ENERGY*SOLUTIONS*

October 3, 2008
E&L-043-08

Jessica Glenny, Project Manager
Licensing Section
Division of Fuel Storage and Transportation
Office of Nuclear Material Safety and Safeguards
U.S. Nuclear Regulatory Commission
Washington, DC 20555

Dear Ms. Glenny:

Subject: Response to REQUEST FOR ADDITIONAL INFORMATION FOR REVIEW OF THE MODEL NO. 10-160B (Docket No. 71-9204 TAC No. L24162)

Energy*Solutions* provides the attached response (Attachment 1) to the Request for Additional Information dated August 8, 2008. As noted in Attachment 1, responding to several of the RAI questions required revision to portions of the SAR. Those revised pages are included as Attachment 2. The additional information requested by the RAI is contained in Attachment 3.

The three attachments to this letter are listed below:

Attachment 1 Response to the RAI; the NRC questions are printed in italics followed by the Energy*Solutions* response in normal font.

Attachment 2 Revised SAR pages; please replace the previously provided pages with the pages in this attachment. Pages included are: 1-4, 2-100, 3-20, and 6-1 through 6-55 (entire Chapter 6).

Attachment 3 Requested information (provided on enclosed CD): Detector section of output files (detector-output.pdf); SCALE neutron output file (10-160b-pt-n-HAC.out); RH-TRAMPAC, Rev.0, 2006 (rh-trampac.pdf); RH-TRU 72B SAR, Rev.4, 2006 (72B-SAR.pdf); and MCNP output files (10-160b-sphere-F033.out and 10-160b-sphere-F022flat02.out)

Should you or members of your staff have questions about the responses, please contact Mark Whittaker at (803) 758-1898.

Sincerely,

Patrick L. Paquin
GM – Engineering & Licensing

Attachments: As stated

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Attachment 1

Chapter 1 Introduction

1-1 Evaluate the void volume change due to the fabrication tolerance changes in Drawing No. C-110-D-29003-010, Sheet 2 of 5, Revision 14, Note 16, particularly the inner diameter and outer diameter of cask body and size of lid stepped diameters gaps.

The fabrication tolerance change could affect the calculation of minimum void volume in the release analysis. The staff needs to know the impact to void volume due to the fabrication tolerance change.

This information is needed to determine compliance with 10 CFR 71.33, 71.43(d).

Response:

The fabrications tolerances were not changed in Rev. 14 of the drawing. However, the minimum void volume, as shown in Chapter 4, depends on the size of the liner as well as the cask cavity. The liner is sized to maintain a minimum clearance, ¾" in radius and 1.5" in height, between the cavity and the liner. By maintaining this clearance, the cask void volume will not significantly change even if the cask fabrication tolerances were changed.

Chapter 3 Thermal

3-1 Justify the assumption that the decay heat load for all thermal and other analyses is 200 watts in spite of the inclusion of 325 fissile gram equivalent (FGE) fissile materials with plutonium in excess of 20 Ci in solid form in the package contents. Provide the calculations that verify the assumption of 200 watts decay heat.

EnergySolutions' letter states that, "EnergySolutions is revising the contents to include up to 325 FGE of fissile material. Also, plutonium in excess of 20 Ci is required to be in solid form." Section 1.2.3.1, Cask Contents, lists as item number five, "Transuranic Waste (TRU) with not more than 325 FGE of fissile radioactive material up to a maximum of $3000A_2$. In spite of the addition of TRU not exceeding 325 FGE of fissile materials up to a maximum of $3000A_2$ to the package contents, the assumed decay heat used in the thermal analysis remains at 200 watts, which is the same as that is assumed in the original SAR.

This information is needed to determine compliance with 10 CFR 71.15, 71.33, and 71.64.

Response:

The heat load for the cask was set at 200 watts for the thermal analysis to evaluate compliance with the NCT and HAC cask temperature limits. Compliance was achieved as demonstrated by the thermal analysis. The decay heat limit specified in the package contents was conservatively set at 100 watts. The cask user must ensure that the contents shipped do not exceed the heat load limit as well as meeting the other contents limits. For example, if a user desired to ship material that was 325 FGE and more than 20 Ci of Pu, the material would have to be in solid form, be less than 3000 A_2, and have a decay heat of less than 100 watts. If the Pu was all ^{239}Pu, the 325 FGE is 325 grams of ^{239}Pu, which has an activity of 20.15 Ci or 746 A_2 and produces a decay heat of 0.62 watts (heat generation from Pu-239= 3.0551e-002 watts/Ci; MicroShield v6.02).

3-2 Justify the use of the older version of ANSYS finite element code (version 5.2, 1996) for thermal evaluation of Model No. 10-160B transportation package for both normal *conditions of transport (NCT) and hypothetical accident conditions (HAC). Demonstrate that this version is validated for this heat transfer analyses given new information or data that has been incorporated since this version.*

Energy Solutions used an earlier version 5.2 (1996) of ANSYS code for its thermal analysis of CNS 10-160B. The current version of ANSYS is version 11. While recognizing the fact that ANSYS code is suitable for thermal analysis of transportation package, the staff finds that the code version used by the licensee is neither supported by the code developer nor the staff will be able to verify the results of the analyses by using the most recent version of the code. The staff has compared the results from earlier version of ANSYS with those from the latest release of ANSYS for some other heat transfer applications, and found that there may be significant variation in the results in some cases.

The applicant should verify that the thermal performance of the CNS 10-160B package during NCT and HAC remains as predicted with ANSYS 5.2, remains valid for this "-96" approval request. The applicant is expected to provide the staff with the details of any new calculations, if performed, to support compliance with the applicable regulations (see ISG-21).

This information is required to verify the licensee's compliance with 10 CFR 71.71 and 71.73.

Response:

EnergySolutions performed the thermal analysis in the submitted revision (Consolidated Rev. 0) using the current version of ANSYS (ANSYS 11, 2007) but neglected to update the reference citation. A corrected reference page, 3-20, is attached.

Chapter 4 Containment

4-1 *Justify the assumption that the cask curie content (3000A_2) in Section 4.2.1 remains valid as the content has changed to 325 FGE and Plutonium more than 20 Ci.*

EnergySolutions requested inclusion of fissile material contents up to 325 FGE and possible Plutonium exceeding 20 Ci. The staff needs to know whether the 3000A_2 Ci content assumption in the containment analysis remains valid.

This information is needed to determine compliance with 10 CFR 71.33, 71.15.

Response:

The 10-160B cask is a Category II container per U.S. Nuclear Regulatory Commission Regulatory Guide 7.11. The radioactivity limit for a Category II container is 3000 A_2 or 30,000 Ci. Energy*Solutions* has conservatively assumed the container contents are at the maximum allowed in performing the containment analysis.

4-2 *Clarify the maximum allowable leakage rate for leak tests.*

The maximum allowable leakage rate in Section 4.2.1 is 3.25e-6 ref-cm^3/sec according to the release analysis provided. However, in Section 4.9.2, the SAR specifies the periodic leak test acceptance criterion as 1.0e-7 atm-cm^3/sec of air (leak tight). The reason for this discrepancy is unclear.

This information is needed to determine compliance with 10 CFR 71.33, 71.51.

Response:

The maximum allowable leak rate for the cask is 3.25 x 10^{-6} atm-cm^3/sec. The option to use a He leak test to demonstrate that the cask can achieve a more conservative leak rate of 1.0 x 10^{-7} atm-cm^3/sec was added in a recent revision to the SAR. As stated in the Safety Evaluation Report issued with Certificate of Compliance No. 9204, Revision No. 12, "The proposed amendment adds a leak test to demonstrate leak tight conditions using helium as an option for the periodic leak test. The proposed addition to the SAR, Section 4.9 Periodic Verification Leak Rate Determination for Leak Tight Status, describes the method for performing a periodic leak test to demonstrate that the criteria per ANSI N14.5-1997 for leak-tight requirements are met."

4-3 Describe the current approval process to determine the acceptability of TRU waste from a particular shipping site in Appendix 4.10.2, Section 1.0, "Introduction." Provide a comparison between the current approval process and the amendment request.

In this amendment, EnergySolutions requests to revise the approval process to give the Model No. 10-160B user responsibility for determining the acceptability of TRU waste from a particular site. The specific revision includes site-specific evaluation and documentation of the evaluation in a Model No. 10-160B TRU payload assessment document. The staff needs information of the current approval process and a comparison of two approval processes.

This information is needed to determine compliance with 10 CFR 71.33.

Response:

The current approval process is as follows:

1. Appendix 4.10.2 describes the requirements and compliance methodology for the shipment of CH-TRU and RH-TRU waste in the 10-160B cask.

2. When potential CH-TRU and RH-TRU waste payloads to be transported in the 10-160B cask are identified at the DOE sites, the waste is evaluated per the methodology of Appendix 4.10.2. The result of the evaluations are documented in sub tier appendices (to Appendix 4.10.2) demonstrating how compliance with the requirements of Appendix 4.10.2 is achieved for each payload. These sub tier appendices are submitted to the NRC for approval and inclusion in the SAR.

The requested revision to this process is to modify Step 2 to allow the 10-160B Cask Payload Engineer to approve these evaluations and demonstrations of compliance, without requiring additional review and approval by the NRC for each site-specific content code, provided that the potential payload is compliant with all requirements of Appendix 4.10.2. Instead of presenting additional sub tier appendices (to Appendix 4.10.2) to the NRC for review and approval as SAR amendments, the 10-160B Cask Payload Engineer will document the evaluation in a "10-160B TRU Waste Payload Assessment" document, which will be maintained on file and available for regulatory review. The 10-160B Cask Payload Engineer does not have the authority to modify any 10-160B SAR requirement or the compliance methodology provided in Appendix 4.10.2. No change to the payload requirements or allowed compliance methodologies is requested and 10-160B TRU Waste Payload Assessment documents will demonstrate compliance with the transportation requirements in Appendix 4.10.2 in the same way that the sub tier appendices documented compliance.

4-4 *Provide the conditions to apply the measurement and sampling method of compliance, particularly the payload parameter of decay heat and hydrogen generation rate.*

In Appendix 4.10.2, Section 2.2, payload parameters compliance method includes sampling and measurement, Sections 2.2.6 and 2.2.7, respectively. These methods are stated as an independent verification of compliance. In the decay heat and hydrogen generation rate, the applicant relies mainly on the calculation and process knowledge. The applicable conditions to apply these two methods for all content codes should be provided.

This information is needed to determine compliance with 10 CFR 71.33, 71.43(d).

Response:

Compliance must be determined for each payload parameter identified in Appendix 4.10.2 using an appropriate compliance methodology. For demonstrating compliance with the hydrogen concentration limit, direct sampling of hydrogen concentration (i.e., headspace sampling) at an appropriate time after sealing a package is an acceptable method. Alternately, use of decay heat and hydrogen generation rate as parameters in a conservative calculational method can be used to ensure the hydrogen concentration at the end of the shipping period does not exceed the 5% limit. If decay heat and hydrogen generation rate are used to demonstrate compliance with the concentration limit, applicable methods of compliance with the decay heat limit or determination of the hydrogen generation rate include process knowledge (e.g., to determine isotopic composition from material accountability records), measurement (e.g., assay to determine decay heat), and sampling (e.g., to determine hydrogen generation rates). Choice of methodology is at the discretion of the user recognizing that certain methods may not be suitable in all circumstances. For instance, if the waste material does not have an established G value, the decay heat limit can not be used and hydrogen sampling may be the only compliance method available.

4-5 *Provide the basis of the 4-liter threshold that a sealed container requires a known, measured or calculated hydrogen release rate or resistance for shipment.*

The staff is not clear on the basis for the 4-liter threshold discussed in Appendix 4.10.2, Section 4.0, "Physical Form Requirement."

This information is needed to determine compliance with 10 CFR 71.33, 71.43(d).

Response:

The 4-liter threshold was chosen as a *de minimus* volume below which inner containers and their contents are considered to be part of the waste. Any inner containers greater than or equal to four liters are required to have quantified release rates for hydrogen and are considered layers of confinement. The 4-liter threshold was established based on the small volume compared to the size of the secondary containers (e.g., 30- and 55-gallon drums) and the cask void volume. As part of the waste, any radioactive material present in inner containers less than 4 liters in size is accounted for in the determination of the payload container decay heat value or hydrogen generation rate that is evaluated for compliance with the decay heat limit or hydrogen generation rate limit, as appropriate.

4-6 *Provide the justification of using different methodology for CH-TRU and RH-TRU in determining maximum allowable decay heat limit in Appendix 4.10.2, Section 10.4. Clarify whether waste handling condition (CH-TRU or RH-TRU) is the only criterion to apply this specific methodology.*

The decay heat limit for CH-TRU is calculated through the relationship of hydrogen generation rate and effective G-value. However, the RH-TRU maximum decay heat limit calculation involves radionuclide contents, decay mechanism, shipping period, scaling of hydrogen gas generation rate, etc. The reasons behind the different methodology are unclear. In the site specific payload appendices (Appendix 4.10.2.1 to 4.10.2.5), some content codes do not specify whether the waste handling condition is CH-TRU or RH-TRU. The staff needs the criteria to apply these two methodologies.

This information is needed to determine compliance with 10 CFR 71.33, 71.43(d).

Response:

As indicated in Appendix 4.10.2, Section 10.4, the decay heat limit for CH-TRU waste content codes is calculated assuming 100% deposition of the emitted energy into the waste within the drum. By definition, CH-TRU waste primarily emits alpha particles from long half-life radionuclides and therefore it is reasonable to assume 100% deposition of the emitted energy into the waste within the drum. The calculated gas generation rate limit, based on the shipping period and packaging configuration, provides a gas generation rate that ensures a maximum concentration less than the 5% limit. By using conservative G-values representing the gas generation potential for the waste material and the decay heat generated by the radionuclide content, the gas generation rate limit can be converted into a decay heat limit.

RH-TRU waste emits alpha particles as well as high energy beta or gamma radiation and therefore some of the emitted energy escapes the waste container and does not interact with the waste within the drum. The radiolytic gas generation potential for RH-TRU waste is highly dependent upon the original radionuclides as well as the daughter radionuclides produced in the waste during the decay chain. Because of this complexity of RH-TRU waste radiolytic gas generation, the software RadCalc is used to determine the gas generation potential of the waste matrix, as described in Appendix 4.10.2, Section 10.4, accounting for types of radiation of the radionuclides and daughter products, as well as the density and geometry of the waste.

4-7 *Provide the criteria of meeting the hydrogen gas generation rate limit through decay heat limits.*

In the site-specific compliance methodologies in Appendix 4.10.2.1 to 4.10.2.5, the decay heat limit compliance method is used as an option to demonstrate the compliance of *hydrogen gas generation rate limit in some content codes. While in some content codes, both the decay heat limit compliance and hydrogen gas generation rate limit compliance are evaluated. In some content codes, only the compliance of hydrogen gas generation rate limit is provided. The staff needs the criteria of applying decay heat limit compliance in these content codes.*

This information is needed to determine compliance with 10 CFR 71.33, 71.43(d).

Response:

As indicated in Section 10.2 of Appendix 4.10.2, compliance with the concentration of hydrogen gas within any confinement layer must be demonstrated. Modeling the movement of hydrogen from the waste material to the payload voids, using the release rates of hydrogen through the various confinement layers, defines the relationship between hydrogen gas generation rate and void concentration. Additionally, based on hydrogen gas generation potential, quantified by hydrogen gas generation G values, and the decay heat of the waste radionuclide content, the gas concentration limit can be converted to a decay heat limit. Where required data for a payload container is available, the compliance with hydrogen gas concentration within a confinement layer is demonstrated by the decay heat of the waste container, relative to the decay heat limit for the content code. When the decay heat limit is exceeded and gas sampling data is available, the compliance with the hydrogen gas concentration within a confinement layer is demonstrated by the hydrogen gas generation rate, relative to the hydrogen gas generation rate limit for the content code. Either method of showing compliance is valid if adequate data on the payload container is available.

In most sub tier appendices both the hydrogen gas generation rate limit (per content code) and the decay heat limit (per content code) are provided. This allows the Transportation Certification Official to verify compliance for an individual payload container by comparison against either the hydrogen gas generation rate limit or the decay heat limit, as deemed applicable based on available payload container data. Typically, the most efficient method of compliance is chosen based on the available data (see response to comment 4-8 below for more detail on the typical use of compliance methodologies). For example, if waste package decay heat data is available at the time of content code development for all packages, the content code may reflect this by specifying only decay heat limits. If data is not available, the content code may include both decay heat and gas generation rate limits so that both compliance options are available for use following the collection of necessary data. For example, in sub tier Appendix 4.10.2.2 for MURR waste, only 7 waste drums were involved and adequate data was available for each drum to determine compliance by decay heat.

4-8 Provide justifications of applying different compliance methods, as noted in Appendices 4.10.2.1 through 4.10.2.5, toward the decay heat limit and hydrogen gas generation rate limit in different sites. Address the applicable condition for various methods and estimate deviation between the methods. Also, discuss the following site specific approaches:

(1) Explain the reason of choosing TRUPACT-II methodology in calculating the decay heat for MURR TRU waste.

(2) Explain the reason of choosing the measurement method to demonstrate compliance of decay heat limit in LLNL.

(3) Explain the reason for no detail decay heat error estimation except for MURR.

This information is needed to determine compliance with 10 CFR 71.33, 71.43(d).

Response:

Multiple methods of compliance with gas generation rate limits are available, including compliance with decay heat limits when G-values are available and flammable VOCs are less than 500 ppm. Another method of compliance with the gas generation rate limits is headspace sampling for flammable gas concentration. This method is implemented if it cannot be shown by process knowledge that the concentration of flammable VOCs is less than 500 ppm or if the decay heat is greater than the decay heat limit.

The typical application of compliance methods used to verify compliance with the limit of hydrogen gas concentration not exceeding 5% in all void volumes within the 10-160B is:

- Determine decay heat of payload container and compare to decay heat limit for content code (waste type and packaging). If the decay heat is less than the decay heat limit, then compliance with the flammable gas generation requirements is shown.

- If it cannot be shown by process knowledge that the concentration of flammable VOCs is less than 500 ppm, then the headspace sampling methodology may be used to show compliance.

- If the decay heat is greater than the decay heat limit, then the headspace sampling method may be used to show compliance.

(1) The decay heat for each of the 7 drums of waste from MURR was calculated using conversion values for watts per gram for various radionuclides provided in the TRUPACT-II TRAMPAC (now referred to as the CH-TRAMPAC). This TRAMPAC table provides watts per gram conversions only and was used to calculate the decay heat in watts of each radionuclide based on the number of grams of each radionuclide that was known to exist in each of the 7 MURR waste drums based on process knowledge and measurement data.

(2) Measurement (assay) is the typical method used at the generating/shipping sites (including LLNL) to determine decay heat and associated measurement error. The shipment of 7 drums from MURR was unique relative to the four other generator site shipments identified in sub tier appendices 4.10.2.1 through 4.10.2.5. The appendices for the other sites provide details on the waste stream(s) to be shipped in the 10-160B from each of these sites, while the appendix for MURR provides specific details for the 7 individual drums that were shipped from MURR.

(3) The four other sites identified in the sub tier appendices had waste streams identified (designated by content codes) but individual drum decay heats had not yet been measured. Therefore individual drum decay heat errors could not be determined at the time of the preparation of the appendix. However, the methodology for determining the decay heat error, recording the error, and accounting for that error in the compliance evaluation are provided in the appendices.

Additionally, because the decay heat for each of the MURR drums was calculated based on the known mass of the radionuclides present (based on process knowledge) a calculation/estimation of the error was needed to assure that the calculated decay heat value plus the error was less than the decay heat limit. For each of the other waste streams/content codes the decay heat is measured by assay and the assay measurement has an associated error. The measured decay heat plus the measurement error must be less than the decay heat limit to be compliant.

Chapter 5 Shielding

Provide the following information regarding the proposed additional contents of the Model No. 10-160B:
(a) Identification and maximum radioactivity of radioactive constituents.
(b) Identification and maximum quantities of fissile constituents.
(c) Chemical and physical form of radioactive constituents.

This information is needed to determine compliance with 10 CFR 71.33(b).

Response:
The contents are described in Section 1.2.3, which is reproduced below with the additional contents underlined:

1.2.3 Contents of Packaging

1.2.3.1 Cask Contents

The contents of the cask will consist of:

1) Greater than Type A quantities (up to a maximum of 3000 A_2) of radioactive material in the form of solids or dewatered materials in secondary containers.

2) Greater than Type A quantities (up to a maximum of 3000 A_2) of radioactive material in the form of activated reactor components or segments of components of waste from a nuclear power plant.

3) That quantity of any radioactive material which does not exceed 3000 A_2 and which does not generate spontaneously more than 100 thermal watts of radioactive decay heat.

4) The weight of the contents in the cask cavity will be limited to 14,500 lbs. If an insert is installed in the cavity, the maximum payload is reduced by the weight of the insert.

5) Transuranic Waste (TRU) with not more than 325 fissile gram equivalents (FGE) of fissile radioactive material up to a maximum of 3000 A_2.

1.2.3.2 Waste Forms

The type and form of waste material will include:

1) By-product, source, or special nuclear material consisting of process solids or resins, either dewatered, solid, or solidified in secondary containers. (See Section 4.2.1 for specific limitations). Contents containing greater than 20 Ci of plutonium must be in solid form.

2) Neutron activated metals or metal oxides in solid form.

3) Miscellaneous radioactive solid waste materials.

4) TRU wastes are limited as described in Appendix 4.10.2, Transuranic (TRU) Waste Compliance Methodology for Hydrogen Gas Generation. TRU exceeding the fissile limits of 10 CFR 71.15 must not be machine compacted and must have no more than 1% by weight of special reflectors and no more than 25% by volume of hydrogenous material.

5-1 *Explain how the radioactive contents will be controlled such that neutron and gamma sources are not shipped together.*

Clarify the statement in Section 5.2.1, which states "A mixed gamma and neutron source will also comply as the sum of the gamma and neutron dose rates must be less than the NCT dose limit and thus, as shown for the independently evaluated sources, the HAC limits will be met." Although it is clear that the HAC limits are met, this does not appear to be the case for NCT. Shipping the allowed gamma and neutron emitting sources together would give doses that exceed the regulator limit for NCT. Since the staff does not have much information about the contents of the Model No. 10-160B the staff does not know if or how these two sources of radiation will be separated.

This information is needed to determine compliance with 10 CFR 71.47(b).

Response:

The 10-160B cask is authorized to transport a wide variety of radionuclides in a variety of configurations. Since the cask user must demonstrate by measurement that the intended shipment meets the dose rate limits for NCT prior to transport, the basis for the shielding evaluation is to start with a source that meets the NCT dose rate limits and show that the HAC limits are not exceeded. If the source emits both gamma and neutrons, the sum of the gamma and neutron dose must also be less than the NCT limit.

5-2 *Justify the 20 Ci assumption for the Pu-Be neutron source.*

In Section 5.2.3 it states that 325 FGE ^{239}Pu-Be source is equivalent to approximately 20 Ci and continues to say that the neutron source is bounded by the analysis. The basis for the 20 Ci value remains unclear to the staff and therefore the staff cannot verify that it is bounded by the analysis.

This information is needed to determine compliance with 10 CFR 71.33(b)(1).

Response:

The amount of ^{239}Pu that would produce the equivalent K_{eff} as that determined for the fissile material in the container (assuming all containers are in an optimally moderated infinite array) is called the ^{239}Pu fissile gram equivalent (FGE). Thus, 325 FGE of ^{239}Pu equates to 325 grams of ^{239}Pu, which has an activity of 20.15 Ci per 10 CFR 71 Appendix A Table A-1.

5-3 *Provide additional information on the specific neutron source configuration.*

The staff recognizes that there may be different reactions and therefore elicit a different spectrum for a homogeneous Pu-Be source versus a non-homogeneous Pu-Be mixture. In addition the source can also depend on the plutonium isotope assumed. The staff viewed the reference for the source spectra (Cember) but did not find any information on the source configuration. The staff is unsure that the spectrum is conservative or representative of what will be stored in the Model No. 10-160B.

This information is needed to determine compliance with 10 CFR 71.33(b)(1).

Response:

We agree that the source configuration is not defined in Cember. However, other references (Lapp and Andrews, *Nuclear Radiation Physics* and NBS Handbook No. 72) also give the maximum energy of neutrons from a ^{239}Pu-Be source as 10.5 – 10.75 MeV. The spectrum from Cember has over 70% of the neutron >3 MeV. The dose conversion factor increases little between 3 and 10 MeV, approximately 15%. If all the neutrons from the source were at the maximum energy, i.e., the most conservative (although unrealistic) spectrum, the HAC dose would increase by less than 50% to approximately 125 mrem/hr (1.15 x 1.30 x 82.7 mrem/hr), which is significantly less than the limit of 1000 mrem/hr. Therefore, we believe the analysis presented is sufficiently conservative.

5-4 *Justify the use of the cask nominal values for the SCALE model used to perform the shielding evaluation.*

The shielding evaluation was performed using nominal cask dimensions. Justify the use of nominal dimensions rather than accounting for manufacturing tolerances.

This information is needed to determine compliance with 10 CFR 71.41(a).

Response:

The cask shield layers are fabricated from steel plate (ASME-SA516 or ASME-SA537) and a poured lead layer. The manufacturing tolerance on thickness for the steel plate is specified in ASTM standard A 20 at 0.06 inches. This possible variance is not significant in the shielding calculation. The gap between the inner and outer steel layers has a tolerance of 1/8", so the lead layer has this as the fabrication tolerance. However, the cask has a gamma scan as part of the acceptance criteria. The acceptance criterion for the cask gamma scan is no more than a 10% reduction in shielding from the nominal thickness. Thus, use of the nominal dimensions for the shielding evaluation is acceptable.

5-5 Justify the positioning of the point source for NCT.

The staff does not find that assuming the source is at the center is necessarily limiting or realistic. Without knowing the exact contents of the waste package, it is possible to concentrate a source near the edge under NCT.

This information is needed to determine compliance with 10 CFR 71.41(a).

Response:

The source was positioned in the center under NCT so that the maximum activity source could be determined, i.e., the largest activity that does not exceed the NCT dose limits. Other source configurations would result in a smaller activity and would not be bounding.

The 10-160B is a multipurpose packaging used for transporting a wide variety of contents. Given this variety of contents, the basis of the shielding evaluation is the determination of the maximum activity source which complies with the NCT dose rate limits and the evaluation of this source under HAC. Since there are an infinite number of source configurations for NCT, the geometry that results in the maximum activity source is used. Also, since no source packaging is evaluated as part of the contents, the source must be evaluated without any additional shielding. The source geometry that gives the maximum source activity is a point source located at the center of the cask cavity. Similarly, the worst case geometry for HAC is a point source located on the cavity wall at the location of the Pb slump.

5-6 Provide additional information on the exact location of the dose points used for the shielding analysis.

Although Section 5 of the SAR specifies that the dose is calculated at the external surface of the side or top/bottom of the package, it does not give any information as to where along the side or top/bottom or if an average was taken, etc. The location of the dose point could give different, less conservative, results depending on where it is and *how it is treated. The staff notes that review of the SAS4 input deck shows multiple point and surface detectors specified but the staff does not know which one was selected for the analysis.*

This information is needed to determine compliance with 10 CFR 71.41(a).

Response:

As shown by the input files, each configuration has multiple detector locations. The doses reported in this section were the maximum dose rates reported in each output file. The detector result section of each output file is attached with the result used in Table 5.5 highlighted.

5-7 Provide a representative SAS4 output file for the neutron shielding analyses.

This file is needed for the staff to review proper convergence is achieved and that the calculated radiation levels from the output agree with those reported in the application.

This information is needed to determine compliance with 10 CFR 71.47.

Response:

A radial neutron output file, 10-160b-pt-n-HAC.out, is provided on the enclosed CD.

5-8 Provide additional details about the transport vehicle.

The staff needs information about the transport vehicle including dimensions and positioning of the packages on the vehicle.

This information is needed to determine compliance with 10 CFR 71.47(b)(4).

Response:

A typical cask trailer has a length of 563" and a width of 102". The cask is mounted vertically on the trailer. The distance from the cask centerline to the kingpin of the typical trailer is 270". The distance from the kingpin to the rear wall of the sleeper compartment is approximately 90".

5-9 Provide a drawing or additional clarifying information on the lead shield.

Section 1.1.2 of the SAR says that there is a 1-1/8 inch inner shell made of carbon steel and an outer carbon steel shell of 2 inches with 1-7/8 inch lead in between the two. The staff was able to confirm this for the side (radial thickness) of the lead shield and carbon steel shells by viewing the referenced drawing. However the drawing lacks information about axial length and position of the shield so the staff is unable to confirm this information. The SAS4 shielding input in Section 5 appears to show that the lead extends to the bottom of the cavity. The MCNP input in Section 6 appears to show that the lead shield extends 1 inch below the stainless steel liner and the top is even with the stainless steel liner.

This information is needed to determine compliance with 10 CFR 71.33.

Response:

Sheet 4 of drawing C-110-D-29003-010 (SAR drawing provided in Section 1 of the SAR) shows the cask outer shell and lead shield layer extending to 4 ½" from the bottom surface of the cask, which is 1" further than the inner shell and 1" below the bottom of the cask cavity. All three layers, inner, outer and lead, extend up to the bottom of the bolt ring. The SAS4 model is conservative in not extending the lead layer below the bottom of the cask cavity.

5-10 Provide additional information addressing the issues in estimating streaming using SAS4.

The staff notes that the SAS4 code has some limitations due to the use of 1-D adjoint flux in the creation of automated biases. Specifically the code has problems in estimating particle streaming through such voids. The Model No. 10-160B has a streaming path where the lead slump occurs. The staff reviewed the SAS4 input deck but did not find where or how this streaming deficiency was compensated for. Reference page 4 of the January 2003 SCALE newsletter, http://www.ornl.gov/sci/scale/news/scale_27jan2003.pdf.

This information is needed to determine compliance with 10 CFR 71.47.

Response:

The concern with streaming paths discussed in the SCALE newsletter results from an insufficient number of particles traveling through the void. The IGO-4 model in the shielding evaluation has a point source positioned adjacent to the void so this problem does not occur. With the source in proximity to the void, there are sufficient particles traveling through the void to give an appropriate answer. Additionally, our internal review of the SCALE calculation included an independent calculation of the dose results using MCNP. The MCNP results for the HAC condition on the cask side, i.e., the dose points affected by the presence of the void, give results that vary from the SCALE results by less than 1% for neutrons and less than 22% for gamma and both at least a factor of 5 less than the limit. Therefore, we feel the SCALE analysis adequately demonstrates compliance with 10 CFR 71.47.

Chapter 6 Criticality

6-1 Provide design information about the drums that will be contained within the Model No. 10-160B, including tolerances. Provide information on whether the drum design tolerances were considered in the criticality analyses.

The staff does not have any information about the drums. The staff acknowledges that no credit is taken for the geometry of the drums; however certain parameters important for criticality are based on the drum volume, such as the amount of CH_2 and the amount of beryllium. Verification is necessary to determine that tolerances for the drums are appropriately accounted for.

This information is needed to determine compliance with 10 CFR 71.33.

Response:

The drums were considered to be nominally 55 gals (208 Liters) for a total of 550 gal (2080 Liters) for a 10 drum payload. The analysis was done with optimum moderation and very conservative assumptions regarding the Pu, CH_2 and beryllium content and geometry. Therefore, small variations in the drum volume due to design tolerances will have an insignificant impact on the overall results and will not change the conclusions of the analysis.

The 1st sentence of the 2nd paragraph of Section 6.2 was revised to read:
"The 10-160B payload is assumed to be 10 drums considered to be nominally 55 gals (208 Liters) for a total of 550 gal (2080 Liters) and conservatively assumed to contain 325 g of pure Pu^{239}."

The 4th bullet in Section 6.3.1 was revised to read as:

4. The total volume of waste for the 10 drums was assumed to be 550 gallons (2080 Liters) based on a nominal drum capacity of 55 gallons. The moderating material is assumed to be bounded with polyethylene at a volume fraction of 25% of the total volume of waste. Because the analysis was done with optimum moderation and very conservative assumptions regarding the Pu, CH_2 and beryllium content and geometry, small variations in the drum volume due to design tolerances will have an insignificant impact on the overall results and will not change the conclusions of the analysis.

A revised Chapter 6 is provided. Please replace the previous version with the one provided with this response.

6-2 *Provide additional information regarding the proposed contents of the Model No. 10-160B.*

(a) Identification and maximum quantities of fissile constituents, (b) chemical and physical form of all package constituents, and (c) extent of reflection, the amount and identity of nonfissile materials used as neutron absorbers or moderators, and the atomic ratio of moderator to fissile constituents are necessary for the staff to perform its evaluation.

This information is needed to determine compliance with 10 CFR 71.33(b).

Response:

(a) Section 6.1, 3rd sentence and Section 6.2 1st sentence says the maximum fissile constituents is 325 FGE, i.e., 325 g Pu-239, and the quantities of all fissile isotopes other than Pu^{239} present in the RH-TRU waste matrix may be converted to a FGE using the conversion factors outlined in the *Remote-Handling Transuranic Waste Authorization Methods for Payload Control* (RH-TRAMPAC) (Reference 6).

The following was added after the 2nd paragraph in Section 6.2:

"There are no criticality controls on the isotopic composition of the plutonium. It is assumed, however, that the ^{240}Pu content exceeds the ^{241}Pu content. With this assumption, the fissile material is conservatively modeled as being 100% ^{239}Pu. The justification for this assumption is that the presence of ^{241}Pu content greater than ^{240}Pu content would require expensive isotopic enrichment. The vast majority of plutonium present in the world today meets this isotopic composition assumption. Note that of the plutonium nuclides that may be present, ^{241}Pu has the shortest half-life (14.4 years). It then decays to ^{241}Am, which shall be included in the plutonium mass. This is conservative because ^{241}Am is a parasitic neutron absorber in well moderated systems and, in unmoderated systems, requires a larger mass (~ 34 kg ^{241}Am) to achieve criticality than does ^{239}Pu (~ 5 kg ^{239}Pu). Thus counting ^{241}Am, present as a ^{241}Pu decay product, as ^{239}Pu is conservative."

(b) The following was added as the 1st paragraph of Section 6.2:

The type and form of waste material will include:

1) By-product, source, or special nuclear material consisting of process solids or resins, either dewatered, solid, or solidified in secondary containers. (See Section 4.2.1 for specific limitations). Contents containing greater than 20 Ci of plutonium must be in solid form.

2) Neutron activated metals or metal oxides in solid form.

2) Miscellaneous radioactive solid waste materials.

3) TRU wastes are limited as described in Appendix 4.10.2, Transuranic (TRU) Waste Compliance Methodology for Hydrogen Gas Generation. TRU exceeding the fissile limits of 10 CFR 71.15 must not be machine compacted and must have no more than 1% by weight of special reflectors and no more than 25% by volume of hydrogenous material.

Section 1.2.3.2 was revised to have equivalent language. The revised page, 1-4, is attached.

(c) 30 cm water reflector was used for single package cases along with the materials of the cask (steel and lead). There were no nonfissile materials used as neutron absorbers. Water, CH_2, and Beryllium were used as moderators. Tables 6.2 and 6.3 list the compositions used in the evaluation, from which the atomic ratios may be derived.

6-3 Identify any established codes and standards used in the criticality design and control.

Although the appropriate regulations were cited within the SAR, established codes and standards used in the criticality design and control were not provided. The staff reviews this to determine an adequate basis for the quality assurance program. Alternatively the staff would like a basis for the quality assurance program with respect to criticality.

This information is needed to determine compliance with 10 CFR 71.31(c).

Response:

The following will be added as the 4th paragraph of Section 6.1.1:

"The important criticality control features are the containment vessel (CV) and the payload restrictions. The CV provides confinement of the payload during normal conditions of transport (NCT) and hypothetical accident conditions (HAC). The payload restrictions ensure that the analysis basis assumptions used in the criticality evaluation regarding the form and content of the payload are maintained. Any user of the package must have a Quality Assurance program that meets 10 CFR 71 Subpart H requirements."

In response to this question we have added the following (in italics) clarification to the payload waste form description/limitation in Section 1.2.3.2, item 4 –

"TRU exceeding the fissile limits of 10 CFR 71.15 must not be machine compacted and must have no more than 1% by weight of special reflectors *and no more than 25% by volume of hydrogenous material.*"

6-4 *Provide the applicable information from Section 6.9.1, Reference No. 6, to the criticality evaluation: U.S. Department of Energy (DOE), Remote-Handled Transuranic Waste Authorized Methods for Payload Control (RH-TRAMPAC), U.S. Department of Energy, Carlsbad Field Office, Carlsbad, New Mexico. Identify and justify the conversion factors used to determine quantities of fissile isotopes other than Pu-239. Update the SAR to include these conversion factors.*

The staff does not have the above cited reference to determine the conversion factors for fissile isotopes other than Pu-239. The staff needs this information to determine what the conversion factors are and that there is an appropriate basis for these conversion factors. In addition the staff needs to determine that they are applicable to the contents of Model No. 10-160B.

This information is needed to determine compliance with 10 CFR 71.33(b)(2).

Response:

Section 3.1.2 (page 3.1-5) of the RH-TRAMPAC discusses the derivation of the FGE conversion factors and justifies their use. The RH-TRAMPAC, Rev 0, 2006 is enclosed with our response to the RAIs as a .pdf file.

6-5 *Provide the applicable information from Section 6.9.1, Reference No. 7, to the criticality evaluation: Neeley, G.W., D.L. Newell, S.L. Larson and R.J. Green, Reactivity Effects of Moderator and Reflector Materials on a Finite Plutonium System, SAIC-1322-001, Revision 1, Science Applications International Corporation, Oak Ridge, Tennessee, May 2004.*

The above reference is cited as the justification for use of polyethylene as the bounding hydrogenous moderating material. Additionally, this reference is also cited as the justification for using beryllium as the most bounding reflector material. The staff does not have this reference and needs to review the information contained within it to determine that there is an appropriate basis for the amendment request.

This information is needed to determine compliance with 10 CFR 71.55(b)(1).

Response:

Reference 7 was changed to Section 6.2.1 of the *RH-TRU 72-B Safety Analysis Report, Revision 4, 2006*. This document is provided as a pdf file.

6-6 *Provide additional clarifying information on how the most reactive content and dimensions of the fissile sphere were determined.*

Specifically the staff is unclear about the statement on page 6-3 of the SAR, third paragraph, "the volume of the sphere is dependent upon the sum of the Pu-239, beryllium, polyethylene and void volumes." Provide information on how the void volumes were determined. For HAC the void volume is filled with water. The staff also needs additional information on how the water volume within the fissile sphere for HAC is determined.

This information is needed to determine compliance with 10 CFR 71.55(b)(1).

Response:

The void volume was determined by establishing the desired H/X ratio which determined the polyethylene needed for the given mass of PU-239. The mass of beryllium was set as a percentage of the mass of Pu-239 and polyethylene. The polyethylene was limited to 25% of the total volume. Pu-239 and beryllium accounted for a small percentage of the remaining volume. Volume that was not used was either void (NCT) or water (HAC).

6-7 *Identify and justify the density material composition selected for the water moderator and reflector mixture (Be/CH_2 and Be/CH_2/H_2O) used as reflector and to fill the cavity for both NCT and HAC.*

No justification or sensitivity studies were provided to explain why full density water was used to fill the cavity. The staff also does not have any information on the selection of the density including water content of the reflector.

This information is needed to determine compliance with 10 CFR 71.55.

Response:

As described Sections 6.2 and 6.3.1 of the SAR, the void volume was determined by establishing the desired H/X ratio which determined the polyethylene needed for the given mass of Pu-239. The mass of beryllium was set as a percentage of the mass of Pu-239 and polyethylene. The polyethylene was limited to 25% of the total volume. Pu-239 and beryllium accounted for a small percentage of the remaining volume. Volume that was not used was either void (NCT) or water (HAC). Full density water was used for the HAC case since 71.55(b)(2) requires moderation by water to the most reactive credible extent and full density water was found to be most reactive.

The material compositions for NCT were derived based on zero density water in the moderator and reflector, and material compositions for HAC were for full density water in the moderator and reflector.

There was no need to evaluate reduced density water for HAC because the H/X ratio was optimized.

6-8 Provide a representative MCNP output file for the most limiting criticality case.

The staff needs to view this file to determine that the multiplication factors from the output files agree with those reported in the evaluation. The MCNP output file also needs to be viewed to verify that the calculation has passed important statistical checks and has appropriate convergence behavior.

This information is needed to determine compliance with 10 CFR 71.31.

Response:

MCNP output files are provided for the limiting single package case (10-160b-sphere-F033.out) and array case (10-160b-sphere-F022flat02.out).

6-9 Provide justification demonstrating that the position of the fissile sphere within each array element is in the most reactive configuration.

Since the most reactive position for the fissile sphere in each transportation package is non-symmetric (in the lid corner) it is possible that if the casks were placed in an array where the fissile sphere was in a different location for each cask within the array such that the fissile material were all located around the same location, this may be more reactive.

This information is needed to determine compliance with 10 CFR 71.55(b)(1).

Response:

Maximum criticality is achieved when the fissile spheres are located in close proximity to other fissile spheres. As discussed in Sections 6.5 and 6.6 of the SAR, array cases examined 4 fissile spheres that were as close together as possible for the infinite array model with reflective boundary conditions. Array cases were also examined for 6 fissile spheres that were in close proximity but not as close as the 4 fissile spheres. The maximum reactivity occurs with the four base corner casks which have the fissile spheres in closest proximity. The array of lid corner casks reactivity was always slightly less reactive than the array of base corner casks. As shown in Table 6.1 of the SAR, there is only a slight difference (~5 milli-k) between the bounding single cask and infinite array k_{eff} values. Because of the conservatisms used in the array models (full in-flooding, optimized H/X, infinite array of casks in the axial and radial direction, etc.) and the small difference between the bounding single cask and infinite array results, evaluation of additional array configurations was considered not necessary.

6-10 Update the SAR to remove/revise the following statement in Section 6.6.1 (page 6-29): "These conditions are applied to a package that has undergone the tests specified in 10 CFR 71.73, which means that credit may be taken for the cask remaining leaktight *during accident conditions. However, although the 10-160B cask remains leaktight under the accident-condition tests specified in 10 CFR 71.73, the criticality analysis for arrays during accident conditions conservatively assumes in-flooding of the cask containment."*

Section 2.7.4, Water Immersion, of the SAR states that the immersion in water test required by 10 CFR 71.73(c)(5) was not performed because "no fissile materials will be carried in the cask." Although not performing this test has no impact on the criticality analyses since the cask was assumed flooded. The inclusion of the above statement is incorrect and misleading.

This information is needed to determine compliance with 10 CFR 71.7.

Response:

Section 6.6.1 was revised.
Section 2.7.4 was revised to state: "10 CFR 71.73 (c) (4) is not applicable, since water inleakage has been assumed for the criticality analysis." The revised page, 2-100, is attached.

6-11 Provide a discussion on any trends observed in any of the parameters important in the validation of the criticality code.

In some cases, trends can be seen in the benchmarking data for the criticality codes for certain important parameters (Pu-239/Pu-240 content, AEF, H/fissile ratio, etc). Certain data sets should be examined individually to determine if there were any noticeable trends with any particular parameters. The staff did not find a discussion of this in the SAR.

This information is needed to determine compliance with 10 CFR 71.35.

Response:

The following was added to Section 6.8.2:
"There were no observable trends for the benchmark k_{eff} values (i.e., versus AEF, H/X, etc.) that would impact the bias determination. All but 2 of the benchmark experiments had k_{eff} values greater than 1.0. Because the average k_{eff} is greater than 1.0, and the 2 benchmark experiments with k_{eff} values below 1.0 are greater than 0.999, the bias, β, was set to zero in the determination of the effective criticality limit for this evaluation."

Chapter 8

8-1 Explain the reason for no thermal acceptance tests to demonstrate the heat transfer capability of the Model No. 10-160B packaging after fabrication and during the service life of the package as described in Chapter 8. Clarify if thermal tests are performed as part of the maintenance program.

The thermal tests may be needed to confirm that heat transfer performance is consistent with the thermal analyses given uncertainties in calculations, fabrication, or aging of the package during its service life. The staff would like to verify that the maintenance program remains adequate to assure packaging effectiveness for this "-96" approval *request. If thermal tests are performed, the application should indicate the frequency, method of testing, and the equipments used in the tests.*

This information is needed to determine compliance with 10 CFR 71.71 and 71.73.

Response:

No thermal acceptance tests were performed as the cask design is relatively simple and adequately modeled by ANSYS. No thermal tests are performed as part of the maintenance program as the materials of construction, steel and lead, are not subject to changes in material properties or dimensions over the service life of the cask.

8-2 Update Section 8.2 to clarify the specific leak rate criteria for seal replacements and periodic tests.

Section 8.2 will be referenced as a condition of the certificate of compliance. The information located in Section 8.2 should be revised.

This information is needed to determine compliance with 10 CFR 71.35.

Response:

The maximum allowable leak rate for the cask is 3.25 x 10^{-6} atm-cm^3/sec. The option to use a He leak test to demonstrate that the cask can achieve a more conservative leak rate of 1.0 x 10^{-7} atm-cm^3/sec was added in a recent revision to the SAR. This option was explicitly noted in the Safety Evaluation Report issued with Certificate of Compliance No. 9204, Revision No. 12 and was accepted "...the staff finds that the containment design has been adequately described and evaluated and has a reasonable assurance that the package meets the regulatory requirements for containment design."

Since there were no technical changes to Section 8 or any changes to the leak rate portions of Section 4, Section 8.2 was not revised.

Attachment 2

1) By-product, source, or special nuclear material consisting of process solids or resins, either dewatered, solid, or solidified in secondary containers. (See Section 4.2.1 for specific limitations). Contents containing greater than 20 Ci of plutonium must be in solid form.

2) Neutron activated metals or metal oxides in solid form.

3) Miscellaneous radioactive solid waste materials.

4) TRU wastes are limited as described in Appendix 4.10.2, Transuranic (TRU) Waste Compliance Methodology for Hydrogen Gas Generation. TRU exceeding the fissile limits of 10 CFR 71.15 must not be machine compacted and must have no more than 1% by weight of special reflectors and no more than 25% by volume of hydrogenous material.

2.7.4 Water Immersion

10 CFR 71.73 (c) (4) is not applicable, since water inleakage has been assumed for the criticality analysis.

10 CFR 71.73 (c) (5) requires an immersion in water with a pressure of 21. psig for eight hours. Review of the stresses summarized in Table A2-16 for a 25 psig pressure indicates the stresses are low, and this test will have no significant effect on the package.

2.7.5 Summary of Damage

The structural integrity of the CNSI 10-160B package has been demonstrated, by analytical models, to be maintained during the hypothetical accident conditions. The condition of the package after the hypothetical accident is:

(1) Impact limiters are crushed during the 30 foot drop condition. Cask stresses are less than those prescribed by NRC Regulatory Guide 7.6.

(2) Small local deformations to the external shell may result from the 40 inch puncture condition. There will be no loss of shielding and the containment vessel will not be deformed.

Table 2-6 summarizes the maximum Primary Stresses during the hypothetical accident conditions.

2.8 Special Form

Not applicable since no special form is claimed.

3.6 References

1. ASME Boiler and Pressure Vessel Code an American Standard, Section II, Part B Materials, The American Society of Mechanical Engineers, New York, NY, 1995.

2. Heat Transfer, J.P. Holman, Mc-Graw Hill Book Company, New York, Fifth Edition, 1981.

3. Code of Federal Regulations Title 10 Parts 71, Packaging and Transportation of Radioactive Material, 1998.

4. Cask Designers Guide, L.B. Shappert, et. al, Oak Ridge National Laboratory, February 1970, ORNL-NSIC-68.

5. CRC Handbook of Chemistry and Physics, Robert C. Weast and Melvin J. Astel, eds., CRC Press, Inc., Boca Raton, Florida, 62nd ed., 1981.

6. O-Ring Handbook, Parker Seal Company, Lexington, Kentucky, January 1977.

7. ANSYS Rev. 11 Computer Software, ANSYS Inc., Cannonsburgh, Pennsylvania, 2007.

8. IAEA Safety Series No.6, Regulations for the Safe Transport of Radioactive Material, 1985 Edition (As Amended 1990), International Atomic Energy Agency, Vienna, 1990.

9. IAEA Safety Series No.37, Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material - 1985 Edition, International Atomic Energy Agency, Vienna, 1990.

10. Chemical Engineers' Handbook, Fifth Edition, Robert H. Perry and Cecil H. Chilton, McGraw-Hill Book Company, 1973.

6 CRITICALITY EVALUATION

6.1 DESCRIPTION OF CRITICALITY DESIGN

This criticality safety evaluation supports shipment of up to ten TRU waste drums per 10-160B Cask. This criticality safety evaluation establishes a general payload for the 10-160B Cask. The maximum fissile mass limit for the 10-160B Cask is 325 fissile-gram-equivalent (FGE). The waste drums will be filled with manually compacted waste (i.e., not machine compacted) containing a maximum of 1% by weight of special reflectors.

6.1.1 Design Features

The Model CNS 10-160B packaging consists of a lead and steel containment vessel which provides the necessary shielding for the various radioactive payloads. (Refer to Section 1.2.3 for packaging contents.) Tests and analysis performed and documented within chapters 2.0 and 3.0 have demonstrated the ability of the containment vessel to maintain its shielding integrity under normal conditions of transport.

The cask side wall consists of an outer 2-inch thick steel shell surrounding 1 7/8 inches of lead and an inner containment shell wall of 1 1/8-inch thick steel.

The primary cask lid consists of two steel layers with a total thickness of 5½ inches. The lid closure is made in a stepped configuration to eliminate radiation streaming at the lid/cask body interface. A secondary lid is located at the center of the main lid, covering a 31-inch opening. The secondary lid is constructed of steel plates with a total thickness of 5½ inches with multiple steps machined in its periphery. These steps match those in the primary lid, eliminating radiation streaming pathways.

The important criticality control features are the containment vessel (CV) and the payload restrictions. The CV provides confinement of the payload during normal conditions of transport (NCT) and hypothetical accident conditions (HAC). The payload restrictions ensure that the analysis basis assumptions used in the criticality evaluation regarding the form and content of the payload are maintained. Any user of the package must have a Quality Assurance program that meets 10 CFR 71 Subpart H requirements.

Figures 6-1 and 6-2 present representative views of a single 10-160B Cask with ten 55-gallon drums for a normal as-loaded configuration.

6.1.2 Summary Table of Criticality Evaluation

Table 6.1 summarizes the results of the criticality evaluation for single packages and arrays of packages for the conditions defined in 10 CFR 71.55 and 71.59. These results indicate that the 10-160B Cask with any of the payloads described in Section 6.2 remains safely subcritical under NCT and HAC even with the extremely conservative assumptions used in the analysis.

6.1.3 Criticality Safety Index

As shown in Table 6.1, the maximum calculated k_{eff} value is 0.93873 (Case f022flat02) for an infinite array of fully flooded 10-160B Casks containing an optimally moderated sphere with 325 g of Pu-239. This is below the k_{eff} limit of 0.94 after allowing for bias and uncertainties. Because an infinite array of casks is safely subcritical, N equals infinity and the CSI is zero.

Table 6.1. Summary of Criticality Safety Evaluation Results.

Single Package Results [10 CFR 71.55(b), (d), (e)]	
Package calculated to be subcritical under conditions for maximum reactivity	Maximum k_{eff}[a] = 0.93252, σ = 0.00020 (case f033)
Most reactive configuration	Compact sphere containing 325 g of Pu^{239} homogenized with 25% by volume of CH_2 and 1% by weight of Be based on CH_2 and Pu^{239} with the remaining volume filled with H_2O
Moderation for most reactive configuration	Cask flooded
Reflection for most reactive configuration (package materials and/or 30 cm water)	30 cm water around the cask
Array Results	
NCT array [10 CFR 71.59(a)(1)]	Maximum k_{eff}[a] = 0.45328, σ = 0.00015 (case f369a)
Number of packages	Analyzed: infinite array (CSI = 0)
Most reactive fissile content	Compact sphere containing 325 g of Pu^{239} homogenized with 25% by volume of CH_2 and 1% by weight of Be based on CH_2 and Pu^{239}
Interstitial moderation	No interstitial moderation
Reflection surrounding array	No reflector since infinite array
HAC array [10 CFR 71.59(a)(2)]	Maximum k_{eff}[a] =0.93873, σ = 0.00020 (case f022flat02)
Number of packages	Analyzed: infinite array (CSI = 0)
Most reactive fissile content:	Compact sphere containing 325 g of Pu^{239} homogenized with 25% by volume of CH_2 and 1% by weight of Be based on CH_2 and Pu^{239} with the remaining volume filled with H_2O
Interstitial moderation	0.001 g/cm^3 water interstitial moderation
Reflection surrounding array	No reflector since infinite array

[a] The effective criticality limit for this evaluation is $k_{eff} < 0.94$ which accounts for bias and uncertainties (see Section 6.8).

6.2 FISSILE MATERIAL CONTENTS

The type and form of waste material will include:

1) By-product, source, or special nuclear material consisting of process solids or resins, either dewatered, solid, or solidified in secondary containers. (See Section 4.2.1 for specific limitations). Contents containing greater than 20 Ci of plutonium must be in solid form.

2) Neutron activated metals or metal oxides in solid form.

3) Miscellaneous radioactive solid waste materials.

4) TRU wastes are limited as described in Appendix 4.10.2, Transuranic (TRU) Waste Compliance Methodology for Hydrogen Gas Generation. TRU exceeding the fissile limits of 10 CFR 71.15 must not be machine compacted and must have no more than 1% by weight of special reflectors and no more than 25% by volume of hydrogenous material.

The 10-160B payload is assumed to be 10 drums considered to be nominally 55 gals (208 Liters) for a total of 550 gal (2080 Liters) and conservatively assumed to contain 325 g of pure Pu^{239}.
The quantities of all fissile isotopes other than Pu^{239} present in the RH-TRU waste matrix may be converted to a FGE using the conversion factors outlined in the *Remote-Handling Transuranic Waste Authorization Methods for Payload Control* (RH-TRAMPAC) (Reference 6). Section 3.1.2 (page 3.1-5) of the RH-TRAMPAC discusses the derivation of the FGE conversion factors and justifies their use. In addition, the Pu^{239} is conservatively assumed to be contained within a sphere moderated and reflected by polyethylene (CH_2) with the total CH_2 comprising up to a maximum of 25% by volume of the 550 gallons. Beryllium is added as a special reflector/moderator with the total beryllium comprising up to a maximum of 1% by weight of the total masses of CH_2 and Pu^{239}.

There are no criticality controls on the isotopic composition of the plutonium. It is assumed, however, that the ^{240}Pu content exceeds the ^{241}Pu content. With this assumption, the fissile material is conservatively modeled as being 100% ^{239}Pu. The justification for this assumption is that the presence of ^{241}Pu content greater than ^{240}Pu content would require expensive isotopic enrichment. The vast majority of plutonium present in the world today meets this isotopic composition assumption. Note that of the plutonium nuclides that may be present, ^{241}Pu has the shortest half-life (14.4 years). It then decays to ^{241}Am, which shall be included in the plutonium mass. This is conservative because ^{241}Am is a parasitic neutron absorber in well moderated systems and, in unmoderated systems, requires a larger mass (~ 34 kg ^{241}Am) to achieve criticality than does ^{239}Pu (~ 5 kg ^{239}Pu). Thus counting ^{241}Am, present as a ^{241}Pu decay product, as ^{239}Pu is conservative.

The use of polyethylene as the bounding hydrogenous moderating material is justified in Section 6.2.1 of the *RH-TRU 72-B Safety Analysis Report, Revision 4, 2006* (Reference 7) which concludes that polyethylene is the most reactive moderator that could credibly moderate the transuranic waste in a pure form. A 25% volumetric packing fraction for polyethylene is used as a conservative value which is based on physical testing that bounds the packing fraction of polyethylene in manually compacted TRU waste of 13.36% (Reference 8).

This evaluation also addresses the addition of special reflectors in the waste matrix. Materials that can credibly provide better than 25% polyethylene/75% water equivalent reflection are termed "special reflectors" and are not authorized for shipment in quantities that exceed 1% by weight. Based on the studies of reflector material discussed in the *RH-TRU 72-B SAR* (Reference 7), Be, BeO, C, D2O, MgO, and depleted uranium (less than 0.72 wt% and greater than or equal to 0.3 wt% 235U) are the only materials considered special reflectors. Studies discussed in the *RH-TRU 72-B SAR* found that beryllium is the bounding special reflector as it provides the best reflection of the system and results in the highest k_{eff}.

For the NCT cases, the total amount of CH_2 is based on 25% by volume of 10 drums. The total amount of beryllium is based upon 1% by weight of the total mass of the CH_2 and the Pu^{239} in the 10 drums. The NCT configurations are assumed to not contain water. Therefore, the remaining volume not filled with polyethylene, Pu^{239} and beryllium is considered to be void. Densities are based upon smearing the materials with the void in the fissile sphere and the reflector.

For the NCT cases, the fissile sphere contains 325 g Pu^{239} uniformly distributed with 25% by volume of CH_2. Beryllium, added to the fissile sphere as a special reflector/moderator, is uniformly distributed throughout the sphere in the amount of 1% by mass of the total CH_2 and Pu^{239} mass. H/Pu ratios are postulated which determine the masses of CH_2 and beryllium in the fissile sphere for a given H/Pu ratio. The volume of the sphere is dependent upon the sum of the Pu^{239}, beryllium, polyethylene and void volumes. The various NCT fissile sphere compositions, densities and associated radii are presented in Table 6.2.

The remaining CH_2 (at 25% density) and beryllium not used in the fissile sphere are assumed to comprise a reflector completely surrounding the fissile sphere. The beryllium is uniformly distributed throughout the reflector volume in the amount of 1% by mass of the CH_2 mass. For the fissile sphere positioned in the centroid of the cask cavity, the reflector is a sphere. For the fissile sphere on the center floor or corner floor, the reflector occupies the same volume as the sphere but cylindrical in shape filling the lower portion of the cask. The reflector compositions are presented in Table 6.2 and representative views of the various NCT configurations are shown in Figures 6-3 through 6-5.

For the HAC cases, the total amount of CH_2 is based upon a maximum of 25% by volume of 10 drums. The total amount of beryllium is based upon a maximum of 1% by weight of the total mass of the CH_2 and the Pu^{239} in the 10 drums. The drums were considered to be nominally 55 gals (208 Liters) for a total of 550 gal (2080 Liters) for a 10 drum payload. The HAC configurations are assumed to contain water as required by 10 CFR 71.55(b). Therefore, any remaining volume not filled with polyethylene, Pu^{239} and beryllium is considered to be filled with water. Densities are based upon smearing the materials with the water in the fissile sphere and the reflector.

For the HAC cases, the fissile sphere is comprised of 325 g Pu^{239} uniformly distributed with the appropriate amounts of CH_2 and beryllium (as a special reflector/moderator) for the particular configuration. The remaining volume in the fissile sphere is filled with water. H/Pu ratios are postulated which determine the masses of CH_2 and beryllium in the fissile sphere for a given H/Pu ratio. The volume of the sphere is dependent upon the sum of the Pu^{239}, beryllium, polyethylene and water volumes. The various HAC fissile sphere compositions and associated radii are presented in Table 6.3. Modifications of certain compositions were made to examine the effect of less beryllium (0% and 0.5% by mass of total CH_2 and Pu^{239} mass) and by less polyethylene (20% by volume of the 10 drums). Representative views of the various HAC configurations are shown in Figures 6-6 through 6-9.

The HAC reflector contains the remaining CH_2 homogenized with sufficient H_2O to fill the remaining cask cavity volume. Beryllium is added to the reflector as a special reflector and is uniformly distributed throughout the volume in the amount of 1% by mass of the CH_2 mass. The fissile sphere is located in the cask centroid, on the center floor, corner floor or corner ceiling. The reflector compositions are presented in Table 6.3. Modifications of certain compositions were made to examine the effect of less beryllium (0% and 0.5% by mass of total CH_2 mass) and by less polyethylene (20% by volume of the 10 drums).

6.3 GENERAL CONSIDERATIONS

6.3.1 Model Configuration

Section 6.2 describes the fissile and reflector materials used in the criticality models.

Figures 6-1 and 6-2 present representative views of the normal condition 10-160B Cask with 10 drums. The radial and axial zone dimensions are shown in Table 6-4. The criticality model was developed using these dimensions and is essentially the same as the actual cask except that some details such as drain ports, lifting holes, and leak test ports are not included. The thermal barrier and impact limiter are also not included. These modeling simplifications will have a negligible impact on the criticality calculations and do not change the conclusions of the evaluation. A 12 inch water reflector region surrounds the cask.

The following additional assumptions are made in this evaluation.

1. The 10-160B is assumed to maintain its integrity under accident conditions; therefore, the cask model is based on nominal design dimensions and the payload is assumed to remain in the cask cavity under normal and accident conditions.

2. The fissile material is conservatively modeled as Pu^{239} with no credit taken for any neutron poisons that may be present such as Pu^{240} or Pu^{242}, the drums, or internal support structures.

3. The total volume of waste for the 10 drums was assumed to be 550 gallons (2080 Liters) based on a nominal drum capacity of 55 gallons. The moderating material is assumed to be bounded with polyethylene at a volume fraction of 25% of the total volume of waste. Because the analysis was done with optimum moderation and very conservative assumptions regarding the Pu, CH_2 and beryllium content and geometry, small variations in the drum volume due to design tolerances will have an insignificant impact on the overall results and will not change the conclusions of the analysis.

4. The maximum special reflecting material (beryllium) is 1% by weight in 550 gallons total volume of waste, i.e., 1% by weight of total mass of polyethylene and mass of plutonium.

5. Worse case NCT geometry is a sphere of fissile material. All plutonium is uniformly distributed within the sphere, as well as the polyethylene at a volume fraction of 25%. The beryllium is uniformly distributed within the sphere at 1% by weight of the total plutonium and polyethylene mass.

6. Worse case NCT reflector geometry contains the remaining polyethylene and beryllium. The reflector geometry is either a sphere surrounding the fissile material or a cylinder filling the bottom of the cask. In all cases, the polyethylene is at a packing fraction of 25% and the beryllium is uniformly distributed.

7. Worse case HAC geometry is a sphere of fissile material. All plutonium is uniformly distributed within the sphere, as well as the polyethylene (25%). The beryllium is uniformly distributed within the sphere at 1% by weight of the total plutonium and polyethylene mass. Water fills the remaining voids not filled by other materials.

Table 6.2. NCT Fissile Sphere and Reflector Compositions.

NCT Fissile Plus Moderator - 25% CH_2 Volume Fraction[b] - 1% Be Weight Fraction[c]										
Material Identifier	H/Pu	Sphere Radius (cm)	Sphere Density (g/cm^3)	Mass Fractions[a]						
				Hydrogen		Beryllium	Carbon	Oxygen		Plutonium
				H^1	H^2	Be^9	C	O^{16}	O^{17}	Pu^{239}
m130	700	19.04676	0.244252	0.13564500	0.00004067	0.00990099	0.80844128	N/A	N/A	0.04597206
m131	800	19.913170	0.242853	0.13643688	0.00004091	0.00990099	0.81316084	N/A	N/A	0.04046038
m132	850	20.31945	0.242277	0.13676564	0.00004100	0.00990099	0.81512025	N/A	N/A	0.03817212
m133	900	20.71011	0.241765	0.13705920	0.00004109	0.00990099	0.81686988	N/A	N/A	0.03612883
m134	950	21.08656	0.241307	0.13732294	0.00004117	0.00990099	0.81844173	N/A	N/A	0.03429317
m135	1000	21.45002	0.240895	0.13756117	0.00004124	0.00990099	0.81986157	N/A	N/A	0.03263503
m136	1100	22.14214	0.240183	0.13797461	0.00004137	0.00990099	0.82232566	N/A	N/A	0.02975738
m137	1200	22.79349	0.239589	0.13832104	0.00004147	0.00990099	0.82439041	N/A	N/A	0.02734609
m138	1300	23.40961	0.239087	0.13861554	0.00004156	0.00990099	0.82614562	N/A	N/A	0.02529629
m139	1400	23.99489	0.238656	0.13886897	0.00004163	0.00990099	0.82765605	N/A	N/A	0.02353235
m140	1500	24.55294	0.238283	0.13908936	0.00004170	0.00990099	0.82896956	N/A	N/A	0.02199839
m141	1600	25.08671	0.237957	0.13928277	0.00004176	0.00990099	0.83012231	N/A	N/A	0.02065217
m142	1700	25.59869	0.237669	0.13945388	0.00004181	0.00990099	0.83114211	N/A	N/A	0.01946121
m143	1800	26.09097	0.237412	0.13960633	0.00004186	0.00990099	0.83205070	N/A	N/A	0.01840013

NCT Reflector - 25% CH_2 Volume Fraction[b] - 1% Be Weight Fraction[c]										
Material Identifier	H/Pu	Sphere Radius (cm)	Reflector Density (g/cm^3)	Mass Fractions[a]						
				Hydrogen		Beryllium	Carbon	Oxygen		Plutonium
				H^1	H^2	Be^9	C	O^{16}	O^{17}	Pu^{239}
m160	N/A	79.21023	0.233058	0.142249921	4.26486E-05	0.00990099	0.847806441	N/A	N/A	N/A
m161	N/A	79.21023	0.233058	0.142249921	4.26486E-05	0.00990099	0.847806441	N/A	N/A	N/A
m162	N/A	79.21023	0.233058	0.142249921	4.26486E-05	0.00990099	0.847806441	N/A	N/A	N/A
m163	N/A	79.21023	0.233058	0.142249921	4.26486E-05	0.00990099	0.847806441	N/A	N/A	N/A
m164	N/A	79.21023	0.233058	0.142249921	4.26486E-05	0.00990099	0.847806441	N/A	N/A	N/A
m165	N/A	79.21023	0.233058	0.142249921	4.26486E-05	0.00990099	0.847806441	N/A	N/A	N/A
m166	N/A	79.21023	0.233058	0.142249921	4.26486E-05	0.00990099	0.847806441	N/A	N/A	N/A
m167	N/A	79.21023	0.233058	0.142249921	4.26486E-05	0.00990099	0.847806441	N/A	N/A	N/A
m168	N/A	79.21023	0.233058	0.142249921	4.26486E-05	0.00990099	0.847806441	N/A	N/A	N/A
m169	N/A	79.21023	0.233058	0.142249921	4.26486E-05	0.00990099	0.847806441	N/A	N/A	N/A
m170	N/A	79.21023	0.233058	0.142249921	4.26486E-05	0.00990099	0.847806441	N/A	N/A	N/A
m171	N/A	79.21023	0.233058	0.142249921	4.26486E-05	0.00990099	0.847806441	N/A	N/A	N/A
m172	N/A	79.21023	0.233058	0.142249921	4.26486E-05	0.00990099	0.847806441	N/A	N/A	N/A
m173	N/A	79.21023	0.233058	0.142249921	4.26486E-05	0.00990099	0.847806441	N/A	N/A	N/A

[a] Values derived assuming 19.7 g/cm^3 for Pu, 1.85 g/cm^3 for Be, 0.923 g/cm^3 for CH_2, and 1.0 g/cm^3 for H_2O.

[b] CH_2 volume fractions based on ten 55 gallon drums

[c] Be weight fraction based upon mass of CH_2 and Pu (fissile region only)

Table 6.3. HAC Fissile Sphere and Reflector Compositions.

HAC Fissile Plus Moderator													
Material Identifier	H/Pu	CH_2[b] Volume Fraction	Be[c] Weight Fraction	Sphere Radius (cm)	Sphere Density (g/cm^3)	Mass Fractions[a]						
						Hydrogen		Beryllium	Carbon	Oxygen		Plutonium
						H^1	H^2	Be^9	C	O^{16}	O^{17}	Pu^{239}
m100	700	25%	1.0%	12.519999	1.019560	0.11441390	0.00003430	0.00264597	0.19336657	0.65049999	0.00026274	0.03877653
m101	800	25%	1.0%	13.088647	1.014851	0.11497677	0.00003447	0.00261028	0.19431786	0.65370021	0.00026404	0.03409638
m102	850	25%	1.0%	13.355327	1.012911	0.11521015	0.00003454	0.00259548	0.19471229	0.65502711	0.00026457	0.03215585
		25%	0.5%	13.352284	1.012326	0.11535548	0.00003459	0.00129870	0.19484164	0.65600821	0.00026497	0.03219641
		25%	0.0%	13.349243	1.011742	0.11550103	0.00003463	0.00000000	0.19497120	0.65699073	0.00026537	0.03223704
		20%	1.0%	13.393913	1.016274	0.11383931	0.00003413	0.00213088	0.15525677	0.69668428	0.00028140	0.03177324
m103	900	25%	1.0%	13.611761	1.011186	0.11541840	0.00003460	0.00258227	0.19506425	0.65621111	0.00026505	0.03042431
		25%	0.5%	13.608682	1.010604	0.11556323	0.00003465	0.00129208	0.19519253	0.65718959	0.00026545	0.03046248
		25%	0.0%	13.605605	1.010023	0.11570826	0.00003469	0.00000000	0.19532101	0.65816948	0.00026584	0.03050072
		20%	1.0%	13.651092	1.014565	0.11404263	0.00003419	0.00211700	0.15553406	0.69792857	0.00028190	0.03006165
m104	950	25%	1.0%	13.858882	1.009642	0.11560537	0.00003466	0.00257042	0.19538023	0.65727412	0.00026548	0.02886972
		25%	0.5%	13.855767	1.009063	0.11574973	0.00003470	0.00128613	0.19550755	0.65825023	0.00026587	0.02890577
		25%	0.0%	13.852654	1.008484	0.11589430	0.00003475	0.00000000	0.19563507	0.65922774	0.00026627	0.02894188
		20%	1.0%	13.898930	1.013035	0.11422516	0.00003425	0.00210454	0.15578300	0.69904565	0.00028235	0.02852505
m105	1000	25%	1.0%	14.097490	1.008253	0.11577416	0.00003471	0.00255972	0.19566550	0.65823377	0.00026587	0.02746628
		25%	0.5%	14.094340	1.007676	0.11591811	0.00003475	0.00128077	0.19579194	0.65920774	0.00026626	0.02750043
		25%	0.0%	14.091191	1.007100	0.11606226	0.00003480	0.00000000	0.19591858	0.66018308	0.00026665	0.02753463
		20%	1.0%	14.138232	1.011657	0.11438994	0.00003430	0.00209329	0.15600773	0.70005409	0.00028276	0.02713789
m106	1100	25%	1.0%	14.551873	1.005852	0.11606687	0.00003480	0.00254115	0.19616020	0.65989797	0.00026654	0.02503247

HAC Reflector													
Material Identifier	H/Pu	CH_2[b] Volume Fraction	Be[c] Weight Fraction	Sphere Radius (cm)	Reflector Density (g/cm^3)	Mass Fractions[a]						
						Hydrogen		Beryllium	Carbon	Oxygen		Plutonium
						H^1	H^2	Be^9	C	O^{16}	O^{17}	Pu^{239}
m150	N/A	25%	1.0%	N/A	0.991734	0.11510979	0.00003451	0.00105738	0.09054180	0.79293624	0.00032027	N/A
m151	N/A	25%	1.0%	N/A	0.991737	0.11510879	0.00003451	0.00105705	0.09051365	0.79296572	0.00032029	N/A
m152	N/A	25%	1.0%	N/A	0.991738	0.11510828	0.00003451	0.00105689	0.09049956	0.79298046	0.00032029	N/A
		25%	0.5%	N/A	0.991497	0.11516820	0.00003453	0.00052857	0.09052169	0.79342654	0.00032047	N/A
		25%	0.0%	N/A	0.991256	0.11522815	0.00003455	0.00000000	0.09054382	0.79387283	0.00032065	N/A
		20%	1.0%	N/A	0.993391	0.11445521	0.00003432	0.00084408	0.07227755	0.81206084	0.00032800	N/A
m153	N/A	25%	1.0%	N/A	0.991739	0.11510778	0.00003451	0.00105672	0.09048548	0.79299521	0.00032030	N/A
		25%	0.5%	N/A	0.991498	0.11516769	0.00003453	0.00052849	0.09050760	0.79344121	0.00032048	N/A
		25%	0.0%	N/A	0.991257	0.11522763	0.00003455	0.00000000	0.09052974	0.79388743	0.00032066	N/A
		20%	1.0%	N/A	0.993392	0.11445480	0.00003432	0.00084395	0.07226622	0.81207270	0.00032800	N/A
m154	N/A	25%	1.0%	N/A	0.991740	0.11510727	0.00003451	0.00105656	0.09047139	0.79300997	0.00032030	N/A
		25%	0.5%	N/A	0.991500	0.11516717	0.00003453	0.00052841	0.09049351	0.79345589	0.00032048	N/A
		25%	0.0%	N/A	0.991259	0.11522711	0.00003455	0.00000000	0.09051565	0.79390203	0.00032066	N/A
		20%	1.0%	N/A	0.993393	0.11445440	0.00003432	0.00084382	0.07225489	0.81208457	0.00032801	N/A
m155	N/A	25%	1.0%	N/A	0.991742	0.11510677	0.00003451	0.00105639	0.09045730	0.79302472	0.00032031	N/A
		25%	0.5%	N/A	0.991501	0.11516666	0.00003453	0.00052833	0.09047942	0.79347057	0.00032049	N/A
		25%	0.0%	N/A	0.991260	0.11522658	0.00003455	0.00000000	0.09050156	0.79391664	0.00032067	N/A
		20%	1.0%	N/A	0.993394	0.11445399	0.00003431	0.00084369	0.07224356	0.81209644	0.00032801	N/A
m156	N/A	25%	1.0%	N/A	0.991744	0.11510576	0.00003451	0.00105606	0.09042910	0.79305425	0.00032032	N/A

[a] Values derived assuming 19.7 g/cm^3 for Pu, 1.85 g/cm^3 for Be, 0.923 g/cm^3 for CH_2, and 1.0 g/cm^3 for H_2O.

[b] CH_2 volume fractions based on ten 55 gallon drums

[c] Be weight fraction based upon mass of CH_2 and Pu (fissile region only)

8. Worse case HAC reflector geometry contains the remaining polyethylene and beryllium (1% by weight of the polyethylene) surrounding the fissile sphere. In addition, water is used to fill the space not filled by the polyethylene and beryllium. All three components (i.e., water, polyethylene and beryllium) are homogenously mixed and uniformly distributed throughout the remaining cask volume.

9. The criticality analyses were performed for fully reflected external conditions. Therefore, a 30.48 cm (12-in.) water reflector completely surrounding the cask is used in all single cask calculations for normal and accident conditions. This configuration is consistent with the requirements of 10 CFR 71.55(b)(3), which require full reflection, and a U.S. Nuclear Regulatory Commission recommendation that the thickness of the water reflector be at least 30 cm.

The previous paragraphs describe the assumptions used to analyze the 10-160B Cask. These assumptions provide the following conservative attributes, as required by 10 CFR 71.55.

1. Spherical fissile geometry for maximum reactivity
2. Optimum moderation, including special reflecting material (i.e., beryllium)
3. Full reflection
4. No credit for drums and internal drum support structure
5. Flooded for HAC

Figure 6-1. Representative Elevation View of a Single 10-160B Cask
With Ten 55-gal Drums in the Cask Cavity (Normal (As-Loaded) Configuration).

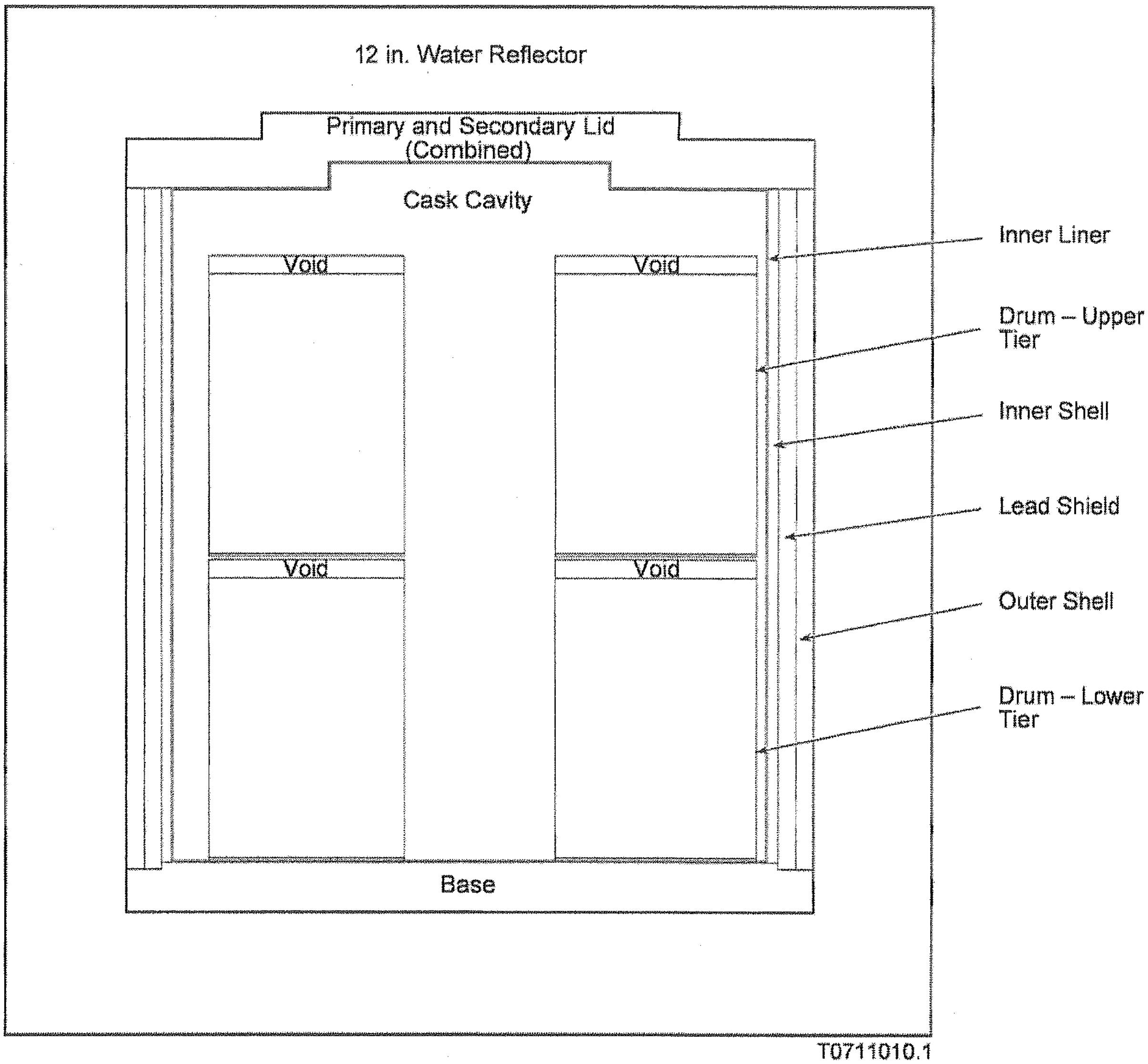


Figure 6-2. Representative Plan View of a Single 10-160B Cask
With Ten 55-gal Drums in the Cask Cavity (Normal (As-Loaded) Configuration).

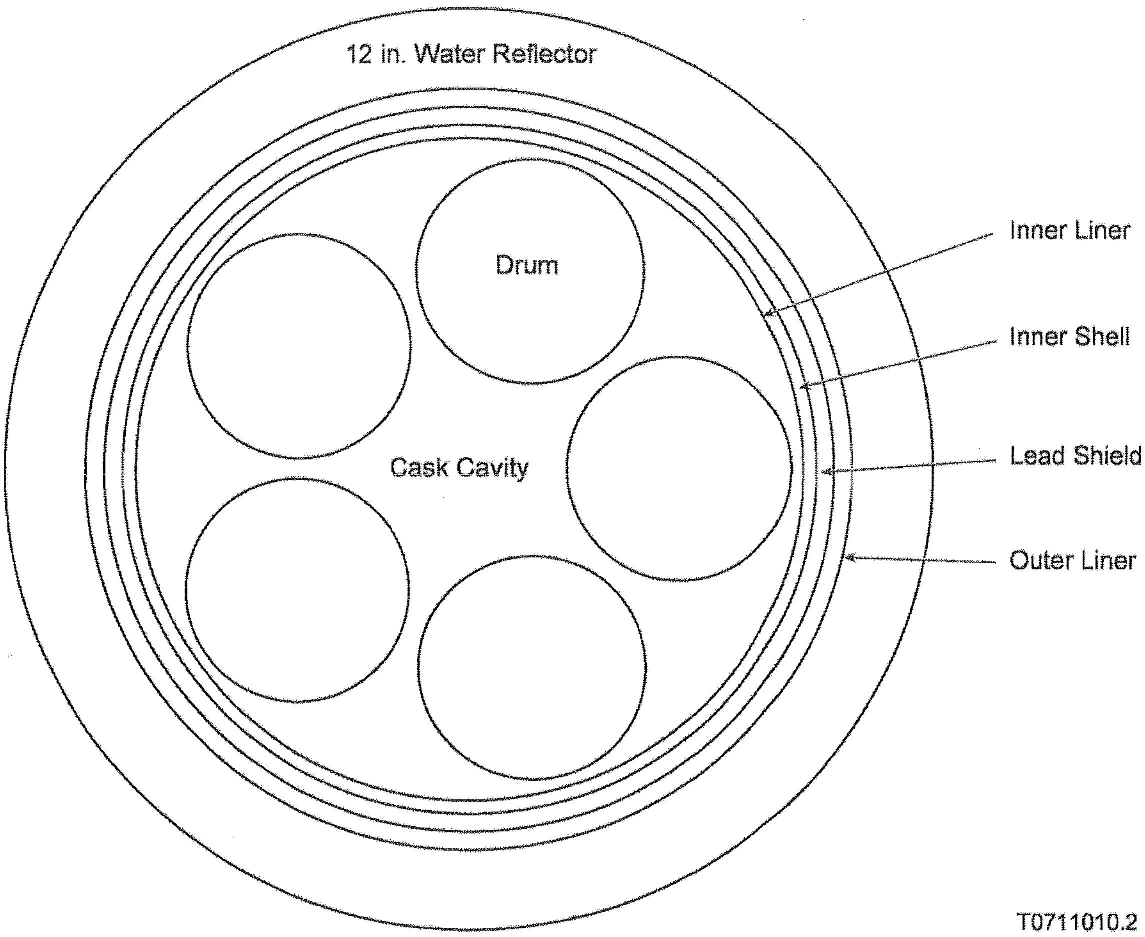


Figure 6-3. Elevation View of a Single 10-160B Cask with
the Fissile and Reflector Regions for the NCT Centroid Case (Case f309).

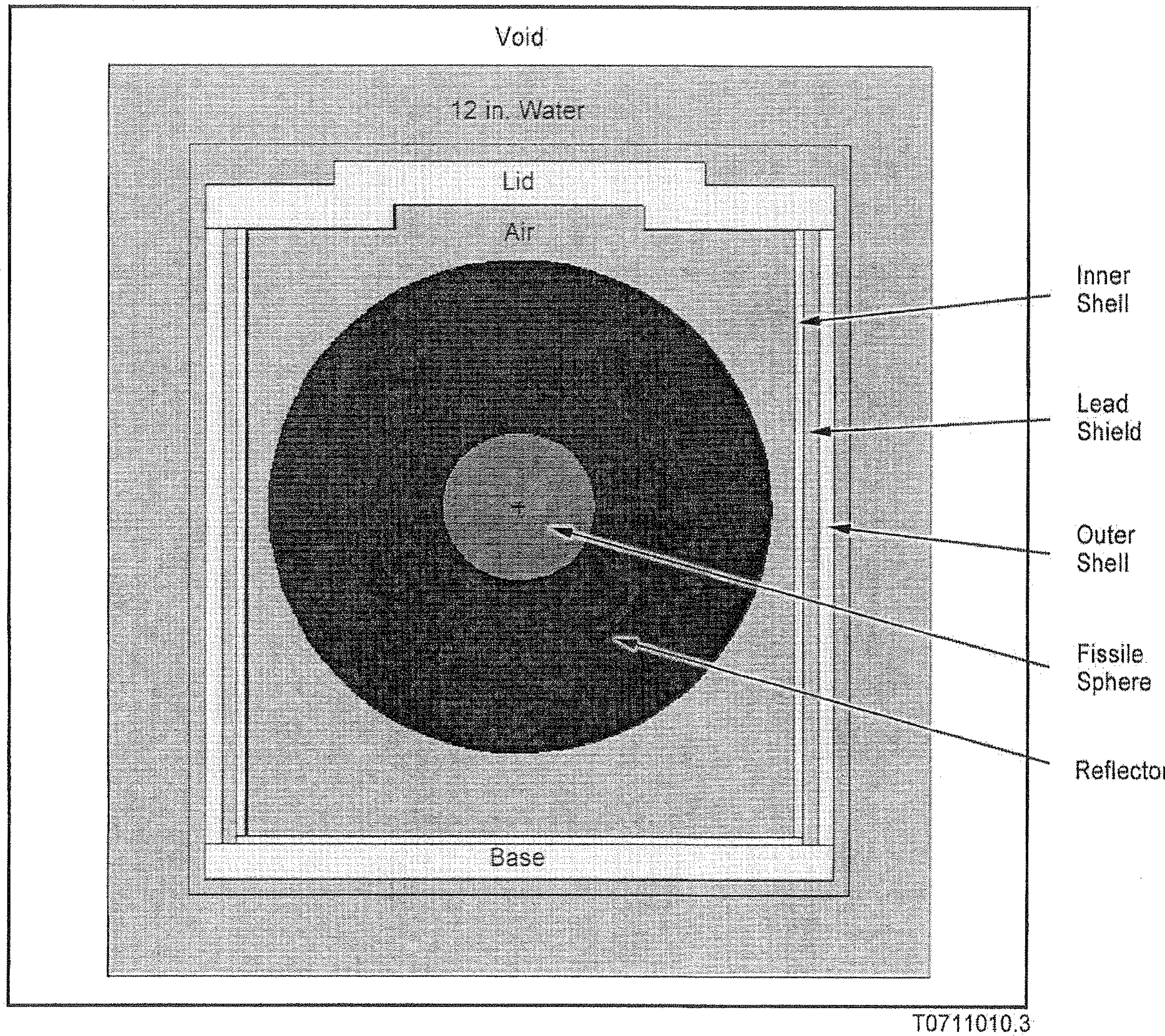


Figure 6-4. Elevation View of a Single 10-160B Cask with the Fissile and Reflector Regions for the NCT Base Center Case (Case f329).

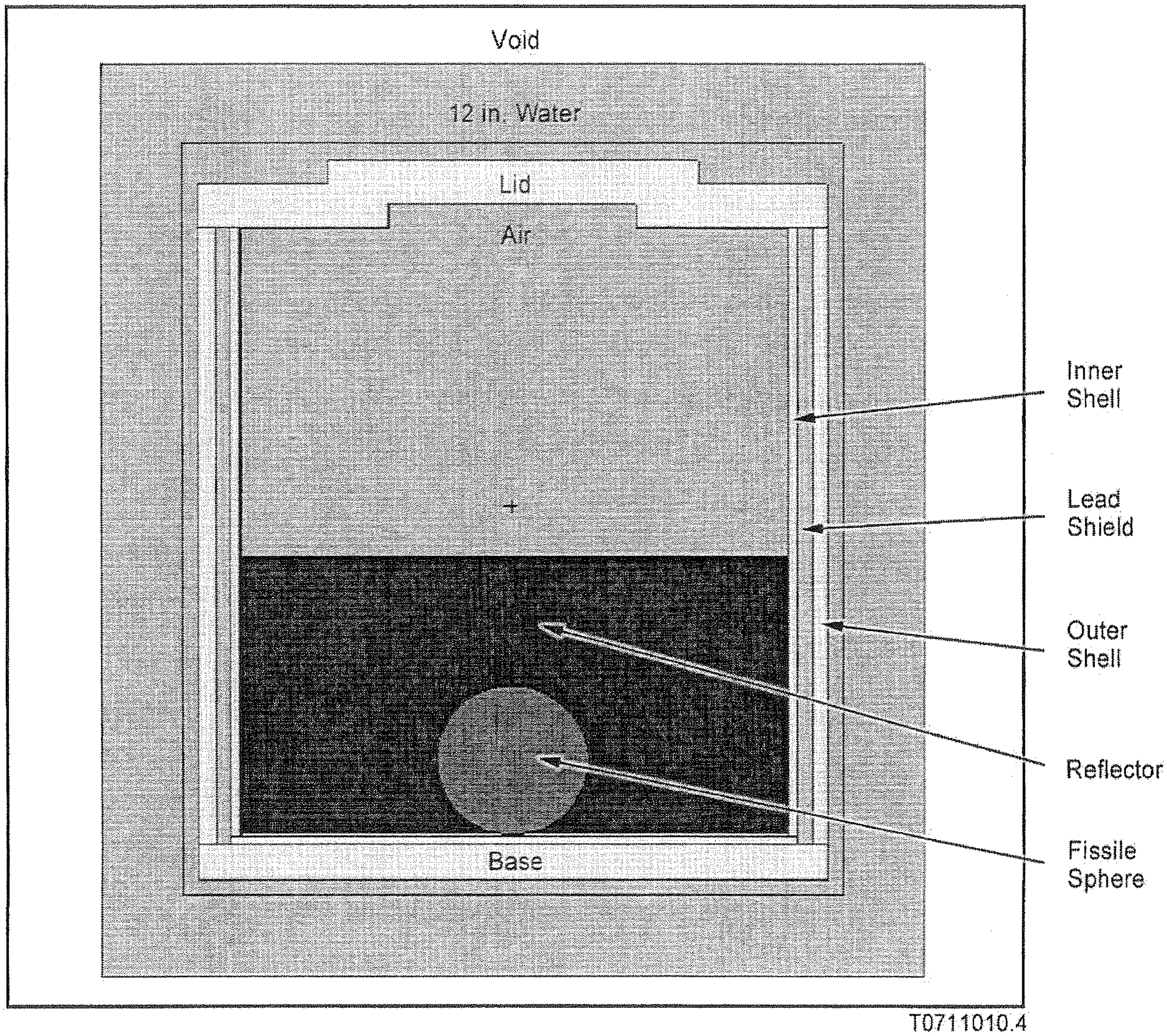


Figure 6-5. Elevation View of a Single 10-160B Cask with
the Fissile and Reflector Regions for the NCT Base Corner Case (Case f349).

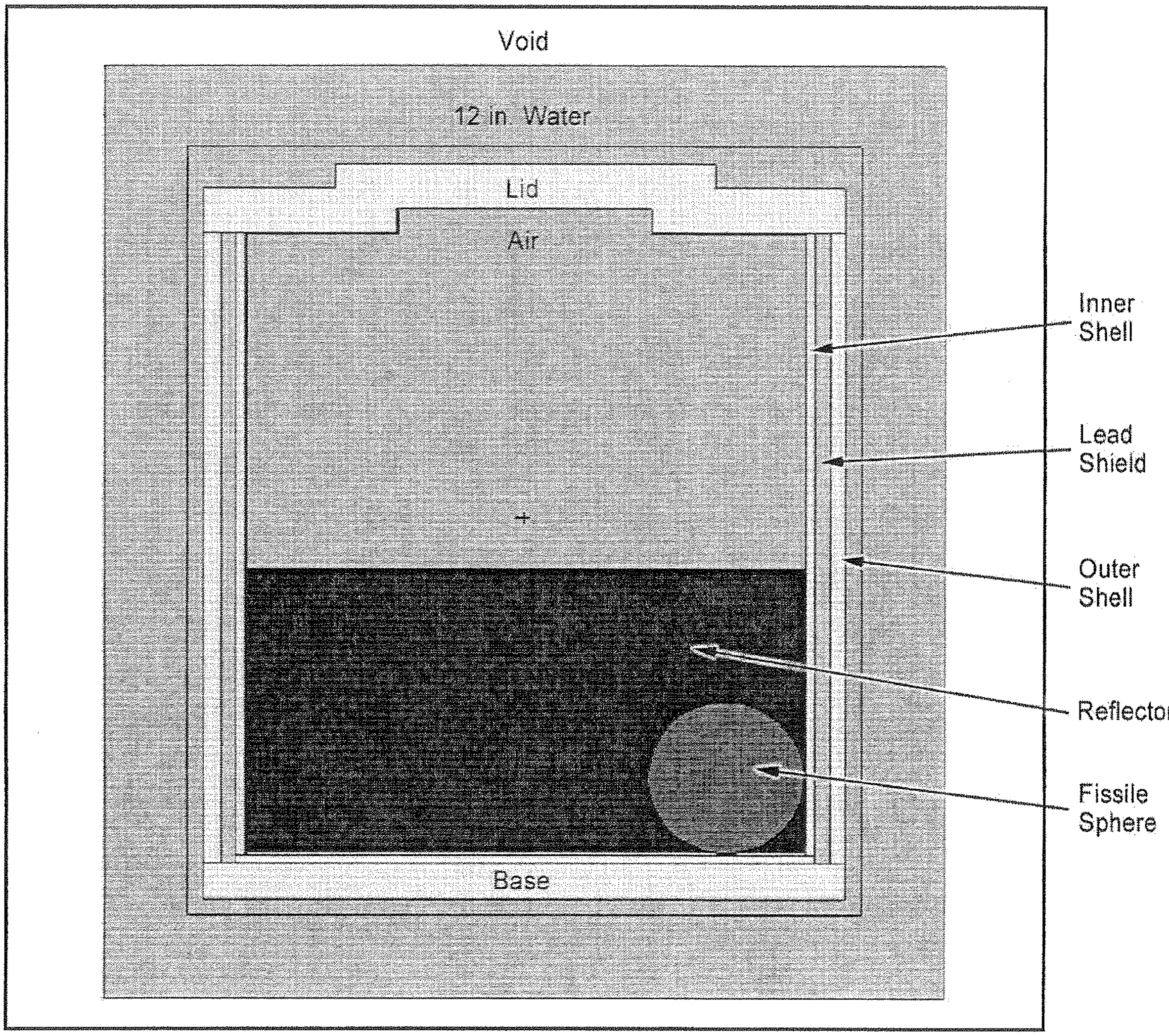


Figure 6-6. Elevation View of a Single 10-160B Cask with the Fissile and Reflector Regions for the HAC Centroid Case (Case f003).

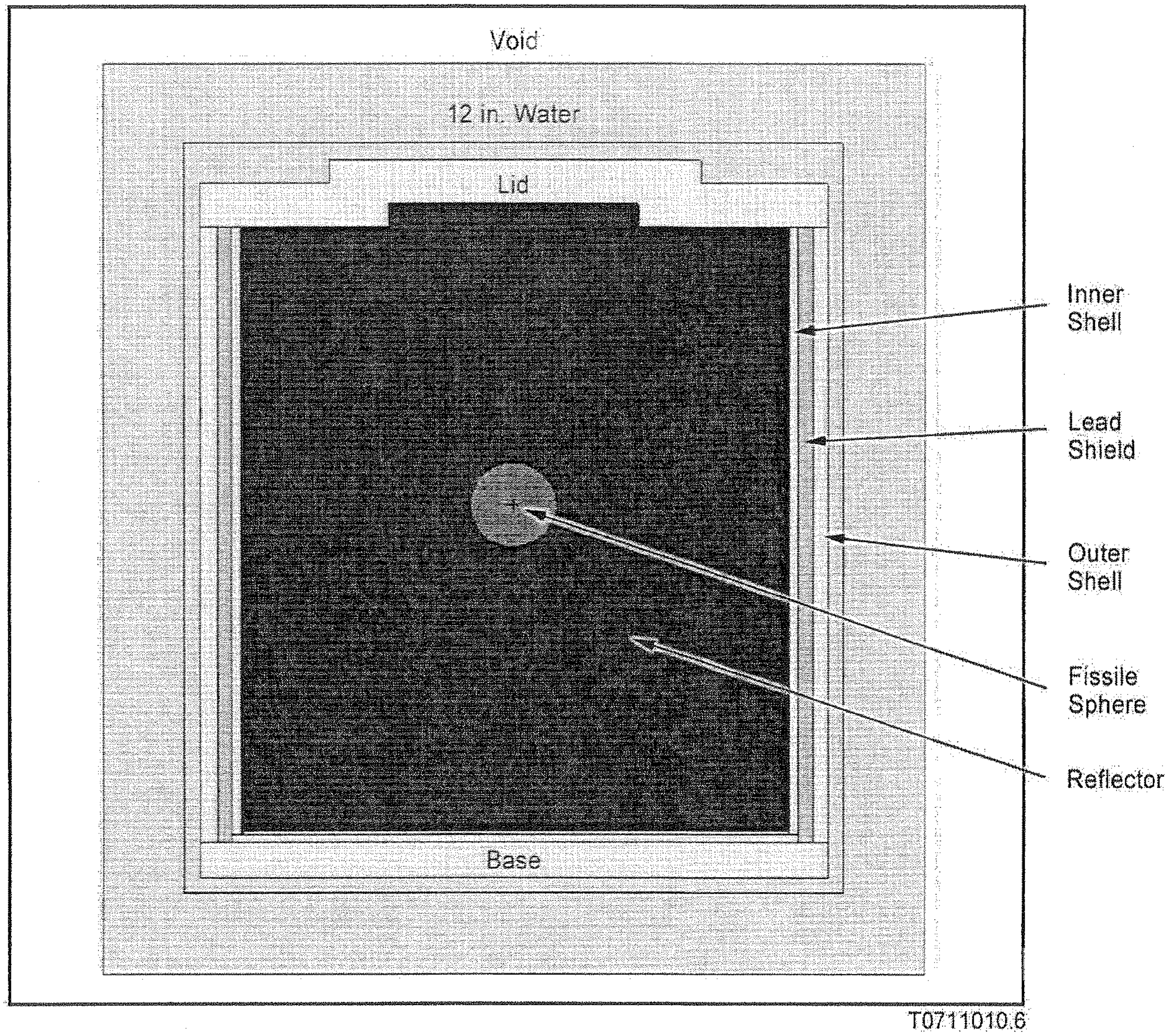


Figure 6-7. Elevation View of a Single 10-160B Cask with the Fissile and Reflector Regions for the HAC Base Center Case (Case f013).

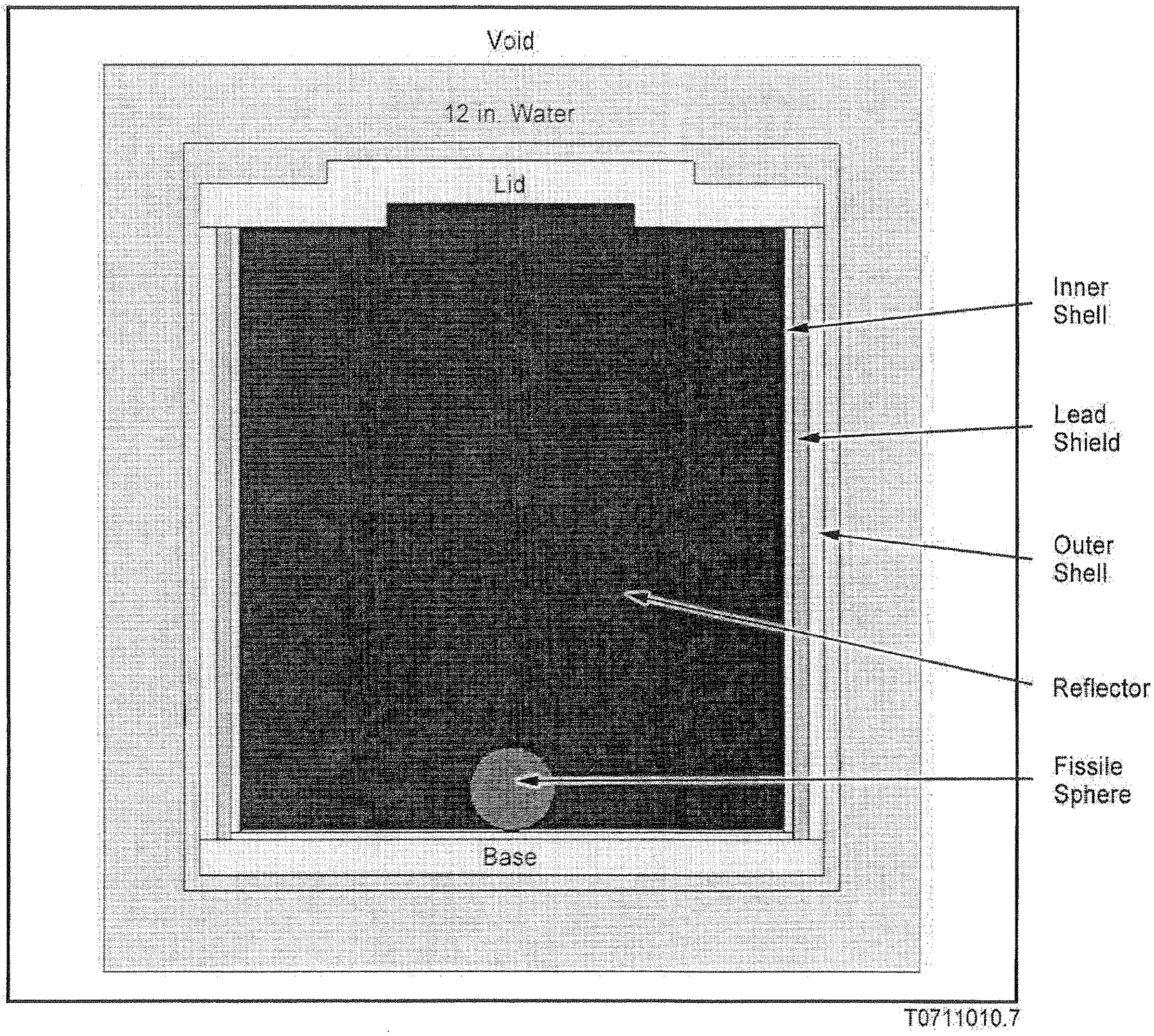


Figure 6-8. Elevation View of a Single 10-160B Cask with
the Fissile and Reflector Regions for the HAC Base Corner Case (Case f023).

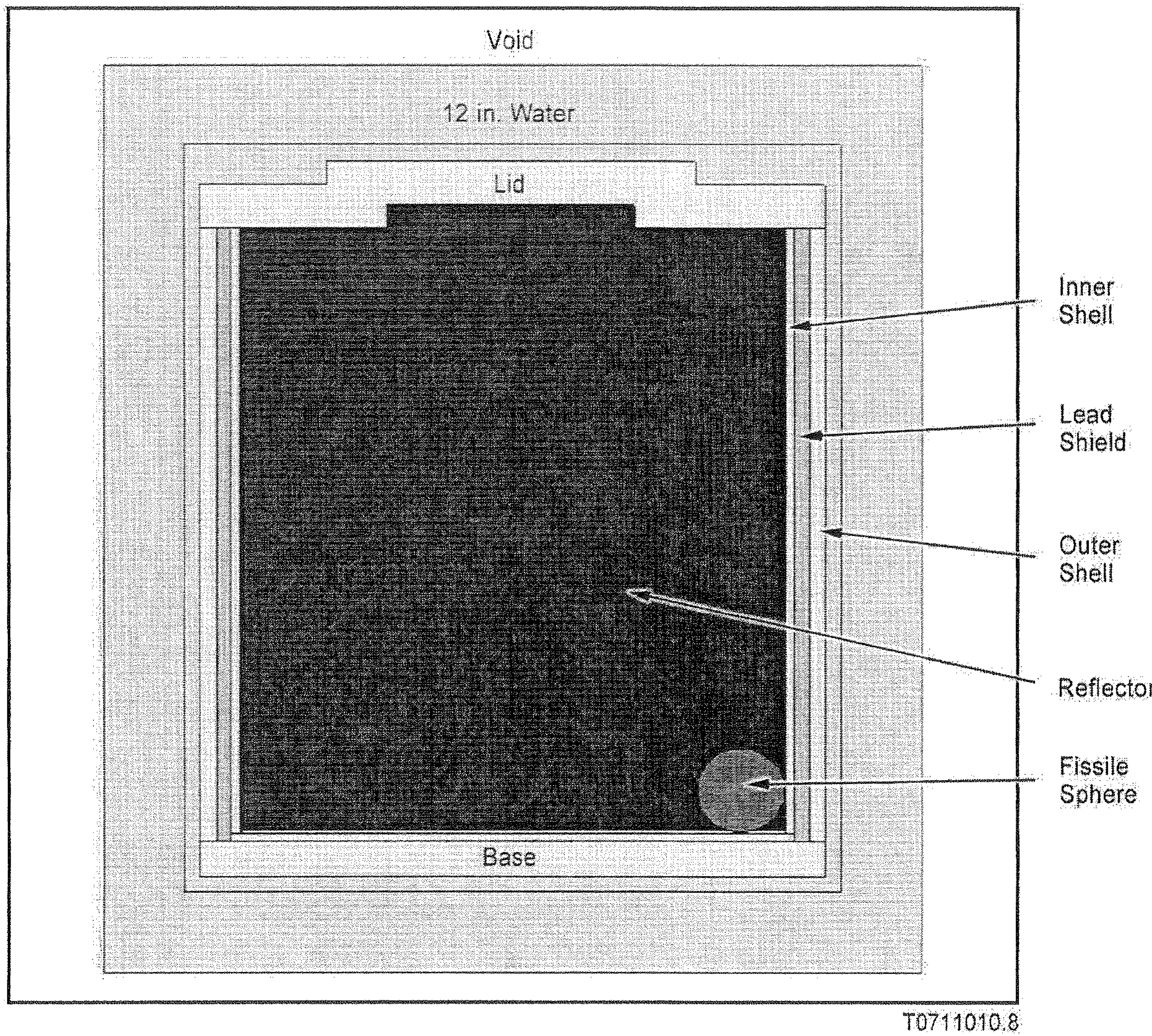


Figure 6-9. Elevation View of a Single 10-160B Cask with
the Fissile and Reflector Regions for the HAC Lid Corner Case (Case f033).

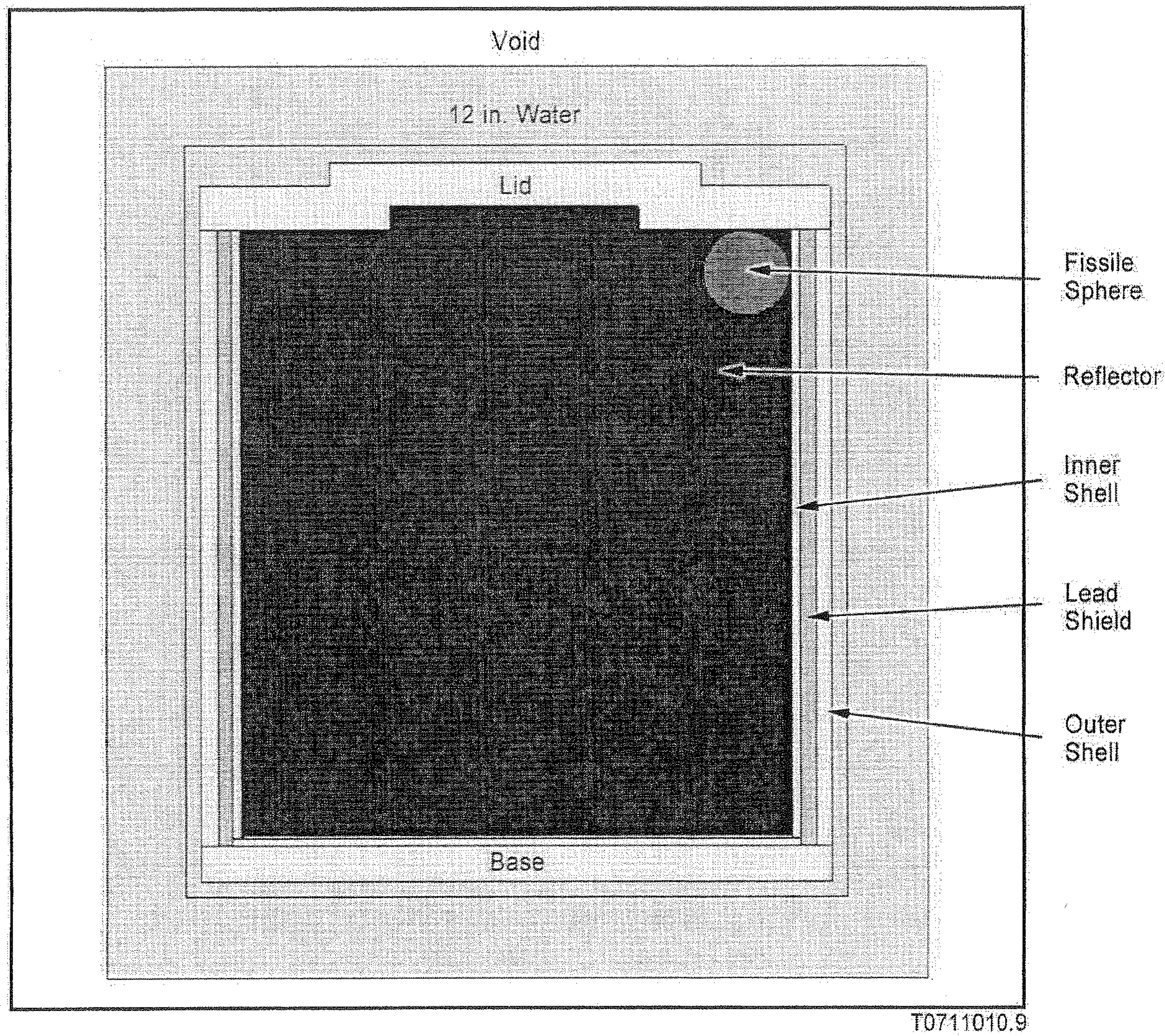


Table 6.4. Assumed Nominal Dimensions of the 10-160B Cask MCNP Criticality Model.

Zone (material)	Axial zone length		Zone outer radius		Zone radial thickness	
	in	cm	in	cm	in	cm
Cask Dimensions[a]						
Secondary Lid[b] (Carbon Steel)	5.5	13.970	23	58.420	23	58.420
Primary Lid[b] (Carbon Steel)	5.5	13.970	39	99.060	23.5	59.690
Cask cavity (void)	76.75	194.945	33.875	86.043	33.875	86.043
Inner liner[c] (SS 304)	77	195.580	34	86.360	0.125	0.318
Inner shell (Carbon Steel)	77	195.580	35.125	89.218	1.125	2.858
Lead shield (Lead)	78	198.120	37	93.980	1.875	4.763
Outer Shell (Carbon Steel)	78	198.120	39	99.060	2	5.080
Base (Carbon Steel)	5.5	13.970	39	99.060	39	99.060

[a] The bottom tapered edge of the cask is not modeled. Also, the impact limiter and thermal barrier are not included in the model. These modeling simplifications have negligible impact on the results.

[b] The primary and secondary lids are stepped. The dimensions listed in the table are the inner/outer-most dimensions.

[c] The inner lining is irregular in shape but essentially consists of 11 gage steel covering the entire cask inner cavity.

6.3.2 Material Properties

Table 6.5 shows the material compositions used in the MCNP models including the density of the material and the MCNP cross-sectional set name. Any changes in material properties under tests in 10 CFR 71.71 and 71.73, *Hypothetical Accident Conditions*, are minor and have a minimal impact on the results of this evaluation due to the conservative assumptions used to model the payload.

The $S(\alpha,\beta)$ cross-sections for hydrogen in the HAC regions were selected as light water (lwtr.60t) since the light water cross-sections provide a slightly higher reactivity than do the corresponding cross-sections for polyethylene.

Dry air was used for the NCT cases where the cask is dry. Air was assumed to only contain N_2 and O_2, thereby ignoring the trace amounts of Ar and other gases.

Table 6.5. Materials and Elemental Compositions Used to Perform the Criticality Analyses for the 10-160B Cask.

Item	Isotope Element	MCNP ZAID	Mass Fraction	Density (g/cm³)
NCT Fissile	H^1	1001.66c	Table 6.2	Table 6.2
	H^2	1002.66c	Table 6.2	Table 6.2
	Be^9	4009.66c	Table 6.2	Table 6.2
	C	6000.66c	Table 6.2	Table 6.2
	Pu^{239}	94239.66c	Table 6.2	Table 6.2
	$S(\alpha,\beta)$	poly.60t		
	$S(\alpha,\beta)$	be.60t		
		Totals	1.00	Table 6.2
HAC Fissile	H^1	1001.66c	Table 6.3	Table 6.3
	H^2	1002.66c	Table 6.3	Table 6.3
	Be^9	4009.66c	Table 6.3	Table 6.3
	C	6000.66c	Table 6.3	Table 6.3
	O^{16}	8016.66c	Table 6.3	Table 6.3
	O^{17}	8017.66c	Table 6.3	Table 6.3
	Pu^{239}	94239.66c	Table 6.3	Table 6.3
	$S(\alpha,\beta)$	lwtr.60t		
	$S(\alpha,\beta)$	be.60t		
		Totals	1.00	Table 6.3
NCT Reflector	H^1	1001.66c	Table 6.2	Table 6.2
	H^2	1002.66c	Table 6.2	Table 6.2
	Be^9	4009.66c	Table 6.2	Table 6.2
	C	6000.66c	Table 6.2	Table 6.2
	Pu^{239}	94239.66c	Table 6.2	Table 6.2
	$S(\alpha,\beta)$	poly.60t		
	$S(\alpha,\beta)$	be.60t		
		Totals	1.00	Table 6.2
HAC Reflector	H^1	1001.66c	Table 6.3	Table 6.3
	H^2	1002.66c	Table 6.3	Table 6.3
	Be^9	4009.66c	Table 6.3	Table 6.3
	C	6000.66c	Table 6.3	Table 6.3
	O^{16}	8016.66c	Table 6.3	Table 6.3
	O^{17}	8017.66c	Table 6.3	Table 6.3
	Pu^{239}	94239.66c	Table 6.3	Table 6.3
	$S(\alpha,\beta)$	lwtr.60t		
	$S(\alpha,\beta)$	be.60t		
		Totals	1.00	Table 6.3
Air	N^{14}	7014.66c	0.761985	9.30E-04
	N^{15}	7015.66c	0.003015	3.68E-06
	O^{16}	8016.66c	0.234905	2.87E-04
	O^{17}	8017.66c	0.000095	1.16E-07
		Totals	1.00	0.00122
Carbon Steel	C	6000.66c	0.003000	0.023550
	Si^{28}	14028.66c	0.002572	0.020190
	Si^{29}	14029.66c	0.000135	0.001060
	Si^{30}	14030.66c	0.000092	0.000722
	P^{31}	15031.66c	0.000400	0.003140
	S	16000.66c	0.000500	0.003925
	Mn^{55}	25055.66c	0.010300	0.080855
	Fe^{54}	26054.66c	0.055383	0.434757
	Fe^{56}	26056.66c	0.901554	7.077199
	Fe^{57}	26057.66c	0.021193	0.166365
	Fe^{58}	26058.66c	0.002870	0.022530
	Cu^{63}	29063.66c	0.001370	0.010755
	Cu^{65}	29065.66c	0.000630	0.004946
		Totals	1.00	7.85
SS-304	C	6000.66c	0.000300	0.002409
	Cr^{50}	24050.66c	0.008345	0.067010
	Cr^{52}	24052.66c	0.167349	1.343812
	Cr^{53}	24053.66c	0.019341	0.155308
	Cr^{54}	24054.66c	0.004905	0.039387
	Mn^{55}	25055.66c	0.019994	0.160552
	Fe^{54}	26054.66c	0.038378	0.308175
	Fe^{56}	26056.66c	0.624743	5.016686
	Fe^{57}	26057.66c	0.014686	0.117929
	Fe^{58}	26058.66c	0.001989	0.015972
	Ni^{58}	28058.66c	0.067178	0.539439
	Ni^{60}	28060.66c	0.026768	0.214947
	Ni^{61}	28061.66c	0.001183	0.009499
	Ni^{62}	28062.66c	0.003834	0.030787
	Ni^{64}	28064.66c	0.001008	0.008094
		Totals	1.00	8.03
Lead	Pb	82000.50c	1.000000	11.34
		Totals	1.00	11.34
Water	H^1	1001.66c	0.111865	0.111865
	H^2	1002.66c	0.000034	3.35E-05
	O^{16}	8016.66c	0.887743	0.887743
	O^{17}	8017.66c	0.000359	0.000359
	$S(\alpha,\beta)$	lwtr.60t		
		Totals	1.00	1.00

6.3.3 Computer Codes and Cross-Sectional Libraries

The k_{eff} values are calculated using the computer program MCNP Version 5, Release 1.40[3]. The MCNP computer program has been approved for use with quality affecting analyses and is under configuration control in accordance with FSWO-QAP-001, *Quality Assurance Procedures*, QP 3-10, *Software Management*[2].

MCNP calculates k_{eff} using the Monte Carlo method from an arbitrary three-dimensional configuration using point wise continuous-energy cross-sectional data. Because of the statistical basis of this method, the results show an average k_{eff} value and a standard deviation, which represents the 1σ (68%) confidence interval. The MCNP criticality runs used 4,000 neutrons per generation with 3950 active generations. This results in a standard deviation of approximately 0.00025 or less for all calculations performed in this evaluation.

Table 6.5 shows the material compositions used in the MCNP models including the density of the material and the MCNP cross-sectional set name. The input for MCNP does not include an entry explicitly for the nuclear properties of materials; rather, it obtains this information automatically based on the particular library specified by the user for each of the isotopes and/or elements of the materials used in the model. The libraries are distributed with the code, and many libraries have been developed over the years by different entities for specific purposes. Although multiple libraries are available for the materials of this package and payload, the library based on Evaluated Nuclear Data Files VI (ENDF-VI) is used exclusively with the exception of elemental lead (Pb) that is not adequately addressed in ENDF-VI. (ENDF-VI has three of the four naturally occurring isotopes of Pb.) This library, named "endf60," is used because it represents the most recent available data from the centralized U.S. organization coordinating the establishment of nuclear data (the National Nuclear Data Center at Brookhaven National Laboratory). The Evaluated Nuclear Data Files V (ENDF-V) is used for elemental lead.

6.3.4 Demonstration of Maximum Reactivity

As mentioned in Section 6.3.1, the fissile material is conservatively configured as a compact sphere of fuel with varying amounts of hydrogenous materials. The optimal H/Pu ratio was determined by selecting the configuration with the maximum reactivity. This is the most reactive configuration consistent with a possible damaged condition and the chemical and physical form of the material. This configuration is extremely conservative and would not be expected to occur under NCT or HAC. However, considering the fact that no credit is taken for geometry control provided by the waste drums, this configuration conservatively meets the requirements of 10 CFR 71.55(b) and 71.55(e)(1). The HAC criticality analyses were performed assuming that water leaked into the cask cavity, filling all voids not occupied by the polyethylene, plutonium or beryllium materials.

In addition, maximum reactivity is assured by other features of the simulation. The inclusion of beryllium as a special moderating/reflecting material was demonstrated to increase reactivity. Credit was not taken for the presence of neutron absorbers in the cask payload volume, such as the metal drums and internal drum support structure, which would lower the reactivity.

The majority of the HAC cases had a 25% volume fraction of polyethylene and 1% by weight of beryllium as a special reflector. Four cases were run with the beryllium reduce to 0.5% and an additional four cases were run with beryllium eliminated. An additional four cases were run with the polyethylene reduced to 20% by volume. These cases establish that the 25% volume fraction of polyethylene and 1% by weight of beryllium were the most reactive configuration.

6.4 SINGLE PACKAGE EVALUATION

6.4.1 Configuration

The general requirements of 10 CFR 71.55(b) are that the package must be subcritical if water were to leak into the containment system so that, under the following conditions, maximum reactivity of the fissile material is attained:

1. Most reactive credible configuration consistent with the chemical and physical form of the material
2. Moderation by water to the most reactive credible extent
3. Close full reflection of the containment system by water on all sides or such greater reflection of the system as may additionally be provided by the surrounding material of the packaging.

The analysis assumes that water leaks into the cask cavity, and the waste drums are not present.

The criticality requirements of 10 CFR 71.55(e) for fissile material packages in accident conditions impose three conditions on the analysis. These conditions must be applied to a package that has undergone the tests specified in 10 CFR 71.73, which means that credit may be taken for the cask remaining leaktight during HAC. The conditions are as follows.

1. The fissile material is in the most reactive credible configuration consistent with the damaged condition of the package and the chemical and physical form of the contents.
2. Water moderation occurs to the most reactive credible extent consistent with the damaged condition of the package and the chemical and physical form of the contents.
3. There is full reflection by water on all sides as close as is consistent with the damaged condition of the package.

6.4.2 Results

With the cask containment dry, the most reactive conditions occur when the quantity of fissile material is in a spherical form and most compact. Although the 10-160B Cask is designed to maintain the payload in the normal, as-loaded configuration shown in Figures 6-1 and 6-2, this evaluation does not take credit for the integrity of the waste drums. The most reactive configuration for this evaluation occurs when the plutonium, polyethylene, and beryllium form a sphere. Various H/Pu ratios are evaluated for the single cask. H/Pu ratio is associated with a given spherical diameter, assuming the material densities, as noted in Tables 6.2 (NCT) and 6.3 (HAC).

The results of the NCT analysis are shown in Figure 6-10 and summarized in Table 6.6. The most reactive NCT configuration was obtained with the fissile sphere in the base corner with water on the outside of the cask and an H/Pu ratio of 1400. The maximum K_{eff} is 0.42656.

The results of the HAC analysis are presented in Figure 6-11 and summarized in Table 6.7. The most reactive HAC configuration was obtained with the fissile sphere in the lid corner with an H/Pu ratio of 900. The maximum K_{eff} is 0.93252 and is below the limit of 0.94. Table 6.7 shows that there is a subcritical margin even if the fissile material is in the worst case configuration. Tables 6.6 and 6.7 summarize these results and demonstrate that all payload configurations meet the NCT and HAC criticality requirements of 10 CFR 71.55(b), (d), and (e).

In addition, Table 6.7 summarizes the results of the analyses that were preformed to examine the effect of less beryllium (0% and 0.5% by mass of total CH_2 and Pu^{239}) and less polyethylene (20% by volume of the 10 drums). The results (Cases f042 through f065) clearly show, by comparison with Case f033, that the most reactive configuration is for 25% by volume CH_2 and 1% by mass for beryllium.

Figure 6-10. Single Unit K_{eff} vs. H/Pu Ratio for NCT for Various Configurations

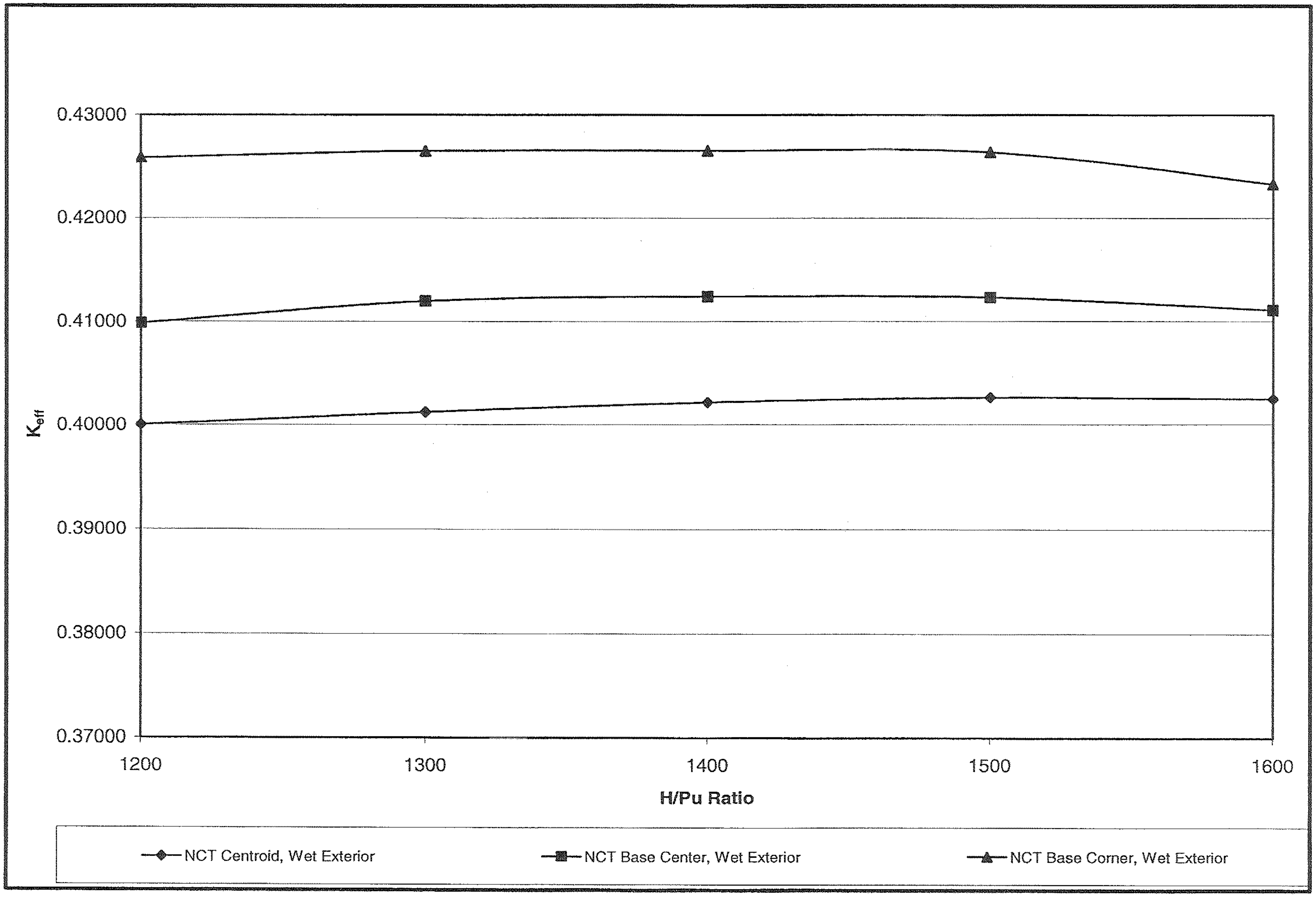


Table 6.6. Single Unit K_{eff} vs. H/Pu Ratio for NCT for Various Configurations

NCT 10-160B Single Cask					
Location	MCNP Case	H/Pu Ratio	K_{eff}	σ_{MCNP}	AEF[a] (eV)
NCT Centroid, Wet Exterior	f307	1200	0.40003	0.00015	0.0498
	f308	1300	0.40121	0.00015	0.0488
	f309	1400	0.40215	0.00014	0.0480
	f310	1500	0.40264	0.00014	0.0472
	f311	1600	0.40249	0.00015	0.0465
NCT Base Center, Wet Exterior	f327	1200	0.40987	0.00015	0.0508
	f328	1300	0.41195	0.00015	0.0497
	f329	1400	0.41236	0.00015	0.0488
	f330	1500	0.41228	0.00015	0.0480
	f331	1600	0.41108	0.00014	0.0473
NCT Base Corner, Wet Exterior	f367	1200	0.42589	0.00015	0.0519
	f368	1300	0.42655	0.00015	0.0507
	f369	1400	0.42656	0.00015	0.0497
	f370	1500	0.42641	0.00015	0.0489
	f371	1600	0.42334	0.00015	0.0481

[a] Energy corresponding to the average neutron lethargy causing fission (AEF)

Figure 6-11. Single Unit K_{eff} vs. H/Pu Ratio for HAC for Various Configurations

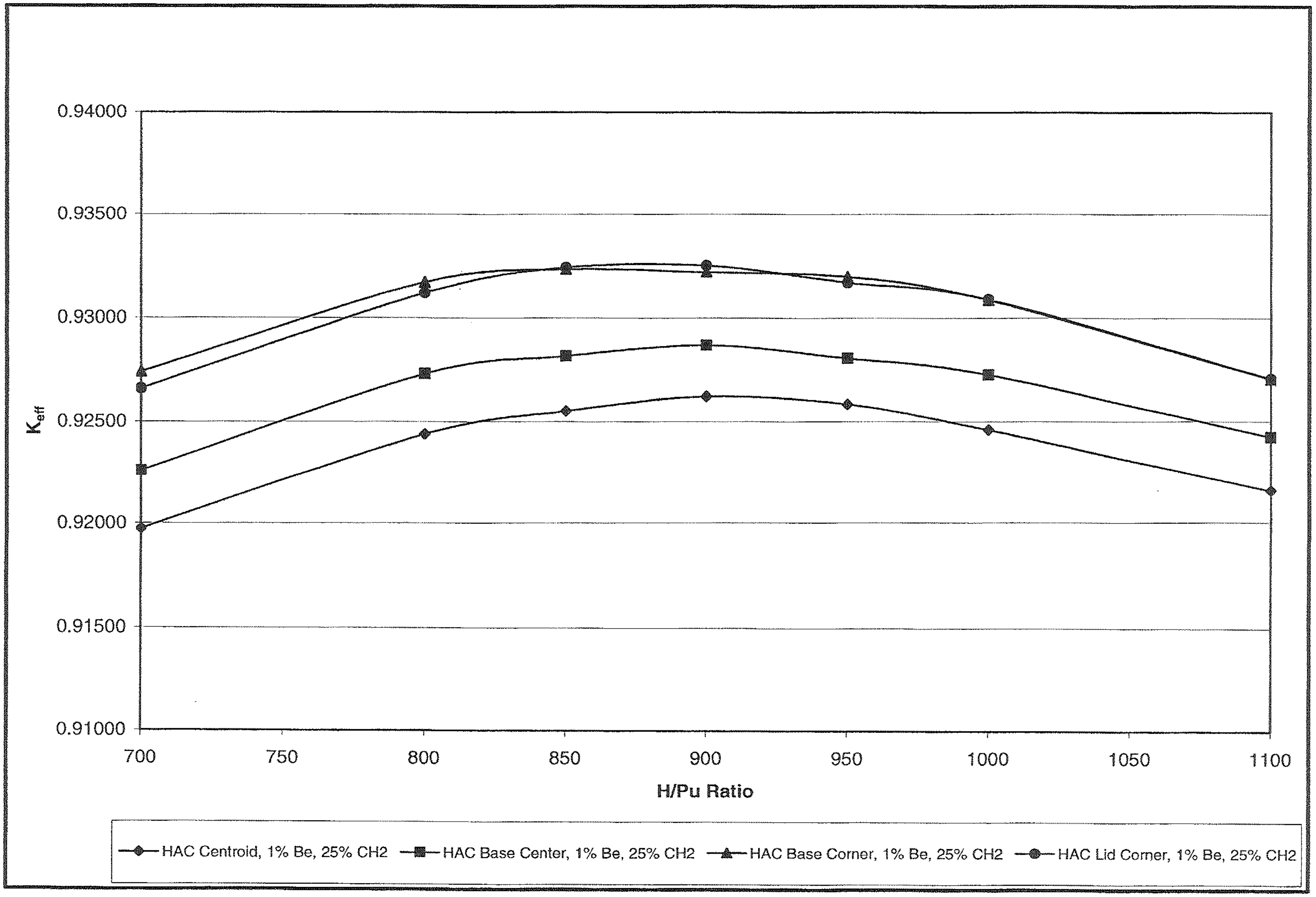


Table 6.7. Single Unit K_{eff} vs. H/Pu Ratio for HAC for Various Configurations

HAC 10-160B Single Cask					
Location	MCNP Case	H/Pu Ratio	K_{eff}	σ_{MCNP}	AEF[a] (eV)
HAC Centroid, 1% Be, 25% CH_2	f000	700	0.91975	0.00022	0.0586
	f001	800	0.92438	0.00020	0.0556
	f002	850	0.92552	0.00021	0.0543
	f003	900	0.92624	0.00020	0.0532
	f004	950	0.92586	0.00021	0.0522
	f005	1000	0.92458	0.00020	0.0513
	f006	1100	0.92158	0.00019	0.0498
HAC Base Center, 1% Be, 25% CH_2	f010	700	0.92261	0.00021	0.0590
	f011	800	0.92731	0.00020	0.0559
	f012	850	0.92816	0.00020	0.0546
	f013	900	0.92869	0.00021	0.0535
	f014	950	0.92806	0.00020	0.0525
	f015	1000	0.92726	0.00020	0.0515
	f016	1100	0.92424	0.00019	0.0499
HAC Base Corner, 1% Be, 25% CH_2	f020	700	0.92741	0.00021	0.0594
	f021	800	0.93169	0.00021	0.0562
	f022	850	0.93232	0.00020	0.0548
	f023	900	0.93219	0.00021	0.0537
	f024	950	0.93197	0.00020	0.0527
	f025	1000	0.93085	0.00020	0.0517
	f026	1100	0.92705	0.00020	0.0502
HAC Lid Corner, 1% Be, 25% CH_2	f030	700	0.92661	0.00021	0.0594
	f031	800	0.93118	0.00021	0.0562
	f032	850	0.93243	0.00020	0.0549
	f033	900	0.93252	0.00020	0.0537
	f034	950	0.93168	0.00020	0.0527
	f035	1000	0.93087	0.00020	0.0518
	f036	1100	0.92707	0.00019	0.0502
HAC Lid Corner, 0.5% Be, 25% CH_2	f042	850	0.93202	0.00020	0.0549
	f043	900	0.93213	0.00020	0.0537
	f044	950	0.93219	0.00020	0.0526
	f045	1000	0.93076	0.00020	0.0518
HAC Lid Corner, 0.0% Be, 25% CH_2	f052	850	0.93188	0.00021	0.0549
	f053	900	0.93199	0.00020	0.0536
	f054	950	0.93127	0.00020	0.0527
	f055	1000	0.93077	0.00020	0.0518
HAC Lid Corner, 1% Be, 20% CH_2	f062	850	0.92786	0.00020	0.0549
	f063	900	0.92859	0.00020	0.0538
	f064	950	0.92790	0.00020	0.0526
	f065	1000	0.92661	0.00019	0.0518

[a] Energy corresponding to the average neutron lethargy causing fission (AEF)

6.5 EVALUATION OF PACKAGE ARRAYS UNDER NCT

6.5.1 Configuration

The criticality requirements in 10 CFR 71.59(a) for arrays of fissile material packages in NCT require that 5 times N undamaged packages with nothing between the packages be subcritical, assuming packages are stacked together in any arrangement and with close full reflection on all sides of the array by water.

Normally, the array calculations begin with an infinite array model because, if the infinite array is adequately subcritical, no additional array calculations are necessary. If the infinite array is not shown to be safely subcritical, a finite array of packages is analyzed until an array size is found that is adequately subcritical. An infinite array of 10-160B Casks with the payloads described in Section 6.2 is adequately subcritical during NCT. Therefore, finite array cases are not necessary.

The MCNP model for the infinite array calculations is identical to the single-cask model except that the 30.5 cm (12-in.) water reflector is removed. Six reflective surfaces are added to form a tight-fitting hexagon around the cask and two reflective surfaces are placed at the top and bottom of the cask, as shown in Figure 6-12. The use of reflective surfaces around the side, top, and bottom simulates an infinite array of casks in the radial and axial directions. Two additional infinite array cases are run where the cask spacing is varied from 5 cm to 10 cm.

6.5.2 Results

Table 6.8 summarizes the results of the NCT infinite array calculations. Because the k_{eff} values decrease slightly with increasing cask spacing (0.45328 for close-packed versus 0.44635 for 10 cm cask spacing), these cases indicate that there is some neutronic communication between the casks in the array when the containment is dry and there is no interspersed moderation. The results for the NCT array calculations indicate that an infinite array of 10-160B Casks loaded with any fissile configurations is safely subcritical with a maximum k_{eff} value of 0.45328 (case f369a).

Figure 6-12. Plan View of an Infinite Array of NCT 10-160B Casks (MCNP case f369a).

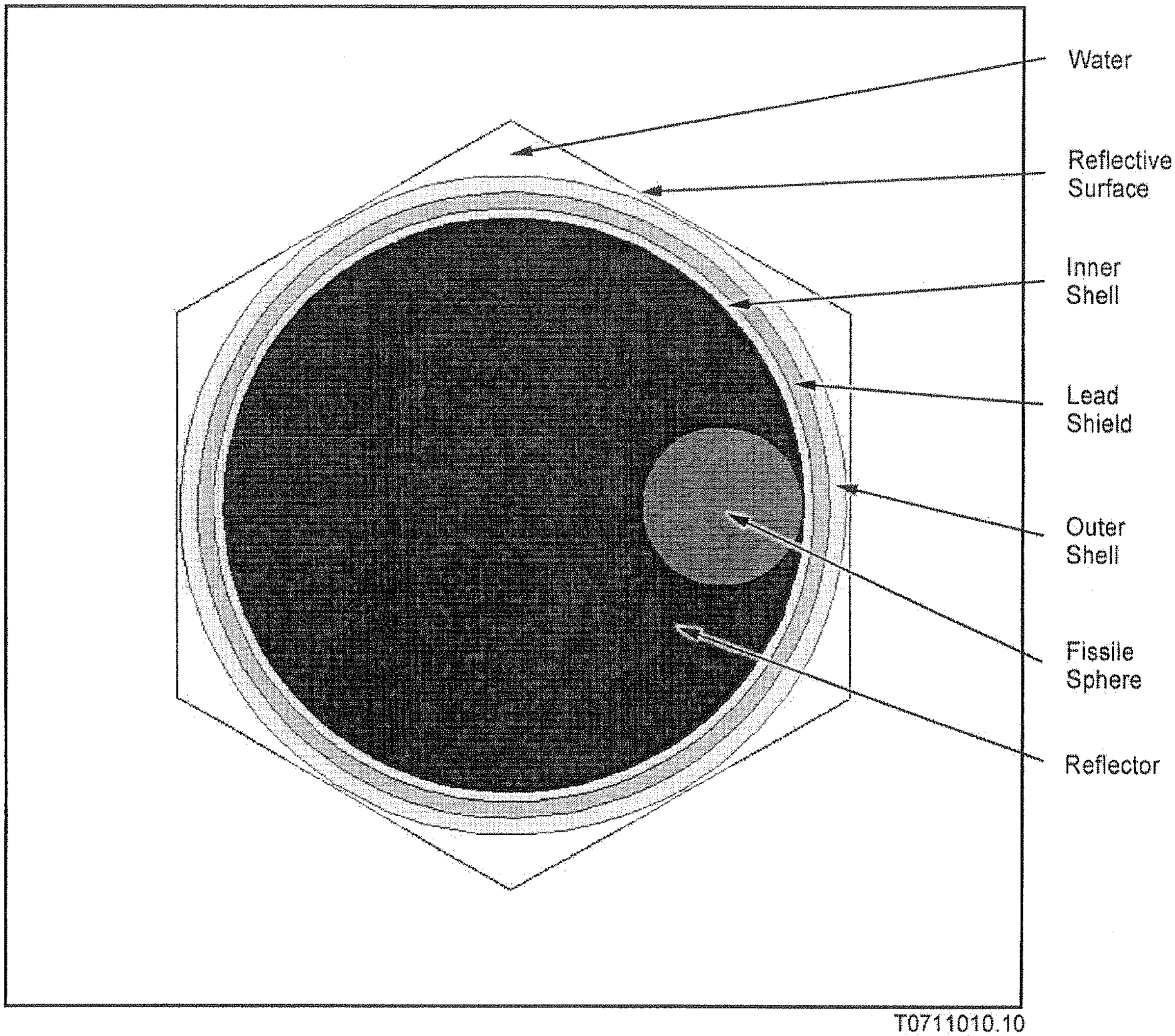


Table 6.8. Values of K_{eff} vs. Array Spacing for an Infinite Array of 10-160B Casks Under NCT.

NCT 10-160B Infinite Array					
Location	MCNP Case	Array Spacing	K_{eff}	σ_{MCNP}	AEF[a] (eV)
Base Corner	f369a	0.00	0.45328	0.00015	0.0495
	f369b	5.00	0.44946	0.00015	0.0496
	f369c	10.00	0.44635	0.00015	0.0496

[a] Energy corresponding to the average neutron lethargy causing fission (AEF)

6.6 EVALUATION OF PACKAGE ARRAYS UNDER HAC

6.6.1 Configuration

The criticality requirements of 10 CFR 71.59(a)(2), for arrays of fissile material packages under accident conditions require that 2 times N ($N \geq 0.5$) damaged packages be subcritical, assuming the packages are stacked together in any arrangement, with close full reflection on all sides of the array by water, and with optimum interspersed hydrogenous moderation. Although the 10-160B Cask remains sealed under the accident-condition tests specified in 10 CFR 71.73, the criticality analysis for arrays during accident conditions conservatively assumes in-flooding of the cask containment.

As discussed in Section 6.5, the array calculations normally begin with an infinite array model. If the infinite array is adequately subcritical, no additional array calculations are necessary. The infinite array model developed for NCT in Section 6.5 is used as the baseline model for the HAC array calculations. The only differences being the addition of interspersed moderation (see Figure 6.4) between the casks in the array per 10 CFR 71.59(a) (2) and the worst case single Cask model evaluated under HAC. The NCT array cases assumed nothing in between the casks per 10 CFR 71.59(a) (1).

With a hexagonal infinite array of casks, there are two basic orientations of the fissile sphere in a hexagonal cell, either at the flat (Figure 6-13) or at the apex (Figure 6-14). If the fissile sphere is at the flat, two spheres in adjacent cells are very close (four spheres if at the base or lid of the cask). If the fissile sphere is at the apex, three spheres in adjacent cell are farther apart (six spheres if at the base or lid of the case).

Figure 6-13. Plan View of an Infinite Array of HAC 10-160B Casks (MCNP case f022flat00).

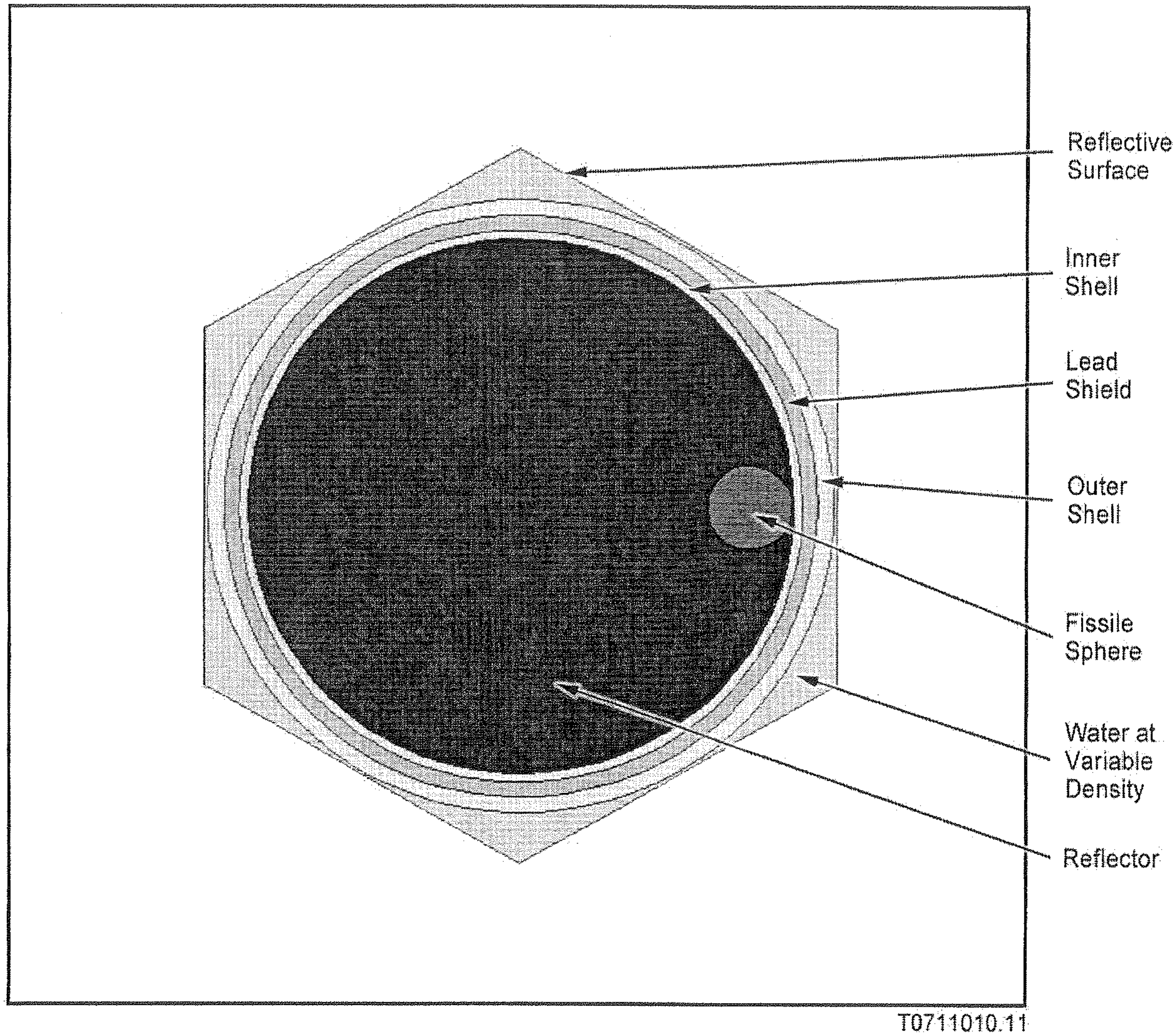
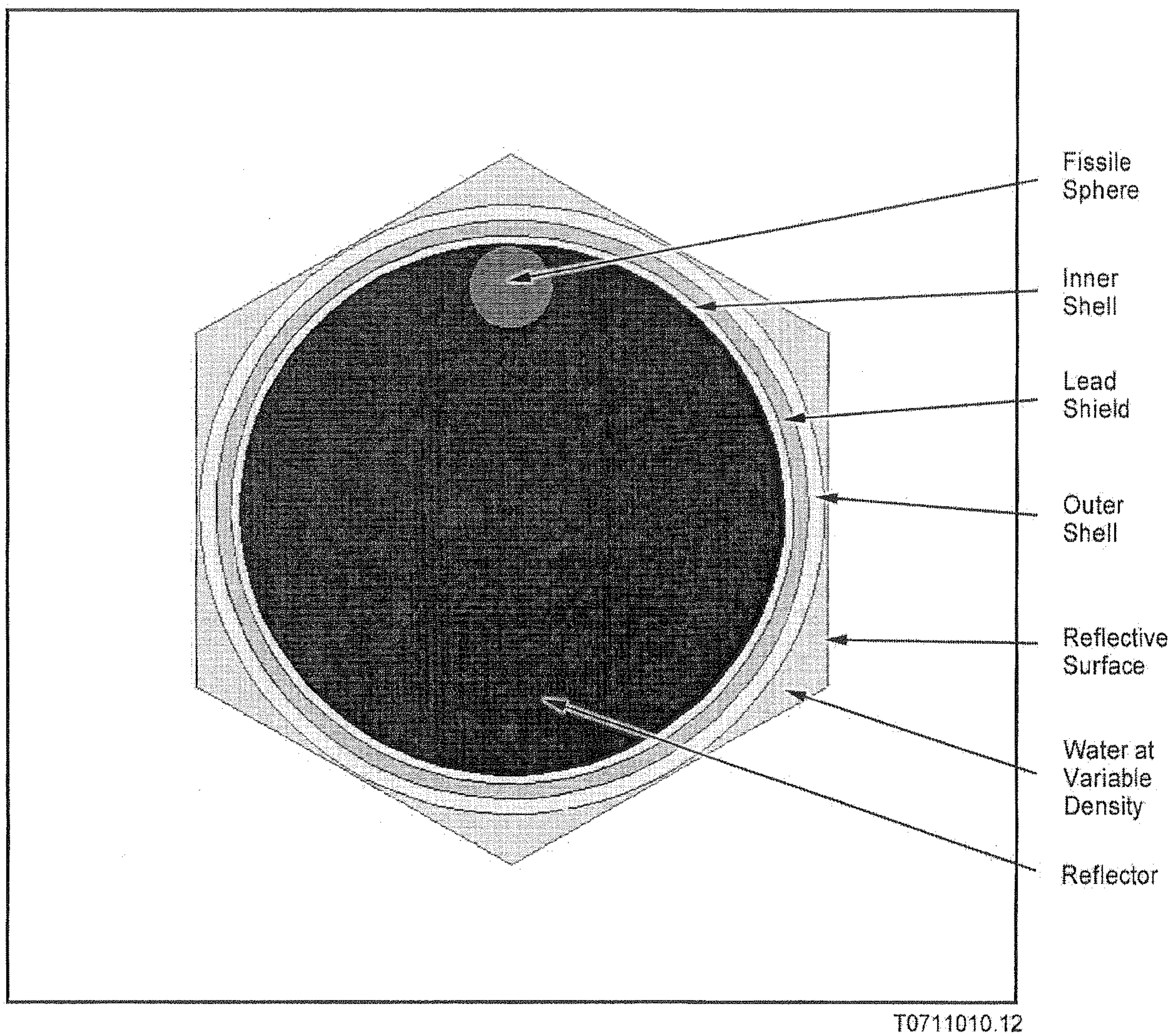


Figure 6-14. Plan View of an Infinite Array of HAC 10-160B Casks (MCNP case f022apex00).



6.6.2 Results

The individual HAC cases, as summarized in Table 6.7, show that case f033 was the most reactive. Case f033 was a lid corner case. Since the effective axial distance between adjacent casks in an infinite array is greater with a lid corner case, the most reactive base corner case (f022) was selected for infinite array evaluation as well.

The HAC array cases have a baseline external configuration identical to the NCT array cases except that the interspersed region is filled with water at various densities and the fissile sphere is evaluated at the apex and flat (see Figures 6.13 and 6.14). Table 6.9 summarizes the values of K_{eff} for an infinite array of 10-160B casks under HAC for various interspersed water densities ranging from 0.00 to 1.00 g/cm^3. As noted before, single unit cases designated as f033 and f022 were selected for infinite array evaluation in the apex and flat orientations. Table 6.9 presents the evaluation of these four general cases for water densities ranging from 0.00 to 0.10 g/cm^3. The f022 flat cases were extended to a maximum water density of 1.00 g/cm^3 since that composition and orientation was the most reactive from 0.00 to 0.10 g/cm^3.

The differences between the k_{eff} values for very low interspersed water densities (i.e., 0 to 0.001 g/cm^3) are statistically insignificant. However, water densities greater than 0.01 g/cm^3 indicate that the k_{eff} values decrease with increasing density. This is most likely due to the increased absorption of neutrons in the water. Therefore, optimum interspersed moderation corresponds to dry, or very low, moderation between the casks in the array.

The results for the HAC array calculations indicate that an infinite array of 10-160B Casks loaded with any of the fissile configurations is safely subcritical with a maximum k_{eff} value of 0.93873 (case f022flat02). Because an infinite array of 10-160B Casks, with the contents described in Section 6.2, are safely subcritical during HAC no finite array cases are necessary. Appendix 6.9.2 contains representative MCNP input files used in this evaluation.

Table 6.9. Values of K_{eff} vs Interspersed Water Densities for an Infinite Array of 10-160B Casks Under HAC.

HAC 10-160 B Infinite Array					
Location	MCNP Case	Water Fraction	K_{eff}	σ_{MCNP}	AEF[a] (eV)
HAC Base Corner	f022apex00	0.00000	0.93764	0.00021	0.0548
	f022apex01	0.00010	0.93749	0.00020	0.0548
	f022apex02	0.00100	0.93770	0.00020	0.0548
	f022apex03	0.01000	0.93754	0.00020	0.0548
	f022apex04	0.10000	0.93594	0.00020	0.0549
	f022flat00	0.00000	0.93871	0.00020	0.0548
	f022flat01	0.00010	0.93870	0.00020	0.0548
	f022flat02	0.00100	0.93873	0.00020	0.0548
	f022flat03	0.01000	0.93829	0.00021	0.0548
	f022flat04	0.10000	0.93745	0.00021	0.0548
	f022flat05	0.20000	0.93708	0.00021	0.0549
	f022flat06	0.30000	0.93674	0.00020	0.0548
	f022flat07	0.40000	0.93611	0.00020	0.0548
	f022flat08	0.50000	0.93551	0.00021	0.0549
	f022flat09	0.60000	0.93535	0.00020	0.0549
	f022flat10	0.70000	0.93529	0.00021	0.0549
	f022flat11	0.80000	0.93518	0.00020	0.0548
	f022flat12	0.90000	0.93461	0.00020	0.0548
	f022flat13	1.00000	0.93468	0.00020	0.0549
HAC Lid Corner	f033apex00	0.00000	0.93610	0.00020	0.0537
	f033apex01	0.00010	0.93613	0.00020	0.0537
	f033apex02	0.00100	0.93609	0.00020	0.0537
	f033apex03	0.01000	0.93603	0.00020	0.0537
	f033apex04	0.10000	0.93391	0.00020	0.0537
	f033flat00	0.00000	0.93692	0.00020	0.0536
	f033flat01	0.00010	0.93700	0.00020	0.0537
	f033flat02	0.00100	0.93713	0.00020	0.0537
	f033flat03	0.01000	0.93666	0.00020	0.0537
	f033flat04	0.10000	0.93568	0.00021	0.0537

[a] Energy corresponding to the average neutron lethargy causing fission (AEF)

6.7 FISSILE MATERIAL PACKAGES FOR AIR TRANSPORT

This section is not applicable. The Applicant did not design the 10-160B Cask for air transport nor does the Applicant seek authorization for air transport.

6.8 BENCHMARK EVALUATIONS

This section summarizes calculations for experimental criticality benchmarks used to validate the computer code MCNP 5 (LANL 2003) with pointwise ENDF/B-VI cross sections processed as described in Appendix G of the MCNP manual. The bias factor obtained from these calculations of the critical experiments is applied to the MCNP-calculated k_{eff} values in Sections 6.4 and 6.5 to ensure that adequate subcriticality margin exists for shipment of the 10-160B Cask.

The MCNP 5 executable was verified initially by executing the 42 standard test problems provided by the code developer, Los Alamos National Laboratory, and confirming that the results agree with the standard output (OUTP and MCTAL) files provided by Los Alamos National Laboratory. This section focuses on validation of MCNP's pointwise ENDF/B-VI cross-sectional library using 40 experimental criticality benchmarks involving plutonium.

6.8.1 Applicability of Benchmark Experiments

The experimental benchmarks are taken from NEA/NSC/DOC (95)03, *International Handbook of Evaluated Criticality Safety Benchmark Experiments*, [4] which discusses each experiment in detail. It includes estimates of the uncertainty in the measurements, detailed information regarding dimensions and material compositions, comparisons between the multiplication factor calculated by various computer codes, and a list of input files that are used in their calculations.

The cases of interest to establish a bias for this criticality evaluation involve critical experiments for thermal plutonium solution forms. The plutonium measurements are designated in NEA/NSC/DOC (95)03 as PU-SOL-THERM-001, -002, -003, -004, -006, and -009. These are judged to be the most applicable to the 10-160B Cask criticality evaluation, which contains plutonium in solution form.

The MCNP input files for these critical experiments are taken directly from NEA/NSC/DOC (95)03 with one modification. The material definitions for several elements were modified because some elements in the MCNP ENDF/B-V cross-sectional library no longer have corresponding cross sections in the ENDF/B-VI library. This results in the need to convert material compositions for an element into the corresponding material compositions for the naturally occurring isotopes of that element. For example, if the original input file has a material composition consisting entirely of iron (cross-section ID = 26000.50c), the revised input file for the ENDF/B-VI cross sections contains a material composition as follows:

26054.66c	0.0584	(^{54}Fe)
26056.66c	0.9175	(^{56}Fe)
26057.66c	0.0212	(^{57}Fe)
26058.66c	0.0028	(^{58}Fe)

This procedure is done to reflect the naturally occurring isotopic abundances of iron of 0.058, 0.9172, 0.022, and 0.0028 for ^{54}Fe, ^{56}Fe, ^{57}Fe, and ^{58}Fe, respectively. Similar changes are made for the following elements: silicon (z=14), chromium (z=24), nickel (z=28), copper (z=29), and lead (z=82).

Additionally, three elements were simulated with the single isotope present in the EDF/B-V cross-sectional library. The material compositions were modified to allow for the additional naturally-occurring isotope available in the ENDF/B-VI library. Therefore, hydrogen was expanded from 1001.50c to 1001.66c and 1002.66c. Nitrogen was expanded from 7014.50c to 7014.66c and 7015.66c. Oxygen was expanded from 8016.50c to 8016.66c and 8017.66c. Cross-sections were not available for 8018.66c so that naturally occurring percentage was lumped into the 8016.66c. These are minor changes that reflect the cross-section philosophy used in the criticality evaluations.

6.8.2 Bias Determination

The results of the plutonium benchmark calculations are shown in Table 6.10. The first three columns of this table show a unique case number and case identifier. The fourth column shows the ratio of elemental hydrogen to fissile (Pu^{239} plus Pu^{241}). The fifth column shows the Pu^{240} content as a percentage of the total Pu. The sixth column shows the MCNP calculated k_{eff} value, and the seventh column is the one-standard-deviation statistical uncertainty in the MCNP calculation. The eighth column is an estimate of the one-standard-deviation experimental uncertainty. The ninth column of Table 6.10 shows the average neutron energy causing fission (AEF) for these experiments that is calculated by MCNP. This parameter is useful for characterizing the neutron spectrum of the system.

These benchmark cases were chosen to bracket the criticality simulations of the 10-160B Cask. As presented at the bottom of Table 6.10, the H/X ratio of the benchmark cases ranged from a low of 91 to a high of 2807, with eighteen between 700 and 1100.

The Pu^{240} content of the 10-160B criticality simulations was assumed to be zero since Pu^{240} acts as a neutron poison. However, Pu^{239} without Pu^{240} would be unusual so benchmark cases with low Pu^{240} content were chosen when possible. All forty benchmark cases had Pu^{240} contents less than 4.65%. Thirty-three benchmark cases had Pu^{240} contents less than 3.1% and four cases less than 0.54% Pu^{240}.

The AEF values for the criticality cases for the 10-160B Cask (see Tables 6.6, 6.7, 6.8, and 6.9) range from 0.0495 to 0.0594, and are well bracketed by the AEF values for the benchmark cases.

Table 6.10. Results of Monte Carlo N-Particle Calculations of the Forty Plutonium Benchmark Experiments.

	Case Identifier[a]		H/X	Pu240/Pu	K_{eff}	σ_{MCNP}	$\sigma_{experiment}$	AEF (eV)[b]
1	pust.001	Case 1.T8A	370	0.04650	1.00441	0.00045	0.005	0.0877
2	pust.001	Case 2.T8A	271	0.04650	1.00505	0.00045	0.005	0.1106
3	pust.001	Case 3.T8A	215	0.04650	1.00735	0.00046	0.005	0.1344
4	pust.001	Case 4.T8A	190	0.04650	1.00338	0.00046	0.005	0.1507
5	pust.001	Case 5.T8A	180	0.04650	1.00682	0.00047	0.005	0.1591
6	pust.001	Case 6.T8A	91	0.04650	1.00752	0.00046	0.005	0.3477
7	pust.002	Case 1	524	0.03107	1.00393	0.00044	0.0047	0.0707
8	pust.002	Case 2	505	0.03107	1.00401	0.00044	0.0047	0.0724
9	pust.002	Case 3	451	0.03107	1.00264	0.00043	0.0047	0.0775
10	pust.002	Case 4	421	0.03107	1.00527	0.00045	0.0047	0.0808
11	pust.002	Case 5	393	0.03107	1.00835	0.00044	0.0047	0.0844
12	pust.002	Case 6	344	0.03107	1.00344	0.00044	0.0047	0.0924
13	pust.002	Case 7	309	0.03107	1.00599	0.00044	0.0047	0.0998
14	pust.003	Case 1	788	0.01753	1.00347	0.00041	0.0047	0.0579
15	pust.003	Case 2	756	0.01753	1.00198	0.00041	0.0047	0.0590
16	pust.003	Case 3	699	0.03107	1.00564	0.00042	0.0047	0.0615
17	pust.003	Case 4	682	0.03107	1.00431	0.00042	0.0047	0.0623
18	pust.003	Case 5	627	0.03107	1.00564	0.00042	0.0047	0.0651
19	pust.003	Case 6	563	0.03107	1.00524	0.00043	0.0047	0.0690
20	pust.003	Case 7	738	0.03107	1.00698	0.00042	0.0047	0.0588
21	pust.003	Case 8	714	0.03107	1.00567	0.00042	0.0047	0.0598
22	pust.004	Case 1	987	0.00538	1.00454	0.00039	0.0047	0.0530
23	pust.004	Case 2	977	0.00538	0.99927	0.00039	0.0047	0.0532
24	pust.004	Case 3	935	0.00538	1.00143	0.00039	0.0047	0.0543
25	pust.004	Case 4	889	0.00538	0.99917	0.00039	0.0047	0.0555
26	pust.004	Case 5	942	0.01753	1.00023	0.00040	0.0047	0.0542
27	pust.004	Case 6	927	0.03107	1.00216	0.00040	0.0047	0.0544
28	pust.004	Case 7	892	0.03107	1.00588	0.00040	0.0047	0.0555
29	pust.004	Case 8	869	0.03107	1.00186	0.00040	0.0047	0.0562
30	pust.004	Case 9	805	0.03107	1.00147	0.00041	0.0047	0.0583
31	pust.004	Case 10	689	0.03107	1.00171	0.00040	0.0047	0.0629
32	pust.004	Case 11	592	0.03107	1.00023	0.00041	0.0047	0.0679
33	pust.004	Case 12	893	0.03107	1.00326	0.00039	0.0047	0.0554
34	pust.004	Case 13	903	0.03416	1.00041	0.00040	0.0047	0.0553
35	pust.006	Case 1	1061	0.03107	1.00133	0.00037	0.0035	0.0521
36	pust.006	Case 2	1018	0.03107	1.00273	0.00038	0.0035	0.0531
37	pust.006	Case 3	940	0.03107	1.00220	0.00038	0.0035	0.0548
38	pust.009	Case 1A	2652	0.02511	1.01585	0.00043	0.0033	0.0413
39	pust.009	Case 2A	2783	0.02511	1.02009	0.00041	0.0033	0.0408
40	pust.009	Case 3A	2807	0.02511	1.01875	0.00040	0.0033	0.0408
Average of All Experiments					1.00474	0.00042	0.00455	
Range		Minimum	91	0.00538	0.99917	0.00037		0.0408
		Maximum	2807	0.04650	1.02009	0.00047		0.3477

[a] All cases from NEA/NSC/DOC(95)03.

[b] Energy corresponding to the average neutron lethargy causing fission (AEF), in units of electronvolts.
NEA/NSC/DOC(95)03, *International Handbook of Evaluated Criticality Safety Benchmark Experiments* [4]

NUREG/CR-5661, *Recommendations for Preparing the Criticality Safety Evaluation of Transportation Packaging for Radioactive Material*, [5] recommends the following general relationship for establishing acceptance criteria for criticality calculations:

$$k_c - \Delta k_u \geq k_{eff} + 2\sigma + \Delta k_m,$$

where:

k_c = k_{eff} resulting from the calculation of benchmark critical experiments using a specific calculational method and data

Δk_u = An allowance for the calculational uncertainty

Δk_m = A required margin of subcriticality (0.05)

k_{eff} = The calculated value obtained from the Monte Carlo analysis for the package or array of packages

σ = The standard deviation of the k_{eff} value obtained from the Monte Carlo analysis.

If the calculational bias β is defined as $\beta = 1 - k_c$, then the bias is positive if $k_c < 1$ and negative if $k_c > 1$. The acceptance relationship may be rewritten as:

$$1.00 - \beta - \Delta k_u \geq k_{eff} + 2\sigma + 0.05, \text{ or}$$

$$k_{eff} + \beta + 2\sigma + \Delta k_u \leq 0.95.$$

To account for the calculational and experimental uncertainty for the benchmark criticals, the mean value of σ_{MCNP} from MCNP for the critical experiments and the experimental uncertainty $\sigma_{experiment}$ (=Δk_u) are combined in quadrature with the standard deviation (σ) of the k_{eff} value obtained from the MCNP NCT or HAC analysis. This results in the following acceptance relationship:

$$k_{eff} + \beta + 2(\sigma^2 + \sigma^2_{MCNP} + \sigma^2_{experiment})^{0.5} \leq 0.95$$

The statistical summary at the bottom of Table 6-10 is used to obtain the calculational and experimental uncertainties for the benchmark criticals. There were no observable trends for the benchmark k_{eff} values (i.e., versus AEF, H/X, etc.) that would impact the bias determination. All but 2 of the benchmark experiments had k_{eff} values greater than 1.0. Because the average k_{eff} is greater than 1.0, and the 2 benchmark experiments with k_{eff} values below 1.0 are greater than 0.999, the bias, β, was set to zero in the determination of the effective criticality limit for this evaluation. Therefore, with the bias and uncertainties, the acceptance criteria is:

$$k_{eff} + 0.00 + 2(\sigma^2 + 0.00092^2 + 0.00479^2)^{0.5} \leq 0.95$$

In a typical MCNP calculation for the 10-160B Cask, the standard deviation (σ_{MCNP}) is less than 0.00025. Therefore, solving for keff yields:

$$k_{eff} \leq 0.95 - [0.00 + 2(\sigma^2 + 0.00092^2 + 0.00479^2)^{0.5}]$$

The k_{eff} from the above equation is 0.94002 for $\sigma = \sigma_{MCNP} = 0.00025$.

The effective criticality limit for this evaluation is set to 0.9400, which assumes that the MCNP calculation is run long enough to obtain a $\sigma_{MCNP} \leq 0.00025$. This means that the MNCP-calculated k_{eff} values must be less than 0.9400 to demonstrate adequate subcriticality margin after accounting for bias and uncertainties as long as $\sigma_{MCNP} \leq 0.00025$.

6.9 APPENDIX

The appendices to Chapter 6 include a list of references and representative MCNP input listings.

6.9.1 References

1 *Packaging and Transportation of Radioactive Material*, Code of Federal Regulations, Title 10, Part 71, Washington, DC (January 2006)

2. FSWO-QAP-001, *Quality Assurance Procedures*, Procedure QP 3-10, *Software Management*, Energy*Solutions* Federal Services, Inc., Western Operations, Richland, Washington

3. *MCNP—A General Monte Carlo N-Particle Transport Code, Version 5*, LA-UR-03-1987, Release 1.4, Los Alamos National Laboratory, Los Alamos, New Mexico (2003)

4. *International Handbook of Evaluated Criticality Safety Benchmark Experiments*, NEA/NSC/DOC(95)03, September 2002 Edition, *Organization for Economic Co-operation and Development*, Nuclear Energy Agency, Paris, France (2002)

5. *Recommendations for Preparing the Criticality Safety Evaluation of Transportation Packaging for Radioactive Material,* NUREG/CR-5661, U.S. Nuclear Regulatory Commission, Washington, DC (1997)

6. U.S. Department of Energy (DOE), *Remote-Handled Transuranic Waste Authorized Methods for Payload Control* (RH-TRAMPAC), Revision 0, 2006, U.S. Department of Energy, Carlsbad Field Office, Carlsbad, New Mexico.

7. *RH-TRU 72-B Safety Analysis Report, Revision 4, 2006.*

8. WP-8-PT.09, *Test Plan to Determine the TRU Waste Polyethylene Packing Fraction*, Washington TRU Solutions, LLC., Revision 0, June 2003.

6.9.2 Representative MCNP Input Files

NCT Single Cask – f369

```
10-160B
c
3000   139 -0.238656          -2000
                                    imp:n=1
3001   169 -0.233058   +2000 +120  -2100 -30
                                    imp:n=1
4000   500 -0.00122    +120  -149   -30 +2100
c     4000   901 -0.983047   +120  -149   -30
c     4000   902 -0.985333   +120  -149   -30
c     4000   903 -0.987607   +120  -149   -30
                     #(+130  +10    )
                                    imp:n=1
c
c  Cask Regions
5     300 -8.03 ((30:-120)(-40 110 -130)):(130 -140 10 -40):
              (10 -20 140 -149):(149 -150 -20)     imp:n=1   $ Liner
11 ga - SS304
10    200 -7.85 (100 -109 -70)                     imp:n=1   $ Base-
Carbon Steel
15    200 -7.85 (109 -110 -50)                     imp:n=1   $ Base-
Carbon Steel
20    200 -7.85 (110 -140 40 -50)                  imp:n=1   $ Inner
Shell-Carbon Steel
25    400 -11.34 (109 -140 50 -60)                 imp:n=1   $ Lead
wall
30    200 -7.85  (109 -140 60 -70)                 imp:n=1   $ steel
40    200 -7.85 (140 -150 20 -70):(150 -160 -70):(160 -170 -25)
                                                   imp:n=1 $
Prim/2ndary lid-Carbon Steel
c
c     Water reflector
5000  600 -1.0     (-500 510 -520) (((70:-100) -160):(160 25):170)
                                                   imp:n=1 $ 1st 5 cm
5001  600 -1.0     (-501 511 -521) (500:-510:520)  imp:n=0.25 $ Out to
12 inches
5002  0                   (501:-511:521)           imp:n=0    $
Outside universe
c
9000  0                         -2001              imp:n=1
c

c  Cask Radial Zones
10       cz       39.0525  $ Lid recess liner
20       cz       39.37    $ Lid recess
25       cz       58.42    $ 2ndary lid
30       cz       86.0425  $ Inner cavity
40       cz       86.36    $ OD Liner (11 ga)
50       cz       89.2175  $ OD Inner shell
```

```
60      cz      93.98     $ OD Lead
70      cz      99.06     $ OD Outer shell
80      cz      99.695    $ OD Thermal barrier-not included in model
c  Cask Axial Zones
100     pz      0.0001    $ Bottom cask
109     pz      11.43     $ Bottom lead in side wall
110     pz      13.97     $ Base plate
120     pz      14.2875   $ Bottom liner
125     pz      174.32655  $ Top of mixture for H/D=0.93
130     pz      209.2325 $ Cavity hgt
140     pz      209.55    $ Top liner
149     pz      216.8525 $ Lid recess liner
150     pz      217.17    $ Top of lid recess
160     pz      223.52    $ Primary lid
170     pz      231.14    $ Top of 2nd lid
c
c Planes for water reflector - 1st 5 cm and out to 12 inches
c
500     cz   104.06
501     cz   129.54
510     pz  -5
511     pz  -30.48
520     pz   236.14
521     pz   261.62
c
1000   so   1000            $ beyond problem
c
2000   s    61.948    0.000     38.382    23.994894
2001   s    61.948    0.000     38.382    19.0
2002   s    61.948    0.000     38.382    79.210227
c
2100  pz 103.79361
c

c
mode n
kcode   4000 0.9   50  4000
sdef   x=d1   y=d2   z=d3    ccc=9000 eff=0.00001
c     ksrc     0   0  120
c
si1    -19.0     86.1
sp1      0         1
c
si2    -19.0     19.0
sp2      0         1
c
si3     14.0    210.0
sp3      0         1
c
c Material Definitions
c
c
```

```
c     H/Pu     1400
c     H2O/CH2     0.0000000
c     Be w%     1.000000%     of CH2 + Pu
c     Radius     23.994894     cm
c     Pu-239 Mass     325.000000     g
c     Density     0.238656     g/cc
c      0.000     0.000     120.000     23.99489        Center
c      0.000     0.000      38.382     23.99489        Bottom
c     61.948     0.000      38.382     23.99489        Lower Corner
c     61.948     0.000     185.138     23.99489        Upper Corner
c
m139     1001.66c     -0.13886897     $     H-1
         1002.66c     -0.00004163     $     H-2
         4009.66c     -0.00990099     $     Be-nat
         6000.66c     -0.82765605     $     C-nat
c         8016.66c     0.00000000     $     O-16 & O-18
c         8017.66c     0.00000000     $     O-17
        94239.66c     -0.02353235     $     Pu-239
mt139    poly.60t     be.60t
c
c
c     H2O/CH2     0.000
c     Be w%     1.00%     of CH2
c     Density     0.104514     g/cc     Full Vessel
c     Density     0.233058          Sphere Reflector
c     Radius     79.210227          Sphere Reflector
c     Height     0.000000
c
m169     1001.66c     -0.14224992     $     H-1
         1002.66c     -0.00004265     $     H-2
         4009.66c     -0.00990099     $     Be-nat
         6000.66c     -0.84780644     $     C-nat
c         8016.66c     0.00000000     $     O-16 & O-18
c         8017.66c     0.00000000     $     O-17
mt169    poly.60t     be.60t
c
c
c
c      Carbon Steel
c     Density     7.85          g/cc
c
m200     6000.66c     -0.003000          $ C-nat
        14028.66c     -0.002572          $ Si-28
        14029.66c     -0.000135          $ Si-29
        14030.66c     -0.000092          $ Si-30
        15031.66c     -0.000400          $ P-31
        16000.66c     -0.000500          $ S-nat
        25055.66c     -0.010300          $ Mn-55
        26054.66c     -0.055383          $ Fe-54
        26056.66c     -0.901554          $ Fe-56
        26057.66c     -0.021193          $ Fe-57
        26058.66c     -0.002870          $ Fe-58
```

```
      29063.66c    -0.001370        $ Cu-63
      29065.66c    -0.000630        $ Cu-65
c
c     SS-304 - from STDNEUT.dos file
c    Density     8.03         g/cc
c
m300   6000.66c    -0.000300        $ C-nat
      24050.66c    -0.008345        $ Cr-50
      24052.66c    -0.167349        $ Cr-52
      24053.66c    -0.019341        $ Cr-53
      24054.66c    -0.004905        $ Cr-54
      25055.66c    -0.019994        $ Mn-55
      26054.66c    -0.038378        $ Fe-54
      26056.66c    -0.624743        $ Fe-56
      26057.66c    -0.014686        $ Fe-57
      26058.66c    -0.001989        $ Fe-58
      28058.66c    -0.067178        $ Ni-58
      28060.66c    -0.026768        $ Ni-60
      28061.66c    -0.001183        $ Ni-61
      28062.66c    -0.003834        $ Ni-62
      28064.66c    -0.001008        $ Ni-64
c
c     Lead
c    Density   11.34         g/cc
c
m400  82000.50c    -1.0             $ Lead
c
c     Air
m500   7014.66c    -0.761985        $ N-14
       7015.66c    -0.003015        $ N-15
       8016.66c    -0.234905        $ O-16 & O-18
       8017.66c    -0.000095        $ O-17
c
c    Water
c    Density     1.00         g/cc
c
m600     1001.66c    -0.11186481    $    H-1
         1002.66c    -0.00003354    $    H-2
         8016.66c    -0.88774309    $    O-16 & O-18
         8017.66c    -0.00035857    $    O-17
mt600    lwtr.60t
c
c
c        Be        1.85         g/cc
c
m800     4009.66c    -0.00497513    $    Be-nat
mt800    be.60t
c
print
```

HAC Single Cask – f033

```
10-160B
c
3000   103 -1.011186        -2000
                                  imp:n=1
4000   153 -0.991739   +120   -149   -30
                       +2000
                     #(+130   +10    )
                                  imp:n=1
c
c  Cask Regions
5      300 -8.03 ((30:-120)(-40 110 -130)):(130 -140 10 -40):
              (10 -20 140 -149):(149 -150 -20)      imp:n=1   $ Liner
11 ga - SS304
10     200 -7.85 (100 -109 -70)                      imp:n=1   $ Base-
Carbon Steel
15     200 -7.85 (109 -110 -50)                      imp:n=1   $ Base-
Carbon Steel
20     200 -7.85 (110 -140 40 -50)                   imp:n=1   $ Inner
Shell-Carbon Steel
25     400 -11.34 (109 -140 50 -60)                  imp:n=1   $ Lead
wall
30     200 -7.85  (109 -140 60 -70)                  imp:n=1   $ steel
40     200 -7.85 (140 -150 20 -70):(150 -160 -70):(160 -170 -25)
                                                     imp:n=1 $
Prim/2ndary lid-Carbon Steel
c
c      Water reflector
5000   600 -1.0 (-500 510 -520) (((70:-100) -160):(160 25):170)
                                                     imp:n=1 $ 1st 5 cm
5001   600 -1.0 (-501 511 -521) (500:-510:520)       imp:n=0.25 $ Out to
12 inches
5002   0                   (501:-511:521)            imp:n=0    $
Outside universe
c
9000   0                         -2001               imp:n=1
c

c  Cask Radial Zones
10       cz       39.0525   $ Lid recess liner
20       cz       39.37     $ Lid recess
25       cz       58.42     $ 2ndary lid
30       cz       86.0425   $ Inner cavity
40       cz       86.36     $ OD Liner (11 ga)
50       cz       89.2175   $ OD Inner shell
60       cz       93.98     $ OD Lead
70       cz       99.06     $ OD Outer shell
80       cz       99.695    $ OD Thermal barrier-not included in model
c  Cask Axial Zones
100      pz       0.0001    $ Bottom cask
109      pz       11.43     $ Bottom lead in side wall
```

```
110     pz      13.97    $ Base plate
120     pz      14.2875  $ Bottom liner
125     pz      174.32655  $ Top of mixture for H/D=0.93
130     pz      209.2325 $ Cavity hgt
140     pz      209.55   $ Top liner
149     pz      216.8525 $ Lid recess liner
150     pz      217.17   $ Top of lid recess
160     pz      223.52   $ Primary lid
170     pz      231.14   $ Top of 2nd lid
c
c Planes for water reflector - 1st 5 cm and out to 12 inches
c
500     cz   104.06
501     cz   129.54
510     pz  -5
511     pz  -30.48
520     pz   236.14
521     pz   261.62
c
1000   so   1000            $ beyond problem
c
2000   s  72.331    0.000    195.521    13.611761
2001   s  72.331    0.000    195.521    12.5
c

c
mode n
kcode   4000 0.9   50  4000
sdef   x=d1   y=d2   z=d3    ccc=9000 eff=0.00001
c     ksrc    0   0  120
c
si1    -12.5     86.1
sp1      0        1
c
si2    -12.5     12.5
sp2      0        1
c
si3     14.0    210.0
sp3      0        1
c
c Material Definitions
c
c
c    H/Pu    900
c    H2O/CH2    3.245
c    Be w%    1.00000%    of CH2 + Pu
c    Radius    13.611761    cm
c    Pu-239 Mass    325.0000    g
c    Density    1.011186    g/cc
c     0.000    0.000    120.000    13.611761       Center
c     0.000    0.000     27.999    13.611761       Bottom
c    72.331    0.000     27.999    13.611761       Lower Corner
```

```
c     72.331     0.000     195.521     13.611761        Upper Corner
c
m103      1001.66c     -0.11541840     $     H-1
          1002.66c     -0.00003460     $     H-2
          4009.66c     -0.00258227     $     Be-nat
          6000.66c     -0.19506425     $     C-nat
          8016.66c     -0.65621111     $     O-16 & O-18
          8017.66c     -0.00026505     $     O-17
         94239.66c     -0.03042431     $     Pu-239
mt103     lwtr.60t     be.60t
c
c
c     H2O/CH2     8.453226
c     Be w%     1.00000%     of CH2
c     Density     0.991739     g/cc
c
m153      1001.66c     -0.11510778     $     H-1
          1002.66c     -0.00003451     $     H-2
          4009.66c     -0.00105672     $     Be-nat
          6000.66c     -0.09048548     $     C-nat
          8016.66c     -0.79299521     $     O-16 & O-18
          8017.66c     -0.00032030     $     O-17
mt153     lwtr.60t     be.60t
c
c
c
c       Carbon Steel
c     Density     7.85         g/cc
c
m200     6000.66c     -0.003000         $ C-nat
        14028.66c     -0.002572         $ Si-28
        14029.66c     -0.000135         $ Si-29
        14030.66c     -0.000092         $ Si-30
        15031.66c     -0.000400         $ P-31
        16000.66c     -0.000500         $ S-nat
        25055.66c     -0.010300         $ Mn-55
        26054.66c     -0.055383         $ Fe-54
        26056.66c     -0.901554         $ Fe-56
        26057.66c     -0.021193         $ Fe-57
        26058.66c     -0.002870         $ Fe-58
        29063.66c     -0.001370         $ Cu-63
        29065.66c     -0.000630         $ Cu-65
c
c      SS-304 - from STDNEUT.dos file
c     Density     8.03         g/cc
c
m300     6000.66c     -0.000300         $ C-nat
        24050.66c     -0.008345         $ Cr-50
        24052.66c     -0.167349         $ Cr-52
        24053.66c     -0.019341         $ Cr-53
        24054.66c     -0.004905         $ Cr-54
        25055.66c     -0.019994         $ Mn-55
```

```
      26054.66c    -0.038378        $ Fe-54
      26056.66c    -0.624743        $ Fe-56
      26057.66c    -0.014686        $ Fe-57
      26058.66c    -0.001989        $ Fe-58
      28058.66c    -0.067178        $ Ni-58
      28060.66c    -0.026768        $ Ni-60
      28061.66c    -0.001183        $ Ni-61
      28062.66c    -0.003834        $ Ni-62
      28064.66c    -0.001008        $ Ni-64
c
c     Lead
c    Density   11.34        g/cc
c
m400  82000.50c    -1.0             $ Lead
c
c     Air
m500   7014.66c    -0.761985        $ N-14
       7015.66c    -0.003015        $ N-15
       8016.66c    -0.234905        $ O-16 & O-18
       8017.66c    -0.000095        $ O-17
c
c    Water
c    Density    1.00        g/cc
c
m600    1001.66c    -0.11186481    $    H-1
        1002.66c    -0.00003354    $    H-2
        8016.66c    -0.88774309    $    O-16 & O-18
        8017.66c    -0.00035857    $    O-17
mt600   lwtr.60t
c
c
c       Be        1.85        g/cc
c
m800    4009.66c    -0.00497513    $    Be-nat
mt800   be.60t
c
print
```

NCT Infinite Array – f369a

```
10-160B
c
3000   139 -0.238656         -2000
                                   imp:n=1
3001   169 -0.233058   +2000 +120  -2100 -30
                                   imp:n=1
4000   500 -0.00122    +120  -149   -30 +2100
c     4000   901 -0.983047   +120  -149   -30
c     4000   902 -0.985333   +120  -149   -30
c     4000   903 -0.987607   +120  -149   -30
                     #(+130  +10    )
                                   imp:n=1
c
c  Cask Regions
5     300 -8.03 ((30:-120)(-40 110 -130)):(130 -140 10 -40):
               (10 -20 140 -149):(149 -150 -20)     imp:n=1   $ Liner
11 ga - SS304
10    200 -7.85 (100 -109 -70)                      imp:n=1   $ Base-
Carbon Steel
15    200 -7.85 (109 -110 -50)                      imp:n=1   $ Base-
Carbon Steel
20    200 -7.85 (110 -140 40 -50)                   imp:n=1   $ Inner
Shell-Carbon Steel
25    400 -11.34 (109 -140 50 -60)                  imp:n=1   $ Lead
wall
30    200 -7.85  (109 -140 60 -70)                  imp:n=1   $ steel
40    200 -7.85 (140 -150 20 -70):(150 -160 -70):(160 -170 -25)
                                                    imp:n=1 $
Prim/2ndary lid-Carbon Steel
c
c     Around cask, interspersed
201    0        (-503 504 -508 507 -505 506 501 -502)
                    (((70:-100) -160):(160 25):170) imp:n=1
c     Outside World
200    0      (503:-504:508:-507:505:-506:-501:502) imp:n=0
c
c
9000  0                        -2001                imp:n=1
c

c  Cask Radial Zones
10       cz       39.0525  $ Lid recess liner
20       cz       39.37    $ Lid recess
25       cz       58.42    $ 2ndary lid
30       cz       86.0425  $ Inner cavity
40       cz       86.36    $ OD Liner (11 ga)
50       cz       89.2175  $ OD Inner shell
60       cz       93.98    $ OD Lead
70       cz       99.06    $ OD Outer shell
80       cz       99.695   $ OD Thermal barrier-not included in model
```

```
c  Cask Axial Zones
100     pz      0.0001    $ Bottom cask
109     pz      11.43     $ Bottom lead in side wall
110     pz      13.97     $ Base plate
120     pz      14.2875   $ Bottom liner
125     pz      174.32655  $ Top of mixture for H/D=0.93
130     pz      209.2325 $ Cavity hgt
140     pz      209.55    $ Top liner
149     pz      216.8525 $ Lid recess liner
150     pz      217.17    $ Top of lid recess
160     pz      223.52    $ Primary lid
170     pz      231.14    $ Top of 2nd lid
c
c     Hexagonal Cell Surrounding Cask for Infinite array
c
c       inner hex surfaces bounding lattice, (n-0.5)*p*cos30
c     surfaces for outer hexagonal duct
*501         pz       -1.000  $
*502         pz      232.140  $
*503         px      100.0000
*504         px     -100.0000
*505          p      -1.0000000      1.7320508      0.0000000
200.0000
*506          p      -1.0000000      1.7320508      0.0000000    -
200.0000
*507          p       1.0000000      1.7320508      0.0000000    -
200.0000
*508          p       1.0000000      1.7320508      0.0000000
200.0000
c
1000   so   1000            $ beyond problem
c
2000   s    61.948    0.000     38.382    23.994894
2001   s    61.948    0.000     38.382    19.0
2002   s    61.948    0.000     38.382    79.210227
c
2100  pz 103.79361
c

c
mode n
kcode   4000 0.9   50  4000
sdef   x=d1   y=d2   z=d3    ccc=9000 eff=0.00001
c     ksrc     0    0   120
c
si1    -19.0      86.1
sp1      0         1
c
si2    -19.0      19.0
sp2      0         1
c
si3     14.0     210.0
```

```
sp3      0         1
c
c Material Definitions
c
c
c    H/Pu     1400
c    H2O/CH2     0.0000000
c    Be w%     1.000000%     of CH2 + Pu
c    Radius     23.994894     cm
c    Pu-239 Mass     325.000000     g
c    Density     0.238656     g/cc
c     0.000     0.000     120.000     23.99489        Center
c     0.000     0.000      38.382     23.99489        Bottom
c    61.948     0.000      38.382     23.99489        Lower Corner
c    61.948     0.000     185.138     23.99489        Upper Corner
c
m139     1001.66c    -0.13886897    $    H-1
         1002.66c    -0.00004163    $    H-2
         4009.66c    -0.00990099    $    Be-nat
         6000.66c    -0.82765605    $    C-nat
c         8016.66c    0.00000000    $    O-16 & O-18
c         8017.66c    0.00000000    $    O-17
        94239.66c    -0.02353235    $    Pu-239
mt139    poly.60t    be.60t
c
c
c    H2O/CH2     0.000
c    Be w%     1.00%     of CH2
c    Density     0.104514     g/cc     Full Vessel
c    Density     0.233058        Sphere Reflector
c    Radius     79.210227        Sphere Reflector
c    Height     0.000000
c
m169     1001.66c    -0.14224992    $    H-1
         1002.66c    -0.00004265    $    H-2
         4009.66c    -0.00990099    $    Be-nat
         6000.66c    -0.84780644    $    C-nat
c         8016.66c    0.00000000    $    O-16 & O-18
c         8017.66c    0.00000000    $    O-17
mt169    poly.60t    be.60t
c
c
c
c      Carbon Steel
c    Density     7.85        g/cc
c
m200    6000.66c    -0.003000        $ C-nat
       14028.66c    -0.002572        $ Si-28
       14029.66c    -0.000135        $ Si-29
       14030.66c    -0.000092        $ Si-30
       15031.66c    -0.000400        $ P-31
       16000.66c    -0.000500        $ S-nat
```

```
        25055.66c    -0.010300          $ Mn-55
        26054.66c    -0.055383          $ Fe-54
        26056.66c    -0.901554          $ Fe-56
        26057.66c    -0.021193          $ Fe-57
        26058.66c    -0.002870          $ Fe-58
        29063.66c    -0.001370          $ Cu-63
        29065.66c    -0.000630          $ Cu-65
c
c       SS-304 - from STDNEUT.dos file
c      Density     8.03        g/cc
c
m300     6000.66c    -0.000300          $ C-nat
        24050.66c    -0.008345          $ Cr-50
        24052.66c    -0.167349          $ Cr-52
        24053.66c    -0.019341          $ Cr-53
        24054.66c    -0.004905          $ Cr-54
        25055.66c    -0.019994          $ Mn-55
        26054.66c    -0.038378          $ Fe-54
        26056.66c    -0.624743          $ Fe-56
        26057.66c    -0.014686          $ Fe-57
        26058.66c    -0.001989          $ Fe-58
        28058.66c    -0.067178          $ Ni-58
        28060.66c    -0.026768          $ Ni-60
        28061.66c    -0.001183          $ Ni-61
        28062.66c    -0.003834          $ Ni-62
        28064.66c    -0.001008          $ Ni-64
c
c       Lead
c      Density   11.34         g/cc
c
m400    82000.50c    -1.0               $ Lead
c
c       Air
m500     7014.66c    -0.761985          $ N-14
         7015.66c    -0.003015          $ N-15
         8016.66c    -0.234905          $ O-16 & O-18
         8017.66c    -0.000095          $ O-17
c
c      Water
c      Density    1.00         g/cc
c
m600      1001.66c    -0.11186481    $     H-1
          1002.66c    -0.00003354    $     H-2
          8016.66c    -0.88774309    $     O-16 & O-18
          8017.66c    -0.00035857    $     O-17
mt600     lwtr.60t
c
c
c         Be        1.85         g/cc
c
m800      4009.66c    -0.00497513    $     Be-nat
mt800     be.60t
```

```
c
print
```

HAC Infinite Array – f022flat02

```
10-160B
c
3000   102 -1.012911         -2000
                                   imp:n=1
4000   152 -0.991738   +120  -149   -30
                       +2000
                     #(+130  +10    )
                                   imp:n=1
c
c  Cask Regions
5     300 -8.03 ((30:-120)(-40 110 -130)):(130 -140 10 -40):
              (10 -20 140 -149):(149 -150 -20)     imp:n=1   $ Liner
11 ga - SS304
10    200 -7.85 (100 -109 -70)                     imp:n=1   $ Base-
Carbon Steel
15    200 -7.85 (109 -110 -50)                     imp:n=1   $ Base-
Carbon Steel
20    200 -7.85 (110 -140 40 -50)                  imp:n=1   $ Inner
Shell-Carbon Steel
25    400 -11.34 (109 -140 50 -60)                 imp:n=1   $ Lead
wall
30    200 -7.85  (109 -140 60 -70)                 imp:n=1   $ steel
40    200 -7.85 (140 -150 20 -70):(150 -160 -70):(160 -170 -25)
                                                   imp:n=1 $
Prim/2ndary lid-Carbon Steel
c
c
c     Around cask, interspersed
201   600 -0.0010   (-503 504 -508 507 -505 506 501 -502)
                    (((70:-100) -160):(160 25):170) imp:n=1
c     Outside World
200    0      (503:-504:508:-507:505:-506:-501:502) imp:n=0
c
9000  0                       -2001                imp:n=1
c

c  Cask Radial Zones
10      cz      39.0525  $ Lid recess liner
20      cz      39.37    $ Lid recess
25      cz      58.42    $ 2ndary lid
30      cz      86.0425  $ Inner cavity
40      cz      86.36    $ OD Liner (11 ga)
50      cz      89.2175  $ OD Inner shell
60      cz      93.98    $ OD Lead
70      cz      99.06    $ OD Outer shell
80      cz      99.695   $ OD Thermal barrier-not included in model
c  Cask Axial Zones
100     pz      0.0001   $ Bottom cask
109     pz      11.43    $ Bottom lead in side wall
110     pz      13.97    $ Base plate
```

```
120     pz      14.2875  $ Bottom liner
125     pz      174.32655  $ Top of mixture for H/D=0.93
130     pz      209.2325 $ Cavity hgt
140     pz      209.55   $ Top liner
149     pz      216.8525 $ Lid recess liner
150     pz      217.17   $ Top of lid recess
160     pz      223.52   $ Primary lid
170     pz      231.14   $ Top of 2nd lid
c
c     Hexagonal Cell Surrounding Cask for Infinite array
c
c       inner hex surfaces bounding lattice, (n-0.5)*p*cos30
c     surfaces for outer hexagonal duct
*501        pz       -1.000  $
*502        pz      232.140  $
*503        px      100.0000
*504        px     -100.0000
*505         p      -1.0000000      1.7320508      0.0000000
200.0000
*506         p      -1.0000000      1.7320508      0.0000000    -
200.0000
*507         p       1.0000000      1.7320508      0.0000000    -
200.0000
*508         p       1.0000000      1.7320508      0.0000000
200.0000
c
1000    so   1000           $ beyond problem
c
2000    s  72.587    0.000     27.743    13.355327
2001    s  72.587    0.000     27.743    12.5
c

c
mode n
kcode   4000 0.9   50  4000
sdef   x=d1   y=d2   z=d3    ccc=9000 eff=0.00001
c     ksrc     0   0  120
c
si1    -12.5     86.1
sp1      0        1
c
si2    -12.5     12.5
sp2      0        1
c
si3     14.0    210.0
sp3      0        1
c
c Material Definitions
c
c
c    H/Pu    850
c    H2O/CH2    3.245
```

```
c     Be w%     1.00000%     of CH2 + Pu
c     Radius     13.355327     cm
c     Pu-239 Mass     325.0000     g
c     Density     1.012911     g/cc
c      0.000     0.000     120.000     13.355327
c      0.000     0.000      27.743     13.355327
c     72.587     0.000      27.743     13.355327
c     72.587     0.000     195.778     13.355327
c
m102      1001.66c     -0.11521015     $     H-1
          1002.66c     -0.00003454     $     H-2
          4009.66c     -0.00259548     $     Be-nat
          6000.66c     -0.19471229     $     C-nat
          8016.66c     -0.65502711     $     O-16 & O-18
          8017.66c     -0.00026457     $     O-17
         94239.66c     -0.03215585     $     Pu-239
mt102     lwtr.60t     be.60t
c
c
c     H2O/CH2     8.451753
c     Be w%     1.00000%     of CH2
c     Density     0.991738     g/cc
c
m152      1001.66c     -0.11510828     $     H-1
          1002.66c     -0.00003451     $     H-2
          4009.66c     -0.00105689     $     Be-nat
          6000.66c     -0.09049956     $     C-nat
          8016.66c     -0.79298046     $     O-16 & O-18
          8017.66c     -0.00032029     $     O-17
mt152     lwtr.60t     be.60t
c
c
c
c       Carbon Steel
c     Density     7.85          g/cc
c
m200     6000.66c     -0.003000          $ C-nat
        14028.66c     -0.002572          $ Si-28
        14029.66c     -0.000135          $ Si-29
        14030.66c     -0.000092          $ Si-30
        15031.66c     -0.000400          $ P-31
        16000.66c     -0.000500          $ S-nat
        25055.66c     -0.010300          $ Mn-55
        26054.66c     -0.055383          $ Fe-54
        26056.66c     -0.901554          $ Fe-56
        26057.66c     -0.021193          $ Fe-57
        26058.66c     -0.002870          $ Fe-58
        29063.66c     -0.001370          $ Cu-63
        29065.66c     -0.000630          $ Cu-65
c
c      SS-304 - from STDNEUT.dos file
c     Density     8.03          g/cc
```

```
c
m300   6000.66c    -0.000300         $ C-nat
      24050.66c    -0.008345         $ Cr-50
      24052.66c    -0.167349         $ Cr-52
      24053.66c    -0.019341         $ Cr-53
      24054.66c    -0.004905         $ Cr-54
      25055.66c    -0.019994         $ Mn-55
      26054.66c    -0.038378         $ Fe-54
      26056.66c    -0.624743         $ Fe-56
      26057.66c    -0.014686         $ Fe-57
      26058.66c    -0.001989         $ Fe-58
      28058.66c    -0.067178         $ Ni-58
      28060.66c    -0.026768         $ Ni-60
      28061.66c    -0.001183         $ Ni-61
      28062.66c    -0.003834         $ Ni-62
      28064.66c    -0.001008         $ Ni-64
c
c      Lead
c     Density   11.34        g/cc
c
m400  82000.50c    -1.0              $ Lead
c
c      Air
m500   7014.66c    -0.761985         $ N-14
       7015.66c    -0.003015         $ N-15
       8016.66c    -0.234905         $ O-16 & O-18
       8017.66c    -0.000095         $ O-17
c
c     Water
c     Density    1.00        g/cc
c
m600    1001.66c    -0.11186481    $    H-1
        1002.66c    -0.00003354    $    H-2
        8016.66c    -0.88774309    $    O-16 & O-18
        8017.66c    -0.00035857    $    O-17
mt600   lwtr.60t
c
c
c       Be        1.85        g/cc
c
m800    4009.66c    -0.00497513    $    Be-nat
mt800   be.60t
c
print
```