.57 z=108.039
media 11 1  132 -142 -120 -121 -122 -123 -124
media 1 1  142      -120 -121 -122 -123 -124

'***middle plate***
cylinder   133    20.841  3.2512 0       origin x=4.15 y=-5.57 z=161.125
cylinder   143    20.841  2.5781 0.6731  origin x=4.15 y=-5.57 z=161.125
media 11 1  133 -143 -120 -121 -122 -123 -124
media 1 1  143      -120 -121 -122 -123 -124

'***middle plate***
cylinder   134    20.841  3.2512 0       origin x=4.15 y=-5.57 z=214.211
cylinder   144    20.841  2.5781 0.6731  origin x=4.15 y=-5.57 z=214.211
media 11 1  134 -144 -120 -121 -122 -123 -124
media 1 1  144      -120 -121 -122 -123 -124

'***middle plate***
cylinder   135    20.841  3.2512 0       origin x=4.15 y=-5.57 z=267.297
cylinder   145    20.841  2.5781 0.6731  origin x=4.15 y=-5.57 z=267.297
media 11 1  135 -145 -120 -121 -122 -123 -124
media 1 1  145      -120 -121 -122 -123 -124

'***middle plate***
cylinder   136    20.841  3.2512 0       origin x=4.15 y=-5.57 z=320.383
cylinder   146    20.841  2.5781 0.6731  origin x=4.15 y=-5.57 z=320.383
media 11 1  136 -146 -120 -121 -122 -123 -124
media 1 1  146      -120 -121 -122 -123 -124

'***middle plate***
```

```
cylinder   137    20.841  3.2512 0       origin x=4.15 y=-5.57 z=373.469
cylinder   147    20.841  2.5781 0.6731  origin x=4.15 y=-5.57 z=373.469
media 11 1  137 -147 -120 -121 -122 -123 -124
media 1 1  147      -120 -121 -122 -123 -124

'***middle plate***
cylinder   138    20.841  3.2512 0       origin x=4.15 y=-5.57 z=426.555
cylinder   148    20.841  2.5781 0.6731  origin x=4.15 y=-5.57 z=426.555
media 11 1  138 -148 -120 -121 -122 -123 -124
media 1 1  148      -120 -121 -122 -123 -124

'***top plate
cylinder   139    20.841  2.5781 0       origin x=4.15 y=-5.57 z=479.641
cylinder   149    20.841  2.5780 0.6731  origin x=4.15 y=-5.57 z=479.641
media 11 1  139 -149 -120 -121 -122 -123 -124
media 1 1  149      -120 -121 -122 -123 -124

'***Inside of Oak Ridge Container***
cylinder 200   21.0566  482.60 -0.00001   origin x=4.15 y=-5.57
media 0 1  200 -1 -2 -3 -4 -5 -6 -7 -8 -9 -21 -22 -23 -24 -25 -26 -27 -28 -29
-31 -32 -33 -34 -35 -36 -37 -38 -39 -41 -42 -43 -44 -45 -46 -47 -48 -49
-51 -52 -53 -54 -55 -56 -57 -58 -59 -61 -62 -63 -64 -65 -66 -67 -71 -72 -73
-74 -75 -76 -77 -81 -82 -83 -84 -85 -86 -87 -91 -92 -93 -94 -95 -96 -97 -101
-102 -103 -104 -105 -106 -107 -120 -121 -122 -123 -124 -130 -131 -132 -133
-134 -135 -136 -137 -138 -139

'***outside of Oak Ridge container (including bottom and top plug)***
cylinder  201   21.400    500.38  -2.54   origin x=4.15 y=-5.57
cylinder  202   21.755    500.38  -2.54   origin x=4.15 y=-5.57
cylinder  203   22.555    500.38  -2.54   origin x=4.15 y=-5.57
media 1 1  201 -200
media 11 1  202 -201
media 6 1  203 -202
boundary 203

'************************************************************************

global
unit 30
com='TN-FSV Cask with Oak Ridge Container'
cylinder 2   39.218   508.788 502.438 origin x=4.15 y=-5.57
cylinder 3   39.218   -9.374 -23.344  origin x=4.15 y=-5.57
cylinder 4   22.859   -2.542 -9.373   origin x=4.15 y=-5.57
cylinder 5   22.555   500.38  -2.54   origin x=4.15 y=-5.57
cylinder 6   22.860   502.437 -2.541   origin x=4.15 y=-5.57
cylinder 7   25.705   502.4371 -9.3731   origin x=4.15 y=-5.57
cylinder 8   34.442   502.4372 -9.3732   origin x=4.15 y=-5.57
cylinder 9   38.252   502.4373 -9.3733   origin x=4.15 y=-5.57
cylinder 10  38.583   502.4374 -9.3734   origin x=4.15 y=-5.57
cylinder 11  39.218   502.4375 -9.3735   origin x=4.15 y=-5.57
cylinder 12  69.698   532.917 -33.02  origin x=4.15 y=-5.57
hole 21      5
media 1 1    2
media 1 1    3
media 6 1    4
media 11 1    6 -5
media 1 1    7 -6 -4
media 5 1    8 -7
media 1 1    9 -8
media 11 1    10 -9
media 1 1    11 -10
media 4 1    12 -2 -3 -11
boundary 12

end geom
 end data
end
```

## Loading Pattern 4

## Case ORCL5-5

```
=csas26              parm=size=3000000
Loading Pattern 4
'two Group 3 and two Group 4 ORCs in Fuel Tube 1
'one Group 4 ORC and one IPB in Fuel Tubes 2 - 5
27GROUPNDF4                    INFHOMMEDIUM
ss304            1  1.0 293 END
'POISON
B-10             2  DEN=0.03175 END
'group 4: H/X=375
URANIUM          8  DEN=0.0440  1.0  293  92235 100 end
PLUTONIUMALP     8  DEN=0.0256  1.0  293  94239 100 end
H2O              8  DEN=0.9946  1.0  293  end
'IPB:  H/X=3507
URANIUM          9  DEN=0.0074  1.0  293  92235 100 end
H2O              9  DEN=0.9978  1.0  293  end
'group 4: H/X=300
URANIUM         10  DEN=0.0550  1.0  293  92235 100 end
PLUTONIUMALP    10  DEN=0.0320  1.0  293  94239 100 end
H2O             10  DEN=0.9937  1.0  293  end
'group 3: H/X=300
URANIUM         11  DEN=0.0284  1.0  293  92235 100 end
PLUTONIUMALP    11  DEN=0.0590  1.0  293  94239 100 end
H2O             11  DEN=0.9937  1.0  293  end
H2O              4  1.0 293 END
PB               5  1.0 293.0 END
AL               6  1.0   293.   END
H2O              7  1.0e-20 293 END
END COMP
MORE DATA dab=300 end
read parameters
NB8=300 TME=5000 GEN=300 NPG=400 RUN=yes
end parameters
READ GEOM

unit 2
com='flux trap spacer'
cylinder 1  6.35  40.64 0
cylinder 2  5.08  39.68 34.93
cylinder 3  5.95  33.03 32.95
cylinder 4  5.95  32.51 2.67
cylinder 5  5.95  2.03 1.27
media 1 1   1 -2 -3 -4 -5
media 2 1   3
media 2 1   5
media 0 1   2
media 0 1   4
boundary 1

unit 6
com='ORC, group 4, bottom'
cylinder 1  6.8469  42.40 0.001
cylinder 2  6.847   88.265 0
media 8 1    1
media 7 1    2 -1
boundary 2

unit 7
com='Peach Bottom Assembly'
cylinder 1 6.847  330.20 101.60
cylinder 2 6.847  388.62 0
media  9 1   1
media  7 1   2 -1
boundary 2

unit 10
```

```
com='Fuel Tube - 1 IPB & 1 group 4 ORC'
cylinder 11 6.725  5.08 0    origin z=0.000001
cylinder 1  6.847  388.62 0  origin z=5.081
cylinder 2  6.847 88.265 0   origin z=393.71
cylinder 10 6.847  481.967 0 origin z=0
cylinder 12 7.065  481.967 0 origin z=0
media 1 1 12 -10
media 0 1 10 -11 -2 -1
media 1 1 11 -1
hole 7  1           origin z=5.081
hole 6  2 -1        origin z=393.71
boundary 12

unit 11
com='ORC, group 3, centered'
cylinder 1  6.8469  68.01 20.26
cylinder 2  6.847   88.265 0
media 11 1    1
media 7  1    2 -1
boundary 2

unit 12
com='ORC, group 3, bottom'
cylinder 1  6.8469  47.75  0.001
cylinder 2  6.847   88.265 0
media 11 1    1
media 7  1    2 -1
boundary 2

unit 14
com='ORC, group 4, centered'
cylinder 1  6.8469  61.11 27.16
cylinder 2  6.847   88.265 0
media 10 1    1
media 7  1    2 -1
boundary 2

unit 15
com='ORC, group 4, top'
cylinder 1  6.8469  88.264 54.31
cylinder 2  6.847   88.265 0
media 10 1    1
media 7  1    2 -1
boundary 2

unit 17
com='FT 5'
cylinder 11 6.725  5.08 0    origin z=0.00001
cylinder 1  6.847  88.265 0  origin z=5.081
cylinder 2  6.350  40.64 0   origin z=93.347
cylinder 3  6.847  88.265 0  origin z=133.988
cylinder 4  6.350  40.64 0   origin z=222.254
cylinder 5  6.847  88.265 0  origin z=262.895
cylinder 6  6.350  40.64 0   origin z=351.161
cylinder 7  6.847  88.265 0  origin z=391.802
cylinder 10 6.847  480.069 0 origin z=0
cylinder 12 7.065  480.070 0 origin z=0
media 1 1  12 -10
media 0 1  10 -11 -7 -6 -5 -4 -3 -2 -1
media 1 1  11 -1
hole 15  1            origin z=5.081
hole  2  2 -1 -3      origin z=93.347
hole 14  3            origin z=133.988
hole  2  4 -3 -5      origin z=222.254
hole 11  5            origin z=262.895
hole  2  6 -5 -7      origin z=351.161
hole 12  7            origin z=391.802
boundary 12

'**************************************************************************
```

```
unit 21
com='one complete axial layer - layer 1 (bottom)'
'***one piece of pentagonal poison enclosure - top center****
cuboid 1 8.191 0.110 0 -0.151 482.2217 0
origin x= 0 y= 0 rotate a1=  0
wedge  2 0.110 0 -0.151  482.2217
origin x= 8.192 y= 0 rotate a1=  0
wedge  3 -0.110 0 -0.151  482.2217
origin x= 0.109 y= 0 rotate a1=  0
cuboid 4 1.348 0 0 -0.151 482.2217 0
origin x= 8.191 y= -0.151 rotate a1=  -126
cuboid 5 7.395 0.902 -1.091 -1.242 482.2217 0
origin x= 0 y= 0 rotate a1=  0
cuboid 6 0 -1.348 0 -0.151 482.2217 0
origin x= 0.110 y= -0.151 rotate a1= 126
cuboid 7 7.393 0.908 -0.211 -0.973 482.2217 0
origin x= 0 y= 0 rotate a1=  0
wedge  8 0.554 0 -0.762  482.2217
origin x= 7.394 y= -0.211 rotate a1=  0
wedge  9 -0.554 0 -0.762  482.2217
origin x= 0.907 y= -0.211 rotate a1=  0
media 1 1  1               -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  2               -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  3               -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  4 -1 -5         -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  6 -1 -5         -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  5               -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  7               -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  8               -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  9               -130 -131 -132 -133 -134 -135 -136 -137 -138 -139

'***one piece of pentagonal poison enclosure - top right****

cuboid 21 8.191 0.110 0 -0.151 482.2217 0
origin x= 8.311 y= 0.000 rotate a1=  -72
wedge 22 0.110 0 -0.151  482.2217
origin x= 10.842 y= -7.791 rotate a1=  -72
wedge 23 -0.110 0 -0.151  482.2217
origin x= 8.344 y= -0.103 rotate a1=  -72
cuboid 24 1.348 0 0 -0.151 482.2217 0
origin x= 10.698 y= -7.837 rotate a1=  -198
cuboid 25 7.395 0.902 -1.091 -1.242 482.2217 0
origin x= 8.311 y= 0.000 rotate a1=  -72
cuboid 26 0 -1.348 0 -0.151 482.2217 0
origin x= 8.201 y= -0.151 rotate a1= 54
cuboid 27 7.393 0.908 -0.211 -0.973 482.2217 0
origin x= 8.311 y= 0.000 rotate a1=  -72
wedge 28 0.554 0 -0.762  482.2217
origin x= 10.395 y= -7.097 rotate a1=  -72
wedge 29 -0.554 0 -0.762  482.2217
origin x= 8.391 y= -0.928 rotate a1=  -72
media 1 1  21              -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  22              -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  23              -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  24 -21 -25      -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  26 -21 -25      -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  25              -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  27              -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  28              -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  29              -130 -131 -132 -133 -134 -135 -136 -137 -138 -139

'***one piece of pentagonal poison enclosure - top left****

cuboid 31 8.191 0.110 0 -0.151 482.2217 0
origin x= -2.568 y= -7.904 rotate a1=  -288
wedge 32 0.110 0 -0.151  482.2217
origin x= -0.037 y= -0.113 rotate a1=  -288
wedge 33 -0.110 0 -0.151  482.2217
origin x= -2.535 y= -7.800 rotate a1=  -288
cuboid 34 1.348 0 0 -0.151 482.2217 0
origin x= 0.107 y= -0.161 rotate a1=  -414
```

```
cuboid 35 7.395 0.902 -1.091 -1.242 482.2217 0
origin x= -2.568 y= -7.904 rotate a1=  -288
cuboid 36 0 -1.348 0 -0.151 482.2217 0
origin x= -2.390 y= -7.846 rotate a1=  -162
cuboid 37 7.393 0.908 -0.211 -0.973 482.2217 0
origin x= -2.568 y= -7.904 rotate a1=  -288
wedge 38 0.554 0 -0.762  482.2217
origin x= -0.083 y= -0.937 rotate a1=  -288
wedge 39 -0.554 0 -0.762  482.2217
origin x= -2.088 y= -7.106 rotate a1=  -288
media 1 1  31                -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  32                -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  33                -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  34 -31 -35        -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  36 -31 -35        -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  35                -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  37                -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  38                -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  39                -130 -131 -132 -133 -134 -135 -136 -137 -138 -139

'***one piece of pentagonal poison enclosure - bottom left****

cuboid 41 8.191 0.110 0 -0.151 482.2217 0
origin x= 4.155 y= -12.789 rotate a1=  -216
wedge 42 0.110 0 -0.151  482.2217
origin x= -2.472 y= -7.974 rotate a1=  -216
wedge 43 -0.110 0 -0.151  482.2217
origin x= 4.067 y= -12.725 rotate a1=  -216
cuboid 44 1.348 0 0 -0.151 482.2217 0
origin x= -2.382 y= -7.852 rotate a1=  -342
cuboid 45 7.395 0.902 -1.091 -1.242 482.2217 0
origin x= 4.155 y= -12.789 rotate a1=  -216
cuboid 46 0 -1.348 0 -0.151 482.2217 0
origin x= 4.155 y= -12.602 rotate a1=  -90
cuboid 47 7.393 0.908 -0.211 -0.973 482.2217 0
origin x= 4.155 y= -12.789 rotate a1=  -216
wedge 48 0.554 0 -0.762  482.2217
origin x= -1.703 y= -8.273 rotate a1=  -216
wedge 49 -0.554 0 -0.762  482.2217
origin x= 3.545 y= -12.085 rotate a1=  -216
media 1 1  41                -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  42                -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  43                -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  44 -41 -45        -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  46 -41 -45        -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  45                -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  47                -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  48                -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  49                -130 -131 -132 -133 -134 -135 -136 -137 -138 -139

'***one piece of pentagonal poison enclosure - bottom right****

cuboid 51 8.191 0.110 0 -0.151 482.2217 0
origin x= 10.879 y= -7.904 rotate a1=  -144
wedge 52 0.110 0 -0.151  482.2217
origin x= 4.251 y= -12.719 rotate a1=  -144
wedge 53 -0.110 0 -0.151  482.2217
origin x= 10.791 y= -7.968 rotate a1=  -144
cuboid 54 1.348 0 0 -0.151 482.2217 0
origin x= 4.163 y= -12.596 rotate a1=  -270
cuboid 55 7.395 0.902 -1.091 -1.242 482.2217 0
origin x= 10.879 y= -7.904 rotate a1=  -144
cuboid 56 0 -1.348 0 -0.151 482.2217 0
origin x= 10.701 y= -7.846 rotate a1=  -18
cuboid 57 7.393 0.908 -0.211 -0.973 482.2217 0
origin x= 10.879 y= -7.904 rotate a1=  -144
wedge 58 0.554 0 -0.762  482.2217
origin x= 4.773 y= -12.080 rotate a1=  -144
wedge 59 -0.554 0 -0.762  482.2217
origin x= 10.021 y= -8.267 rotate a1=  -144
media 1 1  51                -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
```

```
media 1 1  52              -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  53              -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  54 -51 -55      -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  56 -51 -55      -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  55              -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  57              -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  58              -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  59              -130 -131 -132 -133 -134 -135 -136 -137 -138 -139

'***radial arm poison enclosure - center bottom***

cuboid 61 5.588 0.151 0.444 -0.444 482.2217 0
origin x= 4.155 y= -12.799 rotate a1= -90
cuboid 62 5.588 0.000 0.595 -0.595 482.2217 0
origin x= 4.155 y= -12.799 rotate a1= -90
cuboid 63 9.144 5.588 0.444 -0.444 482.2217 0
origin x= 4.155 y= -12.799 rotate a1= -90
cuboid 64 9.144 5.588 0.518 -0.518 482.2217 0
origin x= 4.155 y= -12.799 rotate a1= -90
cuboid 65 10.568 9.144 0.444 -0.444 482.2217 0
origin x= 4.155 y= -12.799 rotate a1= -90
cuboid 66 10.719 9.144 0.595 -0.595 482.2217 0
origin x= 4.155 y= -12.799 rotate a1= -90
cuboid 67 10.464 0.255 0.381 -0.381 482.2217 0
origin x= 4.155 y= -12.799 rotate a1= -90
media 1 1  62 -61 -63 -67 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  64 -62 -63     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  66 -64 -65 -67 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  67             -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  61 -63 -67     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  63 -65 -67     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  65 -67         -130 -131 -132 -133 -134 -135 -136 -137 -138 -139

'***radial arm poison enclosure - bottom right***

cuboid 71 5.588 0.151 0.444 -0.444 482.2217 0
origin x= 10.889 y= -7.914 rotate a1= -18
cuboid 72 5.588 0.000 0.595 -0.595 482.2217 0
origin x= 10.889 y= -7.914 rotate a1= -18
cuboid 73 9.144 5.588 0.444 -0.444 482.2217 0
origin x= 10.889 y= -7.914 rotate a1= -18
cuboid 74 9.144 5.588 0.518 -0.518 482.2217 0
origin x= 10.889 y= -7.914 rotate a1= -18
cuboid 75 10.568 9.144 0.444 -0.444 482.2217 0
origin x= 10.889 y= -7.914 rotate a1= -18
cuboid 76 10.719 9.144 0.595 -0.595 482.2217 0
origin x= 10.889 y= -7.914 rotate a1= -18
cuboid 77 10.312 0.104 0.381 -0.381 482.2217 0
origin x= 10.889 y= -7.914 rotate a1= -18
media 1 1  72 -71 -73 -77 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  74 -72 -73     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  76 -74 -75 -77 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  77             -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  71 -73 -77     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  73 -75 -77     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  75 -77         -130 -131 -132 -133 -134 -135 -136 -137 -138 -139

'***radial arm poison enclosure - bottom left***

cuboid 81 5.588 0.151 0.444 -0.444 482.2217 0
origin x= -2.578 y= -7.914 rotate a1= -162
cuboid 82 5.588 0.000 0.595 -0.595 482.2217 0
origin x= -2.578 y= -7.914 rotate a1= -162
cuboid 83 9.144 5.588 0.444 -0.444 482.2217 0
origin x= -2.578 y= -7.914 rotate a1= -162
cuboid 84 9.144 5.588 0.518 -0.518 482.2217 0
origin x= -2.578 y= -7.914 rotate a1= -162
cuboid 85 10.568 9.144 0.444 -0.444 482.2217 0
origin x= -2.578 y= -7.914 rotate a1= -162
cuboid 86 10.719 9.144 0.595 -0.595 482.2217 0
origin x= -2.578 y= -7.914 rotate a1= -162
```

```
cuboid 87 10.312 0.104 0.381 -0.381 482.2217 0
origin x= -2.578 y= -7.914 rotate a1= -162
media 1 1  82 -81 -83 -87 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  84 -82 -83     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  86 -84 -85 -87 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  87             -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  81 -83 -87     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  83 -85 -87     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  85 -87         -130 -131 -132 -133 -134 -135 -136 -137 -138 -139

'***radial arm poison enclosure - top left***

cuboid 91 5.588 0.151 0.444 -0.444 482.2217 0
origin x= 0.010 y= 0.010 rotate a1= 126
cuboid 92 5.588 0.000 0.595 -0.595 482.2217 0
origin x= 0.010 y= 0.010 rotate a1= 126
cuboid 93 9.144 5.588 0.444 -0.444 482.2217 0
origin x= 0.010 y= 0.010 rotate a1= 126
cuboid 94 9.144 5.588 0.518 -0.518 482.2217 0
origin x= 0.010 y= 0.010 rotate a1= 126
cuboid 95 10.568 9.144 0.444 -0.444 482.2217 0
origin x= 0.010 y= 0.010 rotate a1= 126
cuboid 96 10.719 9.144 0.595 -0.595 482.2217 0
origin x= 0.010 y= 0.010 rotate a1= 126
cuboid 97 10.312 0.104 0.381 -0.381 482.2217 0
origin x= 0.010 y= 0.010 rotate a1= 126
media 1 1  92 -91 -93 -97 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  94 -92 -93     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  96 -94 -95 -97 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  97             -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  91 -93 -97     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  93 -95 -97     -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  95 -97         -130 -131 -132 -133 -134 -135 -136 -137 -138 -139

'***radial arm poison enclosure - top right***

cuboid 101 5.588 0.151 0.444 -0.444 482.2217 0
origin x= 8.321 y= 0.010 rotate a1= 54
cuboid 102 5.588 0.000 0.595 -0.595 482.2217 0
origin x= 8.321 y= 0.010 rotate a1= 54
cuboid 103 9.144 5.588 0.444 -0.444 482.2217 0
origin x= 8.321 y= 0.010 rotate a1= 54
cuboid 104 9.144 5.588 0.518 -0.518 482.2217 0
origin x= 8.321 y= 0.010 rotate a1= 54
cuboid 105 10.568 9.144 0.444 -0.444 482.2217 0
origin x= 8.321 y= 0.010 rotate a1= 54
cuboid 106 10.719 9.144 0.595 -0.595 482.2217 0
origin x= 8.321 y= 0.010 rotate a1= 54
cuboid 107 10.312 0.104 0.381 -0.381 482.2217 0
origin x= 8.321 y= 0.010 rotate a1= 54

media 1 1  102 -101 -103 -107 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  104 -102 -103      -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 1 1  106 -104 -105 -107 -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 2 1  107                -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  101 -103 -107      -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  103 -105 -107      -130 -131 -132 -133 -134 -135 -136 -137 -138 -139
media 0 1  105 -107           -130 -131 -132 -133 -134 -135 -136 -137 -138 -139

'***insert fuel compartments***

cylinder 120    7.065  481.967 0   origin x=4.15 y=7.638
hole 10  120                        origin x=4.15 y=7.638
cylinder 121    7.065  480.070 0   origin x=16.736 y=-1.481
hole 17  121                       origin x=16.736 y=-1.481
cylinder 122    7.065  481.967 0   origin x=11.928 y=-16.376
hole 10  122                        origin x=11.928 y=-16.376
cylinder 123    7.065  481.967 0   origin x=-3.628 y=-16.376
hole 10  123                       origin x=-3.628 y=-16.376
cylinder 124    7.065  481.967 0   origin x=-8.436 y=-1.481
hole 10  124                        origin x=-8.436 y=-1.481
```

```
'***bottom plate***
cylinder   130    20.841  5.1181 0        origin x=4.15 y=-5.57 z=0
cylinder   140    20.841  4.445  0.001    origin x=4.15 y=-5.57 z=0
media 0 1  130 -140 -120 -121 -122 -123 -124
media 1 1  140      -120 -121 -122 -123 -124

'***middle plate***
cylinder   131    20.841  3.2512 0        origin x=4.15 y=-5.57 z=54.953
cylinder   141    20.841  2.5781 0.6731   origin x=4.15 y=-5.57 z=54.953
media 0 1  131 -141 -120 -121 -122 -123 -124
media 1 1  141      -120 -121 -122 -123 -124

'***middle plate***
cylinder   132    20.841  3.2512 0      origin x=4.15 y=-5.57 z=108.039
cylinder   142    20.841  2.5781 0.6731 origin x=4.15 y=-5.57 z=108.039
media 0 1  132 -142 -120 -121 -122 -123 -124
media 1 1  142      -120 -121 -122 -123 -124

'***middle plate***
cylinder   133    20.841  3.2512 0        origin x=4.15 y=-5.57 z=161.125
cylinder   143    20.841  2.5781 0.6731   origin x=4.15 y=-5.57 z=161.125
media 0 1  133 -143 -120 -121 -122 -123 -124
media 1 1  143      -120 -121 -122 -123 -124

'***middle plate***
cylinder   134    20.841  3.2512 0        origin x=4.15 y=-5.57 z=214.211
cylinder   144    20.841  2.5781 0.6731   origin x=4.15 y=-5.57 z=214.211
media 0 1  134 -144 -120 -121 -122 -123 -124
media 1 1  144      -120 -121 -122 -123 -124

'***middle plate***
cylinder   135    20.841  3.2512 0        origin x=4.15 y=-5.57 z=267.297
cylinder   145    20.841  2.5781 0.6731   origin x=4.15 y=-5.57 z=267.297
media 0 1  135 -145 -120 -121 -122 -123 -124
media 1 1  145      -120 -121 -122 -123 -124

'***middle plate***
cylinder   136    20.841  3.2512 0        origin x=4.15 y=-5.57 z=320.383
cylinder   146    20.841  2.5781 0.6731   origin x=4.15 y=-5.57 z=320.383
media 0 1  136 -146 -120 -121 -122 -123 -124
media 1 1  146      -120 -121 -122 -123 -124

'***middle plate***
cylinder   137    20.841  3.2512 0        origin x=4.15 y=-5.57 z=373.469
cylinder   147    20.841  2.5781 0.6731   origin x=4.15 y=-5.57 z=373.469
media 0 1  137 -147 -120 -121 -122 -123 -124
media 1 1  147      -120 -121 -122 -123 -124

'***middle plate***
cylinder   138    20.841  3.2512 0        origin x=4.15 y=-5.57 z=426.555
cylinder   148    20.841  2.5781 0.6731   origin x=4.15 y=-5.57 z=426.555
media 0 1  138 -148 -120 -121 -122 -123 -124
media 1 1  148      -120 -121 -122 -123 -124

'***top plate
cylinder   139    20.841  2.5781 0        origin x=4.15 y=-5.57 z=479.641
cylinder   149    20.841  2.5780 0.6731   origin x=4.15 y=-5.57 z=479.641
media 0 1  139 -149 -120 -121 -122 -123 -124
media 1 1  149      -120 -121 -122 -123 -124

'***Inside of Oak Ridge Container***
cylinder 200   21.0566  482.60 -0.00001   origin x=4.15 y=-5.57
media 0 1  200 -1 -2 -3 -4 -5 -6 -7 -8 -9 -21 -22 -23 -24 -25 -26 -27 -28 -29
-31 -32 -33 -34 -35 -36 -37 -38 -39 -41 -42 -43 -44 -45 -46 -47 -48 -49
-51 -52 -53 -54 -55 -56 -57 -58 -59 -61 -62 -63 -64 -65 -66 -67 -71 -72 -73
-74 -75 -76 -77 -81 -82 -83 -84 -85 -86 -87 -91 -92 -93 -94 -95 -96 -97 -101
-102 -103 -104 -105 -106 -107 -120 -121 -122 -123 -124 -130 -131 -132 -133
-134 -135 -136 -137 -138 -139

'***outside of Oak Ridge container (including bottom and top plug)***
```

```
cylinder  201   21.400    500.38  -2.54   origin x=4.15 y=-5.57
cylinder  202   21.755    500.38  -2.54   origin x=4.15 y=-5.57
cylinder  203   22.555    500.38  -2.54   origin x=4.15 y=-5.57
media 1 1  201 -200
media 0 1  202 -201
media 6 1  203 -202
boundary 203

'**************************************************************************

global
unit 30
com='TN-FSV Cask with Oak Ridge Container'
cylinder 2   39.218   508.788 502.438 origin x=4.15 y=-5.57
cylinder 3   39.218   -9.374 -23.344  origin x=4.15 y=-5.57
cylinder 4   22.859   -2.542 -9.373   origin x=4.15 y=-5.57
cylinder 5   22.555   500.38  -2.54   origin x=4.15 y=-5.57
cylinder 6   22.860   502.437 -2.541   origin x=4.15 y=-5.57
cylinder 7   25.705   502.4371 -9.3731   origin x=4.15 y=-5.57
cylinder 8   34.442   502.4372 -9.3732   origin x=4.15 y=-5.57
cylinder 9   38.252   502.4373 -9.3733   origin x=4.15 y=-5.57
cylinder 10  38.583   502.4374 -9.3734   origin x=4.15 y=-5.57
cylinder 11  39.218   502.4375 -9.3735   origin x=4.15 y=-5.57
cylinder 12  69.698   532.917 -33.02  origin x=4.15 y=-5.57
hole 21      5
media 1 1    2
media 1 1    3
media 6 1    4
media 0 1    6 -5
media 1 1    7 -6 -4
media 5 1    8 -7
media 1 1    9 -8
media 0 1    10 -9
media 1 1    11 -10
media 4 1    12 -2 -3 -11
boundary 12

end geom
 end data
end
```

# 7.0 OPERATING PROCEDURES

This chapter contains the TN-FSV packaging loading and handling procedure guidelines that show the general approach to cask operational activities. The guidelines provided in the SAR have been revised to reflect the alternate contents presented in this Addendum, and the package handling capabilities/limitations at the Oak Ridge and INEEL sites. The Oak Ridge Container may remain installed within the TN-FSV cask for the duration of the Oak Ridge SNF transport campaign.

The information in this chapter will be used to prepare site-specific procedures. The operational steps shown must be performed in order to maintain the validity of cask transport regulations and safety analysis conclusions.

The procedures in this section are for those activities associated with the loading and transport of the Oak SNF canisters and the Peach Bottom fuel assemblies. The loading will be performed from an on-site shielded carrier to the TN-FSV packaging at Oak Ridge in an outdoor facility. The SNF will be unloaded from the TN-FSV packaging at INEEL in a cell-type facility.

## 7.1 Package Loading

### 7.1.1 Preparation for Loading

7.1.1.1 Upon arrival of the empty packaging on its semitrailer, perform a receipt inspection to check for any damages or irregularities. Perform a radiation survey. Verify that the records for the packaging are complete and accurate.

7.1.1.2 Back the tractor and semitrailer onto the loading area.

7.1.1.3 Remove the personnel barrier, if used.

7.1.1.4 Remove the security device, the impact limiter attachment bolts, and remove the front and rear impact limiters using a suitable crane and three legged sling.

7.1.1.5 If necessary, clean the cask external surfaces of road dirt.

7.1.1.6 Release the trunnion tie-downs.

7.1.1.7 Release the front saddle tie-downs.

7.1.1.8 Engage the cask lifting apparatus in the recessed lifting sockets. Use hand-crank to lock the balls in the sockets.

7.1.1.9 Raise the shipping cask to the vertical position. This may require moving the trailer forward while the cask is being lifted.

7.1.1.10 Lift cask from the semi-trailer and place in cask loading station.

7.1.1.11 Install cask restraints to secure it in the vertical orientation.

7.1.1.12 Disengage the cask lifting apparatus from the cask.

7.1.1.13 Install the cask lid lifting attachments.

7.1.1.14 Remove and visually inspect for damage the twelve (12) socket bolts that hold the cask lid in place. Replace any bolt found to have stripped or galled threads or any visible deformation of the head or shank. Minor nicks, scrapes or upsets from normal wrench contact are not cause for replacement. Replace defective bolts and note any defect indications on the cask loading report.

7.1.1.15 Lift the cask lid from the cask and store for examination.

7.1.1.16 Install the Oak Ridge Container (ORC) lid lifting attachments.

7.1.1.17 Remove and visually inspect for damage the twelve (12) bolts that hold the Container lid in place. Replace any bolt found to have stripped or galled threads or any visible deformation of the head or shank. Minor nicks, scrapes or upsets from normal wrench contact are not cause for replacement. Replace defective bolts and note any defect indications on the cask loading report.

7.1.1.18 Lift the ORC lid from the cask and store for examination.

7.1.1.19 Remove vent port covers from the cask and ORC lids.

7.1.1.20 Examine the sealing surfaces (including vent port cover surfaces) in the cask lid and ORC lid for defects that may prevent a proper seal.

7.1.1.21 Inspect the lid and vent port o-rings in the cask and Container lids for damage and replace if defects are noted. Record inspection results on the cask loading report. Note: Butyl o-rings are required for this Configuration 2.

7.1.1.22 Visually inspect the ORC fuel compartment cavities for any damage or debris. If any is noted, evaluate and take corrective action if necessary.

## 7.1.2 Dry Loading

Note: The TN-FSV cask drain port is not used for loading operations.

7.1.2.1 Using the Loading Plan established for each shipment, transfer the Oak Ridge canisters, Peach Bottom fuel assemblies and flux trap spacers to the pre-determined location in the ORC (as appropriate) one at a time using the shielded on-site carrier into the cask. The shielded carrier, containing one canister, is positioned above the cask, and the canister is lowered vertically into the designated position in the ORC. The Loading Plan and supporting procedures shall be developed to ensure that the SNF loading into the cask meets the loading arrangements permitted by this addendum. The following criteria apply:

- Each Oak Ridge canister shall be placed into a fissile content group based on the isotopic content limits for each group defined in Table 6-2.
- A flux trap spacer shall be installed between every Oak Ridge Canister.
- When a Peach Bottom fuel assembly and an Oak Ridge canister are placed in the same fuel compartment, the Peach Bottom fuel assembly shall be placed on top.
- The Oak Ridge Container shall be loaded in accordance with the loading patterns defined in Table 6-3.
- The maximum Oak Ridge Container heat load shall not exceed 120 watts.
- The maximum heat load in an Oak Ridge canister shall not exceed 35 watts.
- The maximum heat load in a cross section, with a length corresponding to the axial length of the Oak Ridge canister length shall not exceed 55 watts.
- The maximum heat load in an Oak Ridge canister shall not exceed 7 watts for canisters placed next to the Container lid.
- The measured dose rates on the canisters shall be checked against the "screening" equation (a), in Section 5.1 for load acceptability.
- The maximum weight of a loaded Oak Ridge canister shall not exceed 95 lb.
- The maximum weight of a loaded Peach Bottom canister shall not exceed 155 lb.
- The total weight for all canisters in a shipment (either all Oak Ridge canisters or a combination of Oak Ridge and Peach Bottom canisters) shall not exceed 1600 lb.
- The loading operations shall be performed utilizing a checklist where each item loaded is identified and recorded.
- An independent observation and documentation of the loading operations shall also be performed to assure that the loaded contents meet the Certificate of Compliance.

Note: A loaded ORC with completely empty fuel compartment(s) is acceptable; however, a partially loaded fuel compartment must be filled with empty canisters and spacers to achieve a "fully loaded" height.

7.1.2.2 After the ORC has been loaded, prior to closing, verification that the top canister is within an inch of the top of each fuel compartment shall be performed and documented. An independent verification of this shall also be performed and documented. If a fuel compartment has been loaded incorrectly, all canisters shall be removed and the compartment reloaded correctly.

7.1.2.3 Transfer the ORC lid to a position directly over the ORC cavity. Establish correct lid orientation using the alignment pins and lower the lid on to the Container until fully seated. Visually verify the ORC lid for proper installation.

7.1.2.4 Apply a light coating of Nuclear Grade Neolube to bolt threads and install all 12 ORC lid bolts. Tighten to hand tight. Torque all lid bolts to the required value in several stages. Follow an approved torquing sequence. (Torque values are listed on drawings in Chapter 1.0.)

7.1.2.5 Install Leak Test System (LTS) to vent port and evacuate the ORC. Back fill with dry (bottled) air to 1 atm pressure.

7.1.2.6 Install the vent port cover and bolts. Torque the bolts to the required value. (Torque values are listed on drawings in Chapter 1.0.)

7.1.2.7 Remove ORC lid o-ring test port plug. Install the LTS to the test port and evacuate the lid and vent port cover seal interspace until the pressure is reduced to 10, +2, -0 mbar.

7.1.2.8 Perform a pressure rise leakage test for pre-shipment leakage rate test of the ORC lid inner seal and the vent port cover inner seal.

The leakage rate ($L_T$)is calculated by

$$L_T = \frac{V \times \Delta P \times 298}{t \times 1013 \times T} \qquad (\text{ref}\cdot\text{cm}^3/\text{s})$$

where $V$ = test volume ($cm^3$)
$\Delta P$ = measured pressure difference (mbar)
$t$ = elapsed time for the test (s), and
$T$ = temperature of test ($^oK$)

It is assumed that over the relatively short duration of the test (1-2 minutes), the change in temperature is insignificant.

The test must have a sensitivity of at least $1 \times 10^{-3}$ ref·cm$^3$/s.

The acceptance criterion is no detected leakage.

7.1.2.9 Replace the ORC lid o-ring test port plug.

7.1.2.10 Inspect the lid o-rings for damage and replace if defects are noted. Record on the cask loading report. Note: Butyl o-rings are required for Configuration 2.

7.1.2.11 Transfer the cask lid to a position directly over the cask cavity. Establish correct lid orientation using the orientation marks and lower the lid until fully seated. Visually verify the lid for proper installation.

7.1.2.12 Apply a light coating of Nuclear Grade Neolube to bolt threads and install all 12 cask lid bolts. Tighten to hand tight. Torque all lid bolts to the required value in several stages. Follow an approved torquing sequence. (Torque values are listed on drawings in Chapter 1.0.)

7.1.2.13 Install LTS to the vent port and evaluate the cask cavity. Back fill with dry (bottled) air to 1 atm pressure.

7.1.2.14 Remove cask lid o-ring test port plug. Install the LTS to the test port and evacuate the lid seal interspace until the pressure is reduced to 10, +2, -0 mbar.

7.1.2.15 Perform a pressure rise leakage test for pre-shipment leakage rate test of the cask lid inner seal.

The leakage rate ($L_T$) is calculated by

$$L_T = \frac{V \times \Delta P \times 298}{t \times 1013 \times T} \qquad (\text{ref}\cdot\text{cm}^3/\text{s})$$

where $V$ = test volume ($cm^3$)
$\Delta P$ = measured pressure difference (mbar)
$t$ = elapsed time for the test (s), and
$T$ = temperature of test ($^oK$)

It is assumed that over the relatively short duration of the test (1-2 minutes), the change in temperature is insignificant.

The test must have a sensitivity of at least $1 \times 10^{-3}$ ref·cm$^3$/s.

The acceptance criterion is no detected leakage.

7.1.2.16 Replace the cask lid o-ring test port plug.

7.1.2.17 Install the cask vent port cover and bolts. Torque the bolts to the required value. (Torque values are listed on drawings in Chapter 1.0.)

7.1.2.18 Place the test bell over the vent cover and use the LTS to reduce the pressure between the vent port O-ring and the O-ring on the test bell to 7, +3, -0 mbar. Isolate the vacuum pump and perform a pressure rise leakage rate test of the vent port cover. The acceptance criterion is no detectable leakage rate. The test must have a sensitivity of at leak $1 \times 10^{-3}$ ref·cm$^3$/sec.

7.1.2.19 Remove the lid lifting attachments.

## 7.1.3 Preparation for Transport

7.1.3.1 Engage the cask lifting apparatus in the recessed lifting sockets. Use the hand-crank to lock the balls in the sockets.

7.1.3.2 Remove the restraints from the cask.

7.1.3.3 Lift and move the cask from the cask loading station to the truck.

7.1.3.4 Align the trunnions of the cask with the support pedestals on the semitrailer.

7.1.3.5 Place trunnions on transport vehicle rear trunnion supports and rotate cask from the vertical to horizontal position.

7.1.3.6 Install and torque the rear trunnion tie-downs and the front saddle tie-downs.

7.1.3.7 Install the front and rear impact limiters and torque attachment bolts diametrically in several stages until the required value is obtained._(Torque values are listed on drawings in Chapter 1.0.)

7.1.3.8 Install security seal on the front impact limiter.

7.1.3.9 Perform final radiation and contamination surveys to assure compliance with 10CFR71.47 and 71.87.

7.1.3.10 Apply appropriate DOT labels and placards to the vehicle in accordance with 49CFR172.

7.1.3.11 Install personnel barrier, if used.

7.1.3.12 Prepare final shipping documentation.

7.1.3.13 Release the loaded cask for shipment.

## 7.2 Procedures for Unloading Package

### 7.2.1 Receipt of Package from Carrier

7.2.1.1 Upon arrival of the loaded cask at the receiving site, perform receipt inspection. Inspect for damage, verify security seal is intact and perform radiation survey.

7.2.1.2 Verify that placards, labels and shipping papers are in place and correct.

7.2.1.3 Inspect and clean the tractor, trailer and cask as required

7.2.1.4 Remove the personnel barrier, if used.

7.2.1.5 Remove the security seal from the front impact limiter.

7.2.1.6 Remove the impact limiter attachment bolts and remove the front and rear impact limiters using a suitable crane and three legged sling.

7.2.1.7 Release the front saddle and rear trunnion tie-downs.

7.2.1.8 Attach the cask lifting apparatus to the crane hook.

7.2.1.9 Engage the cask lifting apparatus in the recessed lifting sockets. Use handcrank to lock the balls into the sockets.

7.2.1.10 Lift the cask slowly to the vertical position.

7.2.1.11 Move the cask to the unloading area.

7.2.1.12 Install restraints to secure cask in vertical orientation.

7.2.1.13 Disengage cask lifting apparatus.

### 7.2.2 Preparation for Unloading

7.2.2.1 Remove the cask vent port cover.

7.2.2.2 Install the cavity gas sampling adapter to the vent port.

7.2.2.3 Operate an evacuation system to draw a sample of the cavity gas from the cask.

7.2.2.4 Disconnect the evacuation system.

7.2.2.5 Analyze the gas sample for radioactive material, and add necessary precautions based on the cavity gas sample results. These additional measures may include provision of filter, as well as respiratory protection and other methods to control releases and exposures to ALARA.

7.2.2.6 Install the cask lid lifting attachments.

7.2.2.7 Remove the twelve cask lid bolts.

7.2.2.8 Remove the lid and store.

7.2.2.9 Remove the ORC vent port cover.

7.2.2.10 Install the cavity gas sampling adapter to the ORC vent port.

7.2.2.11 Operate an evacuation system to draw a sample of the cavity gas from the ORC.

7.2.2.12 Disconnect the evacuation system.

7.2.2.13 Analyze the gas sample for radioactive material, and add necessary precautions based on the cavity gas sample results. These additional measures may include provision of filter, as well as respiratory protection and other methods to control releases and exposures to ALARA.

### 7.2.3 Contents Removal

7.2.3.1 Install the ORC lid lifting attachments.

7.2.3.2 Remove the twelve ORC lid bolts.

7.2.3.3 Remove the ORC lid and store.

7.2.3.4 Using suitable remote tools, remove Oak Ridge canisters, Peach Bottom fuel assembly canisters and the flux trap spacers (if any) from the cask. Verification shall be made that the SNF has been completely removed.

## 7.3 Preparation of Empty Package for Transport

7.3.1 Visually examine the cask and ORC sealing surfaces and interior for any damage or debris.

7.3.2 Visually examine the cask and ORC lids, especially the o-ring seals for any damage.

7.3.3 Transfer the ORC lid to a position directly over the ORC cavity. Establish correct lid orientation using the alignment pins and lower the lid until fully seated. Visually verify the lid for proper installation.

7.3.4 Inspect the ORC lid bolts. Replace defective bolts and note any defect indications on the cask loading report. Apply a light coating of Nuclear Grade Neolube to bolt threads and install all 12 ORC lid bolts. Tighten to hand tight. Torque all lid bolts to the required value in several stages. Follow an approved torquing sequence. (Torque values are listed on drawings in Chapter 1.0.)

7.3.5 Inspect the vent port cover, seal and bolts for damage and replace if defects are noted. Record inspection results on the cask loading report.

7.3.6 Install the vent port cover and bolts. Torque the bolts to the appropriate value. (Torque values are listed on drawings in Chapter 1.0.)

7.3.7 Remove the ORC lid lifting attachments.

7.3.8 Transfer the cask lid to a position directly over the cask cavity. Establish correct lid orientation using the orientation marks and lower the lid until fully seated. Visually verify the lid for proper installation.

7.3.9 Inspect the lid bolts. Replace defective bolts and note any defect indications on the cask loading report. Apply a light coating of Nuclear Grade Neolube to bolt threads and install all 12 lid bolts. Tighten to hand tight. Torque all lid bolts to required value in several stages. Follow an approved torquing sequence. (Torque values are listed on drawings in Chapter 1.0.)

7.3.10 Inspect the vent cover, seal and bolts for damage and replace if defects are noted. Record inspection results on the cask loading report.

7.3.11 Install the vent port cover and bolts. Torque the bolts to the required value. (Torque values are listed on drawings in Chapter 1.0.)

7.3.12 Remove the cask lid lifting attachments.

7.3.13 Engage the cask lifting apparatus in the recessed lifting sockets. Use the hand-crank to lock the balls in the sockets.

7.3.14 Remove restraints from cask.

7.3.15 Lift and move the cask to the truck bay.

7.3.16 Align the trunnions of the cask with the support pedestals on the semitrailer.

7.3.17 Place trunnions on transport vehicle rear trunnion supports and rotate cask from the vertical to horizontal position.

7.3.18 Install and torque the rear trunnion tie-downs and the front saddle tie-downs.

7.3.19 Install the front and rear impact limiters and torque attachment bolts diametrically in several stages until the required value is obtained. (Torque values are listed on drawings in Chapter 1.0.)

7.3.20 Perform final radiation and contamination surveys to assure compliance with 10CFR71.47 and 71.87.

7.3.21 Apply appropriate DOT labels and placards to the vehicle in accordance with 49CFR172.

7.3.22 Install personnel barrier, if used.

7.3.23 Prepare final shipping documentation for empty cask.

7.3.24 Release the cask for shipment.

# 8.0 ACCEPTANCE TESTS AND MAINTENANCE PROGRAM

This Chapter primarily describes the activities required to accept and maintain the Oak Ridge Container in compliance with Subpart G of 10CFR71.

The acceptance tests and maintenance activities for the TN-FSV cask are described in detail in Chapter 8.0 of the TN-FSV SAR. The design modification made to the existing packaging is the revision of the leakage rate criterion of the containment boundary from $1 \times 10^{-3}$ ref·cm$^3$/s to a more stringent requirement of $1 \times 10^{-7}$ ref·cm$^3$/s (leaktight). To permit leak testing of the containment boundary of the package to the revised leakage requirement for Configuration 2, the material for the elastomer seals of the packaging has been changed from silicone to butyl.

As a result of this modification, leakage tests shall be performed on the containment boundary of the TN-FSV cask and Oak Ridge Container before the first use and periodically thereafter. Pre-shipment tests of the containment boundary seals will be performed before each shipment. Maintenance leak tests will be performed when the seals are replaced. The required tests are described in Sections 8.1.4 and 8.2.2 of this Chapter.

## 8.1 Acceptance Tests

The following reviews, inspections, and tests shall be performed on the Oak Ridge Container prior to initial transport. Many of these tests will be performed at the Fabricator's facility prior to delivery of the ORC for use. Tests will be performed in accordance with written procedures approved by Transnuclear, Inc.

### 8.1.1 Visual Inspection and Measurements

Visual inspections are performed at the Fabricator's facility to ensure that the ORC conforms to the drawings and specifications. The visual inspection includes verifying the ORC is clean and free of cracks, pinholes, uncontrolled voids or other defects that could significantly reduce its effectiveness. Visual inspection is also performed to verify that the ORC has been fabricated and assembled in accordance with the drawings and other requirements specified in this Addendum. Dimensions and tolerances shown on the drawings provided in Chapter 1 are confirmed by measurements. Prior to shipping, the ORC will be inspected to ensure that it is in good physical condition. This inspection shall include verification that all accessible surfaces are free of grease, oil or other contaminants, and that all components are in an acceptable condition for use. The sealing surfaces on the flange, lid, and covers are inspected to ensure that there are no gouges, cracks, or scratches that could result in unacceptable leakage.

## 8.1.2 Weld Inspections

Weld inspections are performed in accordance with the drawings and applicable ASME code sections specified in this Addendum. All welding is performed using qualified processes and qualified personnel, according to the ASME Boiler and the Pressure Vessel Code[1]. Welds are examined in accordance with the ASME Boiler and Pressure Vessel code requirements. NDE requirements for welds are specified on the drawings provided in Chapter 1. All NDE is performed in accordance with written and approved procedures. The inspection personnel are qualified in accordance with SNT-TC-1A[2]. Location, type, and size of the weld are confirmed by measurement.

## 8.1.3 Structural and Pressure Tests

The structural analyses performed on the Oak Ridge Container are presented in Chapter 2. To ensure that the ORC can perform its design function, the structural materials are chemically and physically tested to confirm that the required properties are met. Base materials are examined in accordance with the ASME Boiler and Pressure Vessel code requirements.

In accordance with 10CFR71.85(b), containment boundaries with an MNOP less than 5 psig are not required to be subjected to a structural pressure test.

## 8.1.4 Leakage Tests

Fabrication leakage tests are performed on the containment boundary for the TN-FSV cask and the Oak Ridge Container at the Fabricator's facility. These tests are performed using the helium mass spectrometer method. The leak test is performed in accordance with ANSI N14.5[3]. The personnel performing the leakage test are qualified in accordance with SNT-TC-1A.

For the Oak Ridge Container, helium is introduced into the cavity and the mass spectrometer connected to the test port in order to test both the inner lid o-ring and the vent port o-ring. The quick disconnect in the vent port will be removed. The ORC body/lid will be tested by the gas filled envelope method, i.e., placing a helium filled bag around the body and evacuating the cavity through the drain port. The combined leakage rate must be less than $1x10^{-7}$ ref $cm^3/s$.

For the TN-FSV Packaging, the inner lid o-ring is tested by utilizing the test port connection for the mass spectrometer with helium in the cask cavity. The body, vent, and drain ports will be tested with the gas filled envelope method, using a helium filled bag around the component and evacuating through one of the ports. The quick disconnect is removed for the port being leak tested. The combined leakage rate must be less than $1x10^{-7}$ ref $cm^3/s$.

The permissible leakage rate for each containment boundary is less than or equal to $1 \times 10^{-7}$ ref $cm^3/sec$ (leaktight). The sensitivity of the leakage test procedure is at least $5 \times 10^{-8}$ ref $cm^3/sec$.

### 8.1.5 Component Tests

Installation and removal tests will be performed for the ORC lid, test port cover, and other fittings and inserts.

Each component will be observed for difficulties in installation and removal. After removal, each component will be visually examined for indications of deformation, galling, ease of use and proper functioning. Any such defects will be corrected prior to acceptance of the ORC.

### 8.1.6 Shielding Tests

The analyses performed to ensure sufficient shielding by the TN-FSV cask and the Oak Ridge Container are presented in Chapter 5. All materials in the ORC for which shielding credit is taken are ASME Code materials. No additional shielding tests are required.

### 8.1.7 Neutron Absorber Tests

The neutron absorber plates serve no other function other than neutron absorption. The plates are enclosed in stainless steel sheets that structurally support the plates on all sides during normal conditions of transport and accident conditions. The radiation and temperature environment in the ORC is not sufficiently severe to damage the aluminum matrix that retains the boron-containing particles. To assure performance of the plates' safety-related function, the only critical variable that need to be verified is the boron 10 areal density.

The boron 10 areal density of the neutron absorber plates shall be verified using approved procedures. There are three acceptable, neutron absorbing materials, as described in Section 6.3.2. These materials are subject to different types of tests and the associated minimum boron 10 contents, as follows.

#### 8.1.7.1 Boron-Aluminum Alloy Using Enriched Boron, 90% B10 Credit

Material Description:

The neutron absorber consists of borated aluminum (containing about 1.7 wt% boron), which is isotopically enriched to 95 wt% B10. Because of the negligibly low solubility of boron in solid aluminum, the boron appears entirely as discrete second phase particles of $AlB_2$ in the aluminum matrix. The matrix is limited to any 1000 series aluminum , aluminum alloy 6063, or aluminum alloy 6351 so that no boron-containing phases other than $AlB_2$ are formed. Titanium may also be added to form $TiB_2$ particles, which are finer.

The 1.7 wt % boron converts to a nominal areal density of boron 10 as follows:
(2.69 g BAl/cm$^3$)x(1.7 wt% B)x(95 wt%B10)x(0.305 in.)x(2.54 cm/in.) = 0.0337 g B10/cm$^2$, which is intentionally slightly above the design minimum of 0.030 g B10/cm$^2$ (see Section 6.3.2).

The boron-containing phase is introduced into the system, during the reaction of a proprietary boron-containing salt with the molten aluminum. The individual $AlB_2$ particles range in size from 5 to 10 microns. If titanium salt is added as well, the resulting $TiB_2$ particles will range in size from 1 to 5 microns. Both $AlB_2$ and $TiB_2$ are thermally stable at all temperatures below the melting point of the aluminum matrix. As such, their effect on the properties of the matrix aluminum alloy are those typically associated with a fine uniform dispersion of an inert, equiaxed, second phase.

The cast ingot may be rolled, extruded, or both, to the final plate dimensions.

Test Coupons:

Each neutron absorber stock plate may be as large as 12 in. x 70 in. long. Coupons, of the full width of the plate, will be removed at the ends of each "stock plate". The minimum dimension of the coupon shall be as required for the neutron transmission measurements; 1 to 2 in. is adequate for the typical 1cm diameter neutron beam.

### 8.1.7.2 Boron Carbide/Aluminum Metal Matrix Composite (MMC), 75% B10 credit

Material Description:

The neutron absorber consists of a composite of aluminum with about 15 volume % boron carbide particulate reinforcement. The material is formed into a billet by powder metallurgical processes and either extruded, rolled, or both to final dimensions. The finished product has near-theoretical density and metallurgical bonding of the aluminum matrix particles. It is uniform from face to face, i.e., it is not a "sandwich" panel.

The 15 volume % boron carbide corresponds to a boron 10 areal density of
$0.15(2.52\ g/cm^3\ B_4C)(0.782\ gB/gB_4C)(0.185\ g\ B10/gB)(0.305\ in.)(2.54\ cm/in.)$
$= 0.0424\ gB10/cm^2$, in excess of the specified minimum, $0.036\ g\ B10/cm^2$ (see Section 6.3.2).

The process specifications for the material shall be subject to qualification testing to demonstrate that the process results in a material that

a) has a uniform distribution of boron carbide particles in an aluminum alloy with few or no voids, oxide-coated aluminum particles, $B_4C$ fracturing, or $B_4C$/aluminum reaction products.
b) meets the requirements for boron 10 areal density, and
c) will be capable of performing its safety-related functions under the thermal and radiological environment of the ORC in the TN-FSV cask.

The production of plates for use in the ORC will be consistent with the process used to produce the qualification test material. "Lessons learned" in the qualification testing, or processing changes that will clearly lead to an improvement in the properties of the material may be incorporated into the production process, provided that they are reviewed and approved by Transnuclear, Inc.

Typical processing consists of:

a) Blending of boron carbide powder with aluminum alloy powder
b) Billet formed by cold isostatic pressing + sintering or by vacuum hot pressing
c) Billet extruded to intermediate or to final size
d) Hot roll, cold roll and flatten as required
e) Annealing

Test Coupons:

Each neutron absorber stock plate may be as large as 12 in. x 70 in. long. Coupons, of the full width of the plate, will be removed at the ends of each "stock plate". End coupons may be slightly shorter due to irregular shape at the end of the stock plate. The minimum dimension of the coupon shall be as required for the neutron transmission measurements; 1 to 2 in. is adequate for the typical 1cm diameter neutron beam.

### 8.1.7.3 Boral® - 75% $^{10}$B Credit

Boral® is a well known product used in many spent fuel pool racks. Boral® is a precision-hot-rolled, composite plate material consisting of a core of mixed aluminum and boron carbide particles with aluminum cladding on both sides. A minimum $^{10}$B areal density of 0.036 g/cm$^2$ will be utilized, assuming only 75% credit.

### 8.1.7.4 Testing

Neutronic Acceptance Testing of Boron-Aluminum Alloy (Borated Aluminum):

Effective boron 10 content is verified by neutron transmission testing of the coupons. The transmission through the coupons is compared with transmission through calibrated standards composed of a homogeneous boron compound without other significant neutron absorbers, for example zirconium diboride or titanium diboride. These standards are paired with aluminum shims sized to match the scattering by aluminum in the neutron absorber plates. Provision shall be made so that the neutron transmission test is not always made in the same location on the coupon. For example, the transmission measurement may be made about 1/4 to 1/3 of the distance from the end of the coupon. Thus, the random placement of the coupons in the test fixture results in testing at two locations across the plate width. The effective boron 10 content of each coupon, minus $3\sigma$ based on the number of neutrons counted for that coupon, must be $\geq$ 30 mg B10/cm$^2$.

In the event that a coupon fails the single neutron transmission measurement, four additional measurements will be made on the coupon, and the average of the 5 measurements, less $3\sigma$ based on the number of neutrons counted for each measurement on that coupon, must be $\geq$ 30 mg B10/cm$^2$.

Macroscopic uniformity of boron-10 distribution is verified by neutron radioscopy or radiography of the coupons. The acceptance criterion is that there be uniform luminance across the coupon. This inspection shall cover the entire coupon.

Acceptance Testing, Visual - Boron Aluminum Alloy (Borated Aluminum)

The finished plates shall be visually examined to verify that they are free of cracks, porosity, blisters, or foreign inclusions. Such defects, where possible, are removed if it does not result in a dimensional non-conformance.

Justification for the Borated Aluminum Acceptance Test Requirements:

According to NUREG/CR-5661[4]

> "Limiting added neutron absorber material credit to 75% without comprehensive tests is based on concerns for potential 'streaming' of neutrons due to nonuniformities. It has been shown that boron carbide granules embedded in aluminum permit channeling of a beam of neutrons between the grains and reduce the effectiveness for neutron absorption."

Furthermore

> "A percentage of neutron absorber material greater than 75% may be considered in the analysis only if comprehensive tests, capable of verifying the presence *and uniformity* of the neutron absorber, are implemented." [Emphasis added]

The calculations in Chapter 6 use a boron areal density of 25 mg B10/cm$^2$, less than 90% of the minimum value required here of 30 mg B10/cm$^2$. This is justified by the following considerations.

a) The coupons for neutronic inspection are removed at the ends of the "stock plate", where under thickness of the plates or defects propagated from the pre-roll ingot would be most likely, and are approximately the full width of the plate. As such, they are taken from locations that are truly representative of the finished product. Coupons are also removed. The use of representative coupons for inspection is analogous to the removal of specimens from structural materials for mechanical testing.

b) Neutron radiography/radioscopy of coupons across the full width of the plate will detect macroscopic non-uniformities in the boron 10 distribution such as could be introduced by the fabrication process. Such defects usually originate from the ingot and propagate in the direction of rolling or extrusion. For example, an ingot with a skin high in boron and a center depleted in boron will exhibit alternating bands of high and low boron concentration, which can be detected with radiography or radioscopy, parallel to the processing direction.

c) Neutron transmission measures effective boron 10 content directly. The term "effective" is used here because if there are any of the effects noted in NUREG/CR-5661, the neutron transmission technique will measure not the physical boron 10 areal density, but a lower value. Thus, this technique by its nature screens out the microscopic non-uniformities which have been the source of the recommended 75% credit for boron 10 in criticality evaluations.

d) The use of neutron transmission and radiography/radioscopy satisfies the "and uniformity" requirement emphasized in NUREG/CR-5661 on both the microscopic and macroscopic scales.

e) The recommendations of NUREG/CR-5661 are based upon testing of a neutron absorber with boron carbide particles averaging 85 microns. The boride particles in the borated aluminum are much finer (5-10 microns). Both the manufacturing process and the neutron radioscopy assure that they are uniformly distributed. For a given degree of uniformity, fine particles will be less subject to neutron streaming than coarse particles. Furthermore, because the material reviewed in the NUREG is a sandwich panel, the thickness of the boron carbide containing center could not be directly verified by thickness measurement. The alloy specified here is uniform throughout its thickness.

f) Visual inspection of the plates verifies that there are no gross mechanical defects that could compromise the neutron absorber's ability to remain intact and in position in the basket.

Neutronic Acceptance Testing - Boron Carbide/Aluminum Metal Matrix Composite

Effective boron 10 content is verified by neutron transmission testing of these coupons, or by chemical, spectrometric, and dimensional inspection.

In the first method, the transmission through the coupons is compared with transmission through calibrated standards composed of a homogeneous boron compound without other significant neutron absorbers, for example zirconium diboride or titanium diboride. These standards are paired with aluminum shims sized to match the scattering by aluminum in the neutron absorber plates. Provision shall be made so that the neutron transmission test is not always made in the same location on the coupon. For example, the transmission measurement may be made about 1/4 to 1/3 of the distance from the end of the coupon. Thus, the random placement of the coupons in the test fixture results in testing at two locations across the plate width. The effective boron 10 content of each coupon, minus $3\sigma$ based on the number of neutrons counted for that coupon, must be $\geq 36$ mg B10/cm$^2$.

In the event that a coupon fails the single neutron transmission measurement, four additional measurements may be made on the coupon, and the average of the 5 measurements, less $3\sigma$ based on the number of neutrons counted for each measurement on that coupon, must be $\geq 36$ mg B10/cm$^2$.

In the second method, the grams B10 per gram of total boron and the grams of total boron per grams of boron carbide are determined by spectrometric and chemical analysis of each lot of boron carbide feed powder (ASTM-C791[5] or equal). The grams of boron carbide per gram of finished composite are then determined by chemical analysis of a specimen selected from a random location on the finished coupon (ASTM D-3553[10] or equal). These three values are then multiplied together, with the composite density, and the minimum allowable plate thickness:

(g B10/g B)*(g B/g $B_4C$)*(g $B_4C$/g MMC)*(g MMC/$cm^3$)*(min thickness, cm) = g B10/$cm^2$

The value for each coupon must be ≥ 36 mg B10/$cm^2$.

Acceptance Testing, Visual Boron Carbide/Aluminum Metal Matrix Composite (MMC):

The finished plates shall be visually examined to verify that they are free of cracks, porosity, blisters, or foreign inclusions. Removal of such defects is permitted, where possible, if the removal does not result in a dimensional non-conformance.

Justification for Acceptance Test Requirements, Metal Matrix Composite

According to NUREG/CR-5661

> " For each calculational model, the atom density of any neutron absorber...should be limited to 75% of the minimum neutron absorber content specified in the application. This minimum neutron absorber content should be verified by chemical analysis, neutron transmission measurements, or other acceptable methods. A percentage of neutron absorber material greater than 75% may be considered in the analysis only if comprehensive tests, capable of verifying the presence and uniformity of the neutron absorber, are implemented."
>
> "...Limiting added neutron absorber material credit to 75% without comprehensive tests is based on concerns for potential 'streaming' of neutrons due to nonuniformities. It has been shown that boron carbide granules embedded in aluminum permit channeling of a beam of neutrons between the grains and reduce the effectiveness for neutron absorption."

The calculations in Chapter 6 use a boron areal density of 25 mg B10/$cm^2$. That is less than 75% of the minimum value required here, 36 mg B10/$cm^2$. Based on the recommendations above, because only 75% credit is used, comprehensive testing for presence and uniformity of boron 10 is not necessary.

Other considerations are:

a) The coupons for neutronic inspection are removed at the end of each stock plate, and are generally the full width of the plate. As such, they are taken from locations that are truly representative of the finished product, where every plate is represented by a contiguous coupon. The use of representative coupons for inspection is analogous to the removal of specimens from structural materials for mechanical testing.

b) Uniformity of B10 distribution must be demonstrated by the qualification testing of the material.

c) The recommendations of NUREG/CR-5661 are based upon testing of a neutron absorber with boron carbide particles on the order of 80-100 microns. The boron carbide particles in a typical metal matrix composite are much finer (1-25 microns). The powder metal manufacturing process controls and the qualification testing assure that they are uniformly distributed. For a given degree of uniformity, fine particles will be less subject to neutron streaming than coarse particles. Furthermore, because the material reviewed in the NUREG was a sandwich panel, the thickness of the boron carbide containing center could not be directly verified by thickness measurement. The metal matrix composite specified here is uniform throughout its thickness.

d) Visual inspection of the plates verifies that there are no gross mechanical defects that could compromise the neutron absorber's ability to remain intact and in position in the basket.

Neutronic Acceptance Testing - Boral®

Sections of each sheet are retained for testing and record purposes. The minimum 10B content per unit area and the uniformity of dispersion within a panel are verified by wet chemical analysis and/or neutron attenuation testing. The acceptable standards are controlled by statistical data to assure the minimum requirements are achieved with a 95/95 confidence level. The maximum variations in the manufacturing process over a significantly large sample size have been determined and are utilized in the establishment of acceptance criteria. All material certifications, lot control records, and test records are maintained to assure traceability.

Justification for Acceptance Test Requirements, Boral®

According to NUREG/CR-5661

> " For each calculational model, the atom density of any neutron absorber...should be limited to 75% of the minimum neutron absorber content specified in the application. This minimum neutron absorber content should be verified by chemical analysis, neutron transmission measurements, or other acceptable methods. A percentage of neutron absorber material greater than 75% may be considered in the analysis only if comprehensive tests, capable of verifying the presence and uniformity of the neutron absorber, are implemented."
>
> "...Limiting added neutron absorber material credit to 75% without comprehensive tests is based on concerns for potential 'streaming' of neutrons due to nonuniformities. It has been shown that boron carbide granules embedded in aluminum permit channeling of a beam of neutrons between the grains and reduce the effectiveness for neutron absorption."

The calculations in Chapter 6 use a boron areal density of 25 mg B10/cm$^2$. That is less than 75% of the minimum value required here, 36 mg B10/cm$^2$. Based on the recommendations above, because only 75% credit is used, comprehensive testing for presence and uniformity of boron 10 is not necessary.

Other considerations are:

a) The coupons for neutronic inspection are removed from each sheet. As such, they are truly representative of the finished product.
b) The use of representative coupons for inspection is analogous to the removal of specimens from structural materials for mechanical testing.
c) Uniformity of dispersion is demonstrated by testing of the material.
d) Visual inspection of the plates verifies that there are no gross mechanical defects that could compromise the neutron absorber's ability to remain intact and in position in the basket.

## 8.2 Maintenance Program

### 8.2.1 Structural and Pressure Tests

There are no periodic structural tests required on the Oak Ridge Container.

### 8.2.2 Leakage Test

The requirements imposed by this section apply to the TN-FSV cask and the Oak Ridge Container.

Maintenance leakage tests shall be performed on the containment boundary seals (TN-FSV cask: inner lid o-ring, vent port cover o-ring & drain port cover o-ring; ORC: inner lid o-ring & inner vent port cover o-ring) when the seals are replaced and when periodic testing is required . These tests are performed using the helium mass spectrometer method as described in section 8.1.4. The leak tests are performed in accordance with ANSI N14.5.

The permissible leakage rate for each containment boundary is less than or equal to $1 \times 10^{-7}$ ref·cm$^3$/sec (leaktight). The sensitivity of the leakage test procedure is at least $5 \times 10^{-8}$ ref·cm$^3$/sec.

### 8.2.3 Subsystem Maintenance

This section does not apply.

### 8.2.4 Valves, Rupture Discs, and Gaskets on Containment Vessel

The lid seals and the vent port cover seals will be replaced annually unless the ORC is not in service. Prior to use, the maintenance shall have been completed within the preceding 12-month period.

No other maintenance is required prior to transport.

### 8.2.5 Shielding

See Section 8.2.5 of the TN-FSV SAR.

### 8.2.6 Thermal

See Section 8.2.6 of the TN-FSV SAR.

### 8.2.7 Miscellaneous

The ORC lid bolts and vent port cover bolts shall be replaced after every 100 round trip shipments to preclude fatigue failure.

## 8.3 References

1 ASME Boiler & Pressure Vessel Code, Division 1, Section III, 1998 Edition.

2 SNT-TC-1A, "American Society for Nondestructive Testing, Personnel Qualification and Certification in Nondestructive Testing," 1992.

3 Leakage Tests on Packages for Shipment, American National Standards Institute, ANSI N14.5-1997.

4 NUREG/CR-5661, Recommendations for Preparing the Criticality Safety Evaluation of Transportation Packages, 1997.

5 ASTM C 791, Standard Methods for Chemical, Mass Spectrometric, and Spectrochemical Analysis of Nuclear-Grade Boron Carbide