5 SHIELDING EVALUATION

This chapter identifies, describes, discusses, and analyzes the AOS cask's principal radiation shielding design, which is important to safety.

5.1 DESCRIPTION OF SHIELDING DESIGN

5.1.1 Design Features

The cask is a cylindrical container with a cylindrical cavity in which radioactive materials are placed. Tungsten alloy or carbon steel shields (depending on model) for radiation attenuation are located on the cask cavity's top, bottom, and sides. Figure 5-1 illustrates the main cask components.

Cask components important to shielding, including the radiation shields and cask cavity, are discussed in this subsection. For all shielding evaluations, the impact limiter is ignored. Other transport package design features, such as the shipping cage, securing lines, and internal structure, are irrelevant from a shielding perspective and are also not considered. The absence of these components in the shielding model helps ensure a bounding dose rate estimate. For the dose rate location, however, the impact limiters are important because they move the normal shipping configuration-accessible surface away from the cask surface. This distance is included in the dose rate location selection; however, the materials occupying the impact limiter space are neglected.

Tests applied to the packaging and its contents, under Normal conditions of transport (NCT) and Hypothetical Accident conditions (HAC) of transport, demonstrated that the cask components modeled can maintain their structural integrity for all considered events. This allowed a single geometric model to be developed for each cask size being considered.

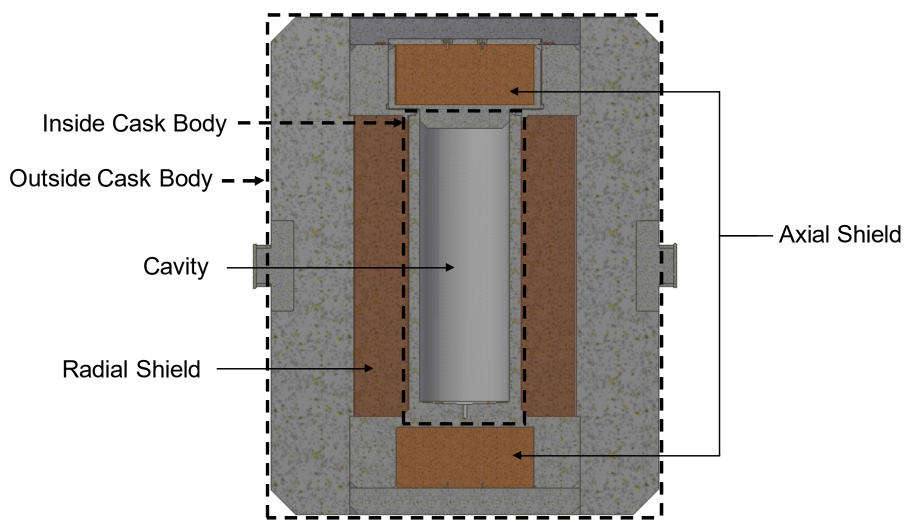

Figure 5-1. Cross-Sectional View of Cask Components

Table 5-1 lists the outside radius and half-height of each model's cask components. The half-height is the distance from the cask's center to the component's top, as illustrated in Figure 5-2. For example, the Model AOS-100's actual cavity height is 50.80 cm (20.00 in.), and the thickness of its axial shield is 11.13 cm (4.38 in.). This is calculated using Equation 5-1. Each cask is symmetric about the cask centerline, as illustrated in Figure 5-2. Dimensions for additional cask details that are included in the shielding models, such as beveling on the cask body corners and the radial shields, are as listed in the certification drawings. (Refer to Table 1-5, "AOS Transport Packaging System Certification Drawing List – All Models.")

$$h_{axial\_shield} = HalfHeight_{axial\_shield} - HalfHeight_{inner\_cask\_body} \tag{5-1}$$

Table 5-1. Cask Component Dimensions, Outside Radius and Half-Height – All Models[a]

Model	Component	Outside Radius		Half-Height[b]	
		cm	in.	cm	in.
AOS-025	Cavity	2.06	0.81	6.35	2.50
	Inside Cask Body	2.59	1.02	7.41	2.92
	Radial Shield	5.03	1.98	6.93	2.73
	Axial Shield	3.15	1.24	10.19	4.01
	Outside Cask Body	8.89	3.50	11.43	4.50
AOS-050	Cavity	4.13	1.63	12.70	5.00
	Inside Cask Body	5.18	2.04	14.84	5.84
	Radial Shield	10.06	3.96	13.84	5.45
	Axial Shield	6.30	2.48	20.40	8.03
	Outside Cask Body	17.78	7.00	22.86	9.00
AOS-100	Cavity	8.26	3.25	25.40	10.00
	Inside Cask Body	10.36	4.08	29.62	11.66
	Radial Shield	20.12	7.92	27.71	10.91
	Axial Shield	12.60	4.96	40.74	16.04
	Outside Cask Body	35.56	14.00	45.72	18.00

a. Dimensions are rounded.

b. Axial distance from cask centerline.

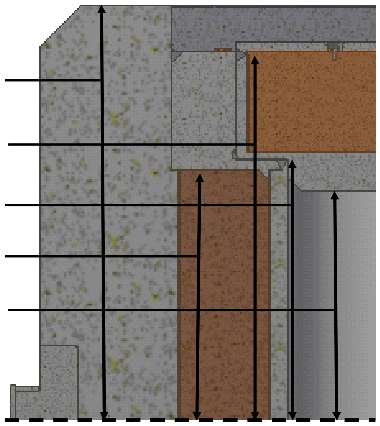

Figure 5-2. Cask Component Half-Height – All Models

Table 5-2 lists the cavity height and axial shield thickness for each AOS Transport Packaging System model.

Table 5-3 lists the materials for each cask component that is important to shielding. Tungsten alloy is used as the shielding material in casks whose model numbers include the suffix A. Carbon steel is used as the shielding material in casks whose model numbers include the suffix B. Therefore, the only difference between the Model AOS-100A and AOS-100B transport packages is the shielding material. The tungsten alloy density and minimum weight fraction of elemental tungsten are based on Class 3 tungsten in *AMS-T-21014* (Reference **[5.6]**).

Table 5-2. Cask Component Dimensions, Cavity Height and Axial Shield Thickness – All Models

Model	Component	Dimensions	
		cm	**in.**
AOS-025A	Cavity Height	12.70	5.00
	Axial Shield Thickness	2.77	1.09
AOS-050A	Cavity Height	25.40	10.00
	Axial Shield Thickness	5.56	2.19
AOS-100A AOS-100B AOS-100A-S	Cavity Height	50.80	20.00
	Axial Shield Thickness	11.13	4.38

Table 5-3. Cask Component Materials Important to Shielding – All Models

Component	Material	Model Type		Material Composition		Density (g/cm^3)
		AOS-025A AOS-050A AOS-100A	AOS-100B	Element	Weight Fraction	
Shield	Tungsten Alloy	✔		Tungsten	0.9500	17.75
				Nickel	0.0350	
				Iron	0.0150	
	Carbon Steel		✔	Carbon	0.0050	7.82
				Iron	0.9950	
Cask	Stainless Steel	✔	✔	Iron	0.7200	8.0
				Manganese	0.0200	
				Chromium	0.1800	
				Nickel	0.0800	

5.1.2 Summary Table of Maximum Radiation Levels

Table 5-4 and Table 5-5 list the maximum dose rates for both Normal conditions and Hypothetical Accident conditions of transport, at the appropriate locations for non-exclusive or exclusive use (or both), as applicable. A conservative 10% reduction in allowable *10 CFR 71.47 (a)* dose rate limits (Reference **[5.1]**) is applied for maximum radiation levels.

Table 5-4. Maximum Radiation Level Summary for Normal Conditions of Transport – All Models

Normal Conditions of Transport	External Surface[a] (mrem/hr)	1m from External Surface[a] (mrem/hr)
Gamma Radiation	180	9
Neutron Radiation	0	0
Total	180	9
10 CFR 71.47(a) Limit **[5.1]**	200	10[b]

a. *For this analysis, the external surface is considered to be the deformed impact limiter surface, unless indicated otherwise. (Refer to Appendix 5.5.8.)*

b. *Transport index may not exceed 10.*

Table 5-5. Maximum Radiation Level Summary for Hypothetical Accident Conditions of Transport – All Models

Hypothetical Accident Conditions of Transport	1m from External Surface[a] (mrem/hr)
Gamma Radiation	472.93
Neutron Radiation	0
Total	472.93
10 CFR 71.51(a)(2) Limit **[5.1]**	1,000

a. *For this analysis, the external surface is considered to be the cask surface.*

5.2 SOURCE SPECIFICATION

Table 5-6 lists the activation products to be loaded in the AOS transport package, for each transport package model. For Models AOS-100A and AOS-100A-S, in addition to the isotopes specifically listed in Table 5-6, low-energy gamma or beta emitters that emit only gammas or betas, respectively, at energies ≤ 0.3 MeV (including emissions from progeny) are also permissible. Single isotope activity limits for all shipping cask variants are listed in Table 1-2, "*10 CFR 71.47(a) Activity Limits (All Isotopes Except Ir-192 and Ir-194) – All Models,*" when meeting *10 CFR 71.47(a)* limits, and for Models AOS-100A and AOS-100A-S in Table 1-2b, "*10 CFR 71.47(b) Activity Limits – Model AOS-100A and AOS-100A-S,*" when meeting *10 CFR 71.47(b)* limits. Ir-194 impurities may be present in Ir-192 shipments, in quantities as designated in Table 1-2a, "*10 CFR 71.47(a) Ir-192 and Ir-194 Activity Limits – All Models.*" Contents with Zr-95 are considered to always include its daughter, as specified in Subsection 5.2.1. Shipments of multiple isotopes are permitted in all shipping casks when meeting *10 CFR 71.47(a)* limits, as specified in Appendix 5.5.5, and in Models AOS-100A and AOS-100A-S when meeting *10 CFR 71.47(b)* limits, as specified in Appendix 5.5.7.

Because of the penetration power of neutral radiation, such as gamma rays, these were the main concern for shielding calculations. The charged particles, such as beta particles, that are emitted by the isotopes listed in Table 5-6 are **not** able to penetrate the cask's thick shield layers, and the assumption was made to ignore these charged particles and their secondary particles (such as bremsstrahlung photons induced by beta particles) for shielding evaluations.

Table 5-6. Isotopes Analyzed for AOS Transport Packages – All Models

Isotope	Model		
	AOS-025	AOS-050	AOS-100
Co-60	✔	✔	✔
Cs-137	✔	✔	✔
Hf-181		✔	✔
Ir-192	✔	✔	✔
Ir-194	✔	✔	✔
Zr/Nb-95		✔	✔
Yb-169	✔	✔	

5.2.1 Gamma Source

The source description for activation products is obtained from isotope decay schemes that detail the gamma particle energies and their absolute probabilities of emission per disintegration (decay). For all isotopes except Zr/Nb-95, these decay schemes are explicitly modeled in the cask, based on discrete gamma energy and emission probability source terms extracted from the SCALE 6.1 ORIGEN (Reference **[5.2]**) gamma spectrum library *origen.rev04.mpdkxgam.data*. All available gamma energies from the library are considered in the shielding calculations. Total photon/decay values are also calculated and used, based on the information contained in the gamma spectrum library, by summing the total absolute probability of emission, per decay, from all possible energies for a given isotope.

Table 5-23 through Table 5-31 in Appendix 5.5.2 list the source spectra used in the shielding models. Low-energy gamma and/or beta emitters (all emissions, including those from their progeny, are ≤ 0.3 MeV) that are acceptable for transport in Models AOS-100A and AOS-100A-S are analyzed separately in Appendix 5.5.6.

The dose rate analyses for the isotopes listed in Table 5-6 are performed only on gamma-ray shielding by neglecting the transport of charged particles. Because charged particles do not have the same penetrating abilities as neutral particles, their energy losses are assumed to be deposited in the shielding material in the form of heat. The production and transport of secondary particles from charged particles (such as bremsstrahlung photons generated by beta particles in the shielding materials) is also neglected. This assumption is valid if the energies and/or emission probabilities of secondary particles are negligible, compared to those of primary gamma rays.

The Zr/Nb-95 source is handled differently than the other radionuclides (the source spectra are combined). This is the case because the activity limit provided in Table 1-2, "*10 CFR 71.47(a) Activity Limits (All Isotopes Except Ir-192 and Ir-194) – All Models,*" and Table 1-2b, "*10 CFR 71.47(b) Activity Limits – Model AOS-100A and AOS-100A-S,*" for the parent/daughter isotope system (Zr/Nb-95) applies only to the parent isotope (Zr-95). The only source of Nb-95 in a shipment must be from a decay of Zr-95. Because this is the case, the maximum amount of Nb-95 relative to Zr-95 occurs when the isotopes are in equilibrium. By assuming Nb-95 exists in equilibrium with Zr-95 in any shipment, the total system activity is maximized. The parent and daughter's activity ratio at equilibrium is determined using Equation 5-2.

$$\frac{A_{\mathrm{Nb}}}{A_{\mathrm{Zr}}} = \frac{\lambda_{\mathrm{Nb}}}{\lambda_{\mathrm{Nb}} - \lambda_{\mathrm{Zr}}} = 2.20 \tag{5-2}$$

where:

A_{Nb} = Activity of Nb (daughter)

A_{Zr} = Activity of Zr (parent)

λ_{Nb} = Nb decay constant

λ_{Zr} = Zr decay constant

Thus, a maximum of 2.2 decays from Nb-95 occur for every one decay from Zr-95. Equation 5-2 is confirmed using basic Bateman equations. For conservatism, the total number of decays per Becquerel of Zr-95 is assumed to be the total from both Nb-95 and Zr-95. This is equivalent to 3.2 photons per Becquerel of Zr-95. The fact that the dominant decay energies from both isotopes are very close allows for the use of a single, bounding decay energy of 0.766 MeV to be assumed for the isotope mixture.

Table 5-23 and Table 5-29 in Appendix 5.5.2 list the source spectra used for Zr/Nb-95 in the shielding models.

The Ir-192/Ir-194 sources each use their own spectra, which is the same as the other radionuclides. Ir-192/Ir-194 are handled differently from the other radionuclides in post processing (the dose rates are combined). This is discussed in Section 5.4.4.

5.2.2 Neutron Source

Not applicable. Neutron-emitting materials are not authorized for this transport package design.

5.3 SHIELDING MODEL

5.3.1 Configuration of Source and Shielding

5.3.1.1 Cask Shielding

An explicit 3D cask model, representative of the dimensions tabulated in Table 5-1 and Table 5-2, was developed using the particle transport code *Monte Carlo N-Particle (MCNP6)*. Use of these nominal dimensions to define the shield model is consistent with standard engineering practices. The increase in possible dose rates, due to the small tolerances on these dimensions, is bounded by the 10% reduction in allowable dose limits described in Subsection 5.1.2. The impact limiter, shipping cage, and any internal or external shoring components were modeled as air, for conservatism. A sketch of the cask components modeled is provided in Figure 5-1. Tests applied to the packaging and their contents, under Normal conditions and Hypothetical Accident conditions of transport, demonstrated that the cask components modeled maintained their structural integrity for all considered events. This allowed a single geometric model to be developed for each cask size that is being considered. Figure 5-3 illustrates the base MCNP6 geometry used for modeling the AOS casks.

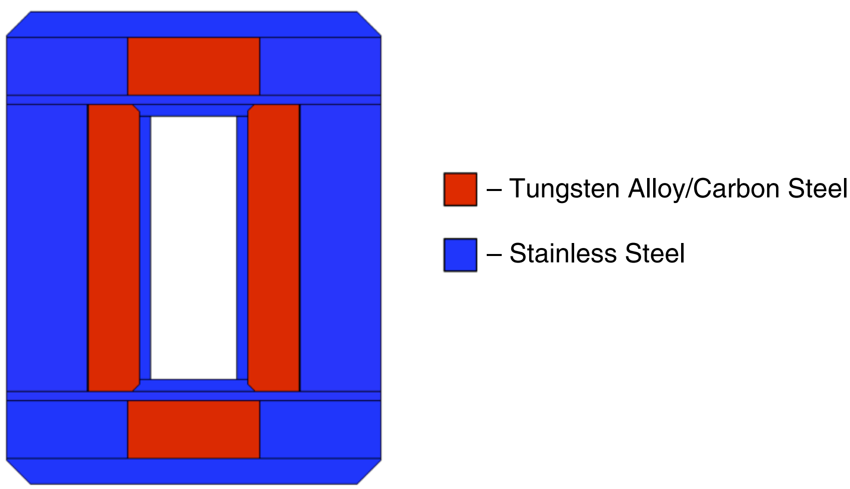

Figure 5-3. MCNP6 Geometry Model

5.3.1.2 Shielding/Spacer Components

Additional components have been designed to allow for activity limits that are desired for each cask. These additional components, for each cask size (Models AOS-025, AOS-050, and AOS-100), are placed inside the cask cavity to provide additional shielding and/or spacing, depending on the model. Table 5-7 summarizes the additional components that are used for each cask. All additional components are modeled in MCNP6 per the dimensions in their respective certification drawings. (Refer to Table 1-5, "AOS Transport Packaging System Certification Drawing List – All Models.")

For all isotopes transported in the Model AOS-025, the tungsten alloy liner shown in certification drawing 183C8485 must be used. The contents to be shipped are loaded into the liner, which is then closed and loaded into the Model AOS-025. The stress analysis for this tungsten alloy liner is presented in Paragraph 2.5.3.3.1, "Stress Analysis of Cavity Liner – Model AOS-025," where it is demonstrated that the liner is capable of surviving any Normal or Hypothetical Accident conditions of transport.

For shipments of Ir-192 and Ir-194 in the Model AOS-050, the stainless steel axial shielding plates shown in certification drawing 183C8519 are used. For this configuration, the contents are loaded into the Model AOS-050 cavity in between the two axial shielding plates so that the plates provide shielding and spacing for dose rates exiting the cask's top and bottom. The MCNP6 models for this configuration include a 3/8-in. hole through each plate's center in consideration of penetrations that will be needed for handling (such as a screw hole). Although the hole in the shielding model is through the entire plate, a requirement for loading the plates is that this screw hole must be filled with a setscrew during shipment. The structural evaluation for the Model AOS-050 axial shielding plates is provided in Paragraph 2.12.15.4, "Axial Shielding Plate Stress Evaluation – Model AOS-050A," where it is demonstrated that the plates are capable of surviving any Normal or Hypothetical Accident conditions of transport. However, for the Model AOS-050 shielding analysis, it is assumed that these stainless steel axial shielding plates are destroyed in Hypothetical Accident conditions of transport and no credit is taken for additional spacing or shielding provided.

For Co-60-B quantities of material in Models AOS-100A and AOS-100A-S, the tungsten alloy axial shielding plates in certification drawing 183C8491 are used. For this configuration, the contents are loaded in the Model AOS-100A/AOS-100A-S cavity, between the two axial shielding plates, so that the plates provide shielding and spacing for dose rates exiting the cask's top and bottom. The structural evaluation for the Model AOS-100A/AOS-100A-S axial shielding plates is provided in Paragraph 2.12.15.5, "Axial Shielding Plate Stress Evaluation – Models AOS-100A and AOS-100A-S," where it is demonstrated that the plates are capable of surviving any Normal or Hypothetical Accident conditions of transport.

For Co-60-C quantities of material in Models AOS-100A and AOS-100A-S, the stainless steel or aluminum cavity spacer plates shown in certification drawing 183C8518 and the tungsten alloy axial shielding plates shown in certification drawing 183C8491 are used. For this configuration, the contents are loaded in the Model AOS-100A/AOS-100A-S cavity, between the two axial shielding plates, with the cavity spacer plates loaded outside the axial shielding plates, such that the cavity spacer plates provide spacing between the axial shielding plates and the cask cavity's top or bottom. The cavity spacer plate materials of construction (stainless steel or aluminum) are based solely on their structural integrity. In the shielding analysis, no credit is taken for the cavity spacer plate material, only the additional distance provided. The structural evaluation for the Model AOS-100A/AOS-100A-S axial shielding plates is provided in Paragraph 2.12.15.5, "Axial Shielding Plate Stress Evaluation – Models AOS-100A and AOS-100A-S," where it is demonstrated that the axial shielding plates are capable of surviving any Normal or Hypothetical Accident conditions of transport. The structural evaluation for the Model AOS-100A/AOS-100A-S cavity spacer plates is provided in Paragraph 2.12.15.6, "Cavity Spacer Plate Stress Evaluation – Models AOS-100A and AOS-100A-S," where it is demonstrated that the cavity spacer plates are capable of surviving any Normal or Hypothetical Accident conditions of transport. However, for the shielding analysis, it is assumed that the cavity spacer plates are destroyed in Hypothetical Accident conditions of transport and no credit is taken for additional spacing provided.

Table 5-7. AOS Cask Components – All Models

<table>
<tr><th rowspan="2">Model</th><th rowspan="2">Isotope</th><th rowspan="2">Certification Drawing</th><th rowspan="2">Construction Material</th><th colspan="2">Radial Dimension[a]</th><th colspan="2">Axial Dimension[b]</th></tr>
<tr><th>cm</th><th>in.</th><th>cm</th><th>in.</th></tr>
<tr><td>AOS-025</td><td>All</td><td>Liner (183C8485)</td><td>Tungsten Alloy</td><td>1.40</td><td>0.55</td><td>2.15</td><td>0.85</td></tr>
<tr><td>AOS-050</td><td>Ir-192/Ir-194</td><td>Axial Shielding Plates (183C8519)</td><td>Stainless Steel</td><td>3.81</td><td>1.50</td><td>3.81</td><td>1.50</td></tr>
<tr><td rowspan="3">AOS-100A
AOS-100A-S</td><td>Co-60-B</td><td>Axial Shielding Plates (183C8491)</td><td>Tungsten Alloy</td><td>8.10</td><td>3.19</td><td>3.81</td><td>1.50</td></tr>
<tr><td rowspan="2">Co-60-C</td><td>Axial Shielding Plates (183C8491)</td><td>Tungsten Alloy</td><td>8.10</td><td>3.19</td><td>3.81</td><td>1.50</td></tr>
<tr><td>Cavity Spacer Plates (183C8518)</td><td>Stainless Steel –or– Aluminum</td><td>8.10</td><td>3.19</td><td>4.62</td><td>1.82</td></tr>
</table>

a. *For the AOS-025 liner, this dimension refers to the radial thickness of tungsten alloy provided by the liner. For all cavity spacer and axial shielding plates, this dimension refers to the plate's radius.*

b. *For the AOS-025 liner, this dimension refers to the axial thickness of tungsten alloy provided individually by the liner top or bottom. For all cavity spacer and axial shielding plates, this dimension refers to the plate's thickness.*

5.3.1.3 Sources

All isotopes, except for the Co-60-C configuration, are modeled as point sources at the locations listed in Table 5-8 and identified in Figure 5-4.Each point source location is analyzed for Normal conditions and Hypothetical Accident conditions of transport. Point sources do not account for self-shielding effects due to the actual source geometry and density or for shielding due to internal components, such as source racks. By placing the point sources in these locations, the most restrictive source locations are analyzed. An actual radioactive load in the container is distributed over significantly more volume than a point source, thereby providing margin for the activity limits calculated using point sources. The point source model provides assurance that the dose rate, at locations fairly close to the source, is over-estimated. Dose rates obtained from the point source model bound the transport packages in their as-shipped configuration.

The Co-60-C corner source dose rate calculation is the only exception to this point source modeling. For this case, the source is modeled as a small volume. With a source activity, a specific activity limit, and a material density, the minimum volume through which the source would occupy is calculated. For this source configuration, it is assumed that all Cobalt material in the cask collects in the worst-case geometry – in the cask's top corner. Appendix 5.5.4 provides further details regarding source volume modeling for the Co-60-C configuration and worst-case source geometry determination.

Table 5-8. Point Source Locations[a]

Point Source Location Label	Location
Top Source	Center of the cask cavity's top edge, used for axial cases (Z axis, positive direction).
Side Source	Center of the cask cavity's radial edge, used for radial cases (Y axis, positive direction).
Corner Source	Top corner of the usable cask cavity, used for axial and radial assessment.

a. Figure 5-4 identifies each point source location.

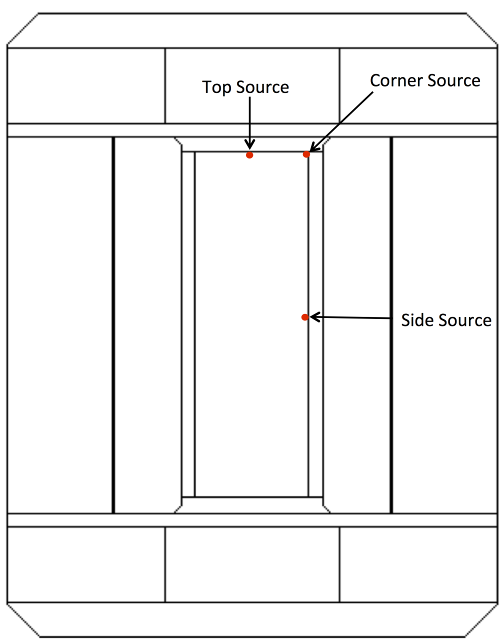

Figure 5-4. MCNP6 Point Source Locations

5.3.1.4 Tallies

Dose rates are calculated using cell tallies to determine the region of the regulatory dose rate location with the peak particle flux, and show the surrounding distribution. For the **Top Source** location, the tally cells are modeled as 1-cm-tall cylinders, increasing in radius, that are rotationally symmetric about the Z axis. Tor the **Side Source** location, the tally cells are modeled as 1-cm-thick arcs with an internal angle of 10° from the cask center. For the **Corner Source** location, the axial and radial external surface tallies are extended to the point at which they meet, and the 1-m (40-in.) transport index and 1m (40 in.) Hypothetical Accident conditions of transport tally cells are curved such that every cell is 1m (40 in.) from the respective surface (that is, impact limiter or cask). Figure 5-5 through Figure 5-7 illustrate the MCNP6 models for the top, side, and corner source locations, respectively, with the tally cells labeled for the External Surface, HAC, and Transport Index dose rate calculations. From these figures, the dimensions ES_{ax} and ES_{rad} are defined in Table 5-11 and Table 5-12. It can be noted from these figures that the tally locations used neglect certain transport packaging and impact limiter features. Specifically, for the transport package surface and 1-m TI locations, the gap between the upper and lower impact limiters in Models AOS-050A, AOS-100A, AOS-100A-S, and AOS-100B, and the recessed region at the axial ends of the impact limiters in every shipping cask model. Because the transport package surface is defined as “all exposed shipping cask and impact limiter surfaces,” a detailed analysis of these tally locations is addressed in Appendix 5.5.8.

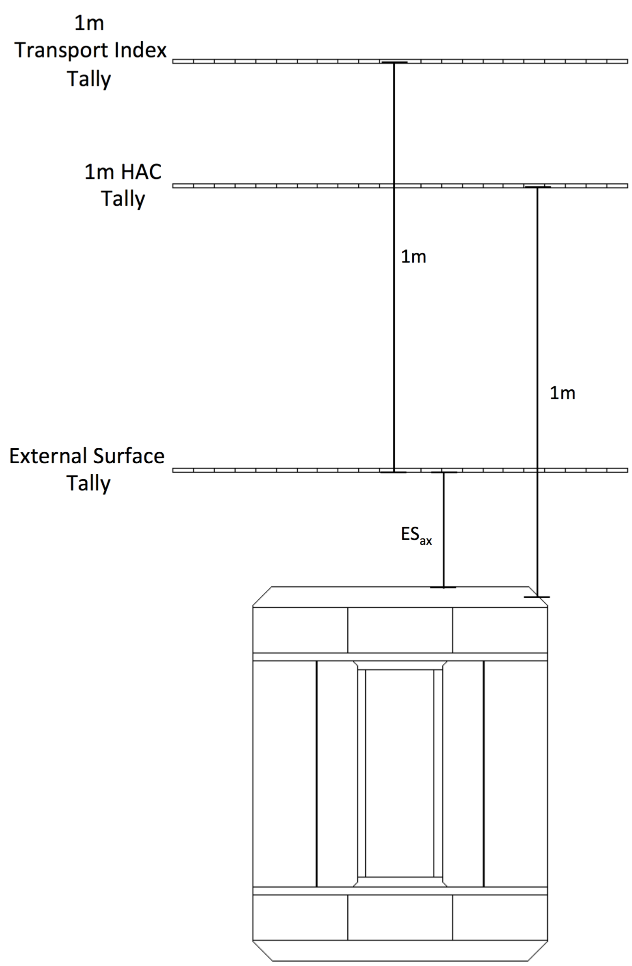

Figure 5-5. Shielding Model Tallies for Top Source Location

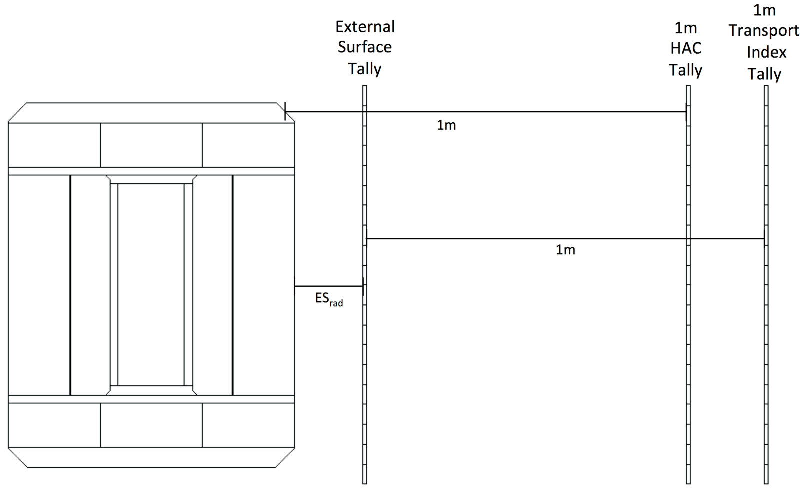

Figure 5-6. Shielding Model Tallies for Side Source Location

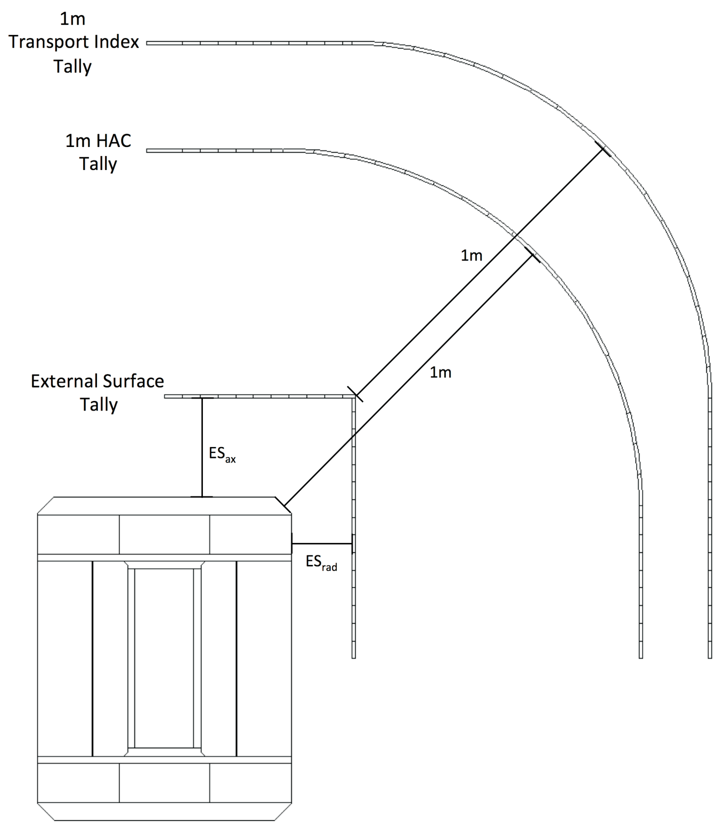

Figure 5-7. Shielding Model Tallies for Corner Source Location

The selection of dose rate locations is based on the impact limiter's deformed surface, which is considered the external package surface under Normal conditions of transport, except as analyzed in Appendix 5.5.8. The impact limiter's crushed and deformed surface creates the closest accessible area during transit and, therefore, is used to calculate the dose rate from radioactive contents under Normal conditions of transport. The maximum deformations in the impact limiter surfaces resulting from an End Drop (axial direction) or Side Drop (radial direction) consistent with Normal conditions of transport are provided in Chapter 2, "Structural Evaluation," for all AOS transport package models. The external surface deformations used in dose calculations, as provided in Table 5-9 and Table 5-10, bound the maximum end and side deformations. For the corner source case, the cumulative deformation from a Normal conditions of transport side and end drop is included for the tally locations.

Table 5-11 and Table 5-12 define the distances from the cask center to the dose rate locations that are used to evaluate the external surface radiation levels, and 1m (40 in.) from the cask and from the external surface.

Table 5-9. External Surface Deformation Used for Dose Calculation in Axial Direction – End Drop

Model	Impact Limiter Half-Height		Impact Limiter End Drop Deformation		Deformed Impact Limiter Half-Height	
	cm	in.	cm	in.	cm	in.
AOS-025	20.64	8.13	1.52	0.60	19.11	7.53
AOS-050	40.23	15.84	3.81	1.50	36.27	14.34
AOS-100	80.42	31.66	6.60	2.60	73.81	29.06

Table 5-10. External Surface Deformation Used for Dose Calculation in Radial Direction – Side Drop

Model	Impact Limiter Radius		Impact Limiter Side Drop Deformation		Deformed Impact Limiter Radius	
	cm	in.	cm	in.	cm	in.
AOS-025	14.42	5.68	0.97	0.38	13.45	5.30
AOS-050	28.84	11.36	3.05	1.20	25.79	10.16
AOS-100	57.71	22.72	5.08	2.00	52.63	20.72

Table 5-11. Distances from Center of Cask Used for Dose Calculations – Axial Location

Model	External Surface[a] (ES_{ax})		1m from Cask Surface		1m from External Surface[a]	
	cm	in.	cm	in.	cm	in.
AOS-025	19.11	7.53	110.85	43.64	119.11	46.90
AOS-050	36.42	14.34	121.70	47.92	136.42	53.71
AOS-100	73.81	29.06	143.41	56.46	173.81	68.43

a. For this analysis, the external surface is considered to be deformed.

Table 5-12. Distances from Center of Cask Used for Dose Calculations – Radial Location

Model	External Surface[a] (ES_{rad})		1m from Cask Surface		1m from External Surface[a]	
	cm	in.	cm	in.	cm	in.
AOS-025	13.45	5.30	108.31	42.64	113.45	44.67
AOS-050	25.79	10.16	116.62	45.91	125.79	49.53
AOS-100	52.63	20.72	133.25	52.46	152.63	60.09

a. For this analysis, the external surface is considered to be deformed.

5.3.2 Material Properties

Material compositions and densities used in the AOS casks are provided in Table 5-3. All material compositions are modeled in the shielding evaluation, as prescribed in Table 5-3.

5.4 SHIELDING EVALUATION

5.4.1 Methods

MCNP6 (Reference **[5.3]**), a general-purpose Monte Carlo N-Particle transport code developed by Los Alamos National Laboratory, is used to calculate the AOS cask dose rates. The code has the capability of simulating neutron, photon, electron, or coupled neutron/photon/electron transport, in an arbitrary 3D geometric configuration of materials.

MCNP6 for photon transport uses continuous-energy atomic data libraries (ENDF/B-VI.8) (Reference **[5.4]**) for all elements from Z = 1 through Z = 100. The data in the photon interaction tables allow MCNP6 to account for coherent and incoherent scattering, photoelectric absorption with the possibility of fluorescent emission, and pair production. Scattering angular distributions are modified by atomic form factors and incoherent scattering functions.

Important standard features that make MCNP6 versatile and easy to use for photon transport include a powerful general source, both geometry and output tally plotters, a rich collection of variance reduction techniques for heavy shielding problems, a flexible tally structure, and an extensive collection of cross-section data.

Use of MCNP6 for dose rate calculations in heavy shielding systems requires application of variance reduction techniques to obtain precise solutions in a timely manner. Correct implementation of variance reduction techniques yields the same solution with a similar statistical variance as an analog Monte Carlo simulation, but in a shorter amount of computer time.

The primary variance reduction techniques used in the MCNP6 modeling of AOS casks are:

- (1) Mesh-Based Weight Windows
- (2) Source Biasing
- (3) Exponential Transform

Each is described in the text that follows.

(1) Mesh-Based Weight Windows

Mesh-based weight window is one of particle population control methods available in MCNP6. This method helps keep the particle weight dispersion within reasonable bounds throughout the problem, by using particle splitting and roulette-style chance to control the quantity of particles taken in various regions of phase space. The mesh weight window generator makes it possible to generate an importance function, with respect to both an energy grid and/or a spatial grid that overlays the problem geometry. Particle splitting and roulette-style chance can then be played as a function of both particle position and energy.

A cylindrical or rectangular mesh is defined with various spatial resolutions in different regions, depending on the tally and the shielding material and location. To enhance the weight window generator's performance, the exponential transform and/or source biasing are used. In addition, the density reduction technique is applied to produce an initial importance function. Use of the initial importance function, with the shield density reset to its natural value, sufficiently improved the importance function through several iterations with reasonable Figure of Merit (FOM; a measure of how quickly the desired precision is achieved).

(2) Source Biasing

Source biasing is one of modified sampling methods that alter the statistical sampling of a problem to increase the quantity of tallies per particle. Source energy biasing is applied in the modeling, as needed.

Source energy biasing involves changing the source's emission energy. For some isotopes, their emission spectra have very low mean energies. It becomes extremely difficult to obtain any answer for low-energy photon transmission in a heavy shielding system. The source energy biasing used in the modeling favors the emission of source particles with higher energies, while adjusting the starting weight of each history, so that the total emitted weight of each energy line is conserved.

(3) Exponential Transform

Exponential transform is also one of modified sampling methods. Applying the exponential transform aids in the MCNP6 tally convergence by making it easier for particles to move in the desired direction by artificially reducing the cross-section in the preferred direction and then increasing the cross-section in the opposite direction. Depending on which direction the particle is travelling, its weight is adjusted so that the expected weight colliding at any tally cell is preserved. In the modeling, this method is used to allow particles more likely to enter a region containing tally cells.

5.4.2 Input and Output Data

5.4.2.1 Input Data

The MCNP6 input data includes:

- Cask's geometry and material description
- Source definition
- Variance reduction (mesh-based weight window, source biasing, and exponential transform
- Flux-to-dose rate conversion factors
- Tally cell locations

The mesh structure parameters for weight window generation and usage are defined by the MESH card in the input, which divides the transport package into coarse and fine subsections. The weight window generator calculates the importance values for subsections. These importance values are problem-dependent (that is, the importance values vary with system geometry and materials, as well as source characteristics, and most importantly the dose rate locations).

MCNP6 input and weight window files are submitted separately

5.4.2.2 Output Data

The MCNP6 output data includes dose rates per starting source photon (mrem/hour-photon) at specified locations and their relative errors. The relative error forms confidence intervals about the calculated dose rate. For cell tallies, a relative error less than 10% is required to produce generally reliable confidence intervals. All tallies in every MCNP6 output pass the 10 statistical checks required by MCNP6 for reliable dose rate estimations.

MCNP6 output files are submitted separately

5.4.3 Flux-to-Dose-Rate Conversion

The dose rate is determined by using flux-to-dose-rate conversion factors, which convert the tally cell flux (particles/cm^2) to the dose rate (mrem/hr). Conversion factors from *ANSI/ANS-6.1.1 1977* (Reference **[5.5]**) are used to obtain the gamma-ray dose rate. The conversion is implemented in MCNP6 by dose rate energy and dose rate function cards (Reference **[5.3]**). The calculated dose rates are normalized values per starting source particle. By also using the tally multiplier card, all tally results are multiplied by 3.7E10 so that the results are normalized per the isotope's curie level. (Refer to Equation 5-5.)

The tally cells are used to obtain the particle flux at the dose calculation points. The tally cell units are in particles per square centimeter. In this analysis, gamma rays are the particles of interest. The particle flux calculated at the dose rate locations can then be used to calculate the limiting curie content that maintains all dose rate values below the regulated values, at all surfaces.

5.4.4 External Radiation Levels

The bounding limit for an isotope is found by determining the curie level that, if any greater, would just exceed the regulatory limits at any one of the regulatory dose rate locations. A margin was added to the final dose rate limits to provide additional assurance that the regulatory dose rate limits will not be exceeded. For this additional margin, the final values were calculated to only 90% of the regulatory dose rate limits:

- 200 mrem/hr limit at the external surface became a 180 mrem/hr limit
- 1m from the external surface for Normal conditions of transport limit became a 9 mrem/hr limit
- 1m from the cask surface for Hypothetical Accident conditions of transport limit became a 900 mrem/hr limit

This methodology provides additional margin to ensure that the cask contents do not exceed the regulatory dose rate limits.

The maximum allowable curie level for each isotope is calculated using Equations 5-3, 5-4, and 5-5. First, the MCNP6 output [$\text{Tally}_{\text{out}}$] for each isotope and dose rate location is converted to units of mrem/hr-Ci, using Equation 5-3.

$$\text{Dose}\left[\frac{\frac{\text{mrem}}{\text{hr}}}{\text{Ci}}\right] = \text{Tally}_{\text{out}}\left[\frac{\frac{\text{mrem}}{\text{hr}}}{\text{photon}}\right] * \left[\frac{\text{photons}}{\text{Bq}}\right] * 3.7\text{E}10\left[\frac{\text{Bq}}{\text{Ci}}\right]$$

(5-3)

To provide assurance that the statistically calculated dose rate bounds the true dose rate, the calculated dose rate is increased by two times the error (2σ) to this term, as is done in Equation 5-4.

$$\text{Dose}_{+2\text{sig}}\left[\frac{\frac{\text{mrem}}{\text{hr}}}{\text{Ci}}\right] = \text{Dose}\left[\frac{\frac{\text{mrem}}{\text{hr}}}{\text{Ci}}\right] + \text{Dose}\left[\frac{\frac{\text{mrem}}{\text{hr}}}{\text{Ci}}\right] * 2\sigma$$

(5-4)

The maximum source strength that will meet the regulatory dose rate limit at the location being analyzed is then calculated using Equation 5-5.

$$\text{Source}_{\text{Max}}[\text{Ci}] = \frac{0.9 * \text{Dose}_{\text{Limit}}\left[\frac{\text{mrem}}{\text{hr}}\right]}{\text{Dose}_{+2\text{sig}}\left[\frac{\frac{\text{mrem}}{\text{hr}}}{\text{Ci}}\right]}$$

(5-5)

For shipments of Ir-192, there is a strong possibility that there will be Ir-194 impurities included in the source. For this case, the total dose rate is calculated as the summed dose rate contributions from the activities of both Ir-192 and Ir-194, as shown in Equation 5-6.

$$0.9 * \mathrm{Dose}_{\mathrm{Total}}\left[\frac{\mathrm{mrem}}{\mathrm{hr}}\right] = \mathrm{Dose}^{192}_{+2\mathrm{sig}}\left[\frac{\frac{\mathrm{mrem}}{\mathrm{hr}}}{\mathrm{Ci}}\right] * \mathrm{A}^{192}[\mathrm{Ci}] + \mathrm{Dose}^{194}_{+2\mathrm{sig}}\left[\frac{\frac{\mathrm{mrem}}{\mathrm{hr}}}{\mathrm{Ci}}\right] * \mathrm{A}^{194}[\mathrm{Ci}]$$

(5-6)

The maximum allowable source strength of Ir-192 is calculated for multiple Ir-194 impurity levels by selecting an Ir-194 activity, A^{194}, and solving Equation 5-6 for A^{192}, as shown in Equation 5-7.

$$\mathrm{A}^{192}[\mathrm{Ci}] = \frac{0.9 * \mathrm{Dose}_{\mathrm{Total}}\left[\frac{\mathrm{mrem}}{\mathrm{hr}}\right] - \mathrm{Dose}^{194}_{+2\mathrm{sig}}\left[\frac{\frac{\mathrm{mrem}}{\mathrm{hr}}}{\mathrm{Ci}}\right] * \mathrm{A}^{194}[\mathrm{Ci}]}{\mathrm{Dose}^{192}_{+2\mathrm{sig}}\left[\frac{\frac{\mathrm{mrem}}{\mathrm{hr}}}{\mathrm{Ci}}\right]}$$

(5-7)

The maximum curie content of each isotope at each dose rate location is solved for using the approaches outlined above. Results are then tabulated, and the minimum of the source values obtained is reported as the maximum source strength viable for shipment based on dose rate limits. The dose rates based on these source values for locations of interest are reported in Table 5-13 through Table 5-20.

A single model (identical geometry and source specifications) is used for both Normal conditions and Hypothetical Accident conditions of transport simulations. The dose rates reported are applicable to both scenarios.

The following dose rate limits are met for all isotopes, in compliance with *10 CFR 71.47(a)* and *71.51(a)(2)* (Reference **[5.1]**; Normal conditions and Hypothetical Accident conditions of transport, respectively):

- Surface limit of 200 mrem/hr (2mSv/h) on the transport package surface to comply with Normal conditions of transport limits
- Limit of 1,000 mrem/hr (10 mSv/h) at 1m from the cask surface to comply with Hypothetical Accident conditions of transport limits
- Limit of 10 mrem/hr at 1m from the transport package surface to comply with Normal conditions of transport limits

For the activity limits of all individual isotopes other than Ir-192 and Ir-194, refer to Table 1-2, *"10 CFR 71.47(a) Activity Limits (All Isotopes Except Ir-192 and Ir-194) – All Models."* For the activity limits of Ir-192 sources with Ir-194 impurities, refer to Table 1-2a, *"10 CFR 71.47(a) Ir-192 and Ir-194 Activity Limits – All Models."*

Shipment Transportation Index (TI) can be calculated by using the highest dose at 1m from the deformed impact limiter or shipping cask surface, for each isotope and transport package combination. These numbers are defined in Table 5-13 through Table 5-20. The dose rates reported result in a single package always having a TI less than 10, allowing for non-exclusive shipment of a single cask. If multiple casks are shipped together, their respective TI values must be summed to determine whether their shipment must be for exclusive or non-exclusive use.

Table 5-13. Maximum Radiation Levels (All Isotopes Except Ir-192 and Ir-194)[a] – Model AOS-025A

Isotope	Source Strength (Ci)	Photon/Bq	Location	Maximum Dose Rate/ Curie (mrem/hr/ Ci)	Peak Dose Rate (mrem/hr)	Limit (mrem/hr)	Shipping Configuration
Co-60	1.33E-01	1.9986	External Surface	1.355E+03	180.00	200	Use of Tungsten Alloy Liner (183C8485) is required
			1m from Cask Surface	1.879E+01	2.50	1,000	
			1m from External Surface	1.713E+01	2.28	10	
Cs-137	1.00E+01	0.9811	External Surface	1.800E+01	180.00	200	
			1m from Cask Surface	3.252E-01	3.25	1,000	
			1m from External Surface	2.835E-01	2.83	10	
Yb-169	1.59E+05	3.7623	External Surface	1.131E-03	180.00	200	
			1m from Cask Surface	2.307E-05	3.67	1,000	
			1m from External Surface	1.995E-05	3.18	10	

a. Refer to Table 5-17 for Ir-192 and Ir-194 maximum radiation levels.

Table 5-14. **Maximum Radiation Levels (All Isotopes Except Ir-192 and Ir-194)[a] – Model AOS-050A**

Isotope	Source Strength (Ci)	Photon/Bq	Location	Maximum Dose Rate/ Curie (mrem/hr/ Ci)	Peak Dose Rate (mrem/hr)	Limit (mrem/hr)	Shipping Configuration
Co-60	7.47E-01	1.9986	External Surface	2.410E+02	180.0	200	No Additional Components
			1m from Cask Surface	1.178E+01	8.80	1,000	
			1m from External Surface	8.837E+00	6.60	10	
Cs-137[b]	1.72E+01	0.9811	External Surface	1.044E+01	179.5	200	
			1m from Cask Surface	3.926E-01	6.75	1,000	
			1m from External Surface	2.933E-01	5.04	10	
Hf-181[b]	7.66E+01	1.8501	External Surface	2.349E+00	180.0	200	
			1m from Cask Surface	7.598E-02	5.82	1,000	
			1m from External Surface	5.774E-02	4.42	10	
Zr/Nb-95[b]	2.66E+00	3.2000	External Surface	6.768E+01	180.0	200	
			1m from Cask Surface	2.755E+00	7.33	1,000	
			1m from External Surface	2.068E+00	5.50	10	
Yb-169[b]	7.77E+03	3.7623	External Surface	2.317E-02	180.0	200	
			1m from Cask Surface	7.277E-04	5.65	1,000	
			1m from External Surface	5.804E-04	4.51	10	

a. *Refer to Table 5-18 for Ir-192 and Ir-194 maximum radiation levels.*

b. *Transport package surface dose rate and activity limit values from Appendix 5.5.8.2, Table 5-53.*

Table 5-15. Maximum Radiation Levels (All Isotopes Except Ir-192 and Ir-194)[a b] – Models AOS-100A and AOS-100A-S

Isotope	Source Strength (Ci)	Photon/ Bq	Location	Maximum Dose Rate/ Curie (mrem/hr/Ci)	Peak Dose Rate (mrem/hr)	Limit (mrem/hr)	Shipping Configuration
Co-60	2.73E+02	1.9986	External Surface	3.912E-01	106.95	200	No Liner
			1m from Cask Surface	5.545E-02	15.16	1,000	
			1m from External Surface	3.292E-02	9.00	10	
Co-60-B	8.23E+02	1.9986	External Surface	1.139E-01	93.77	200	Use of Tungsten Alloy Axial Shielding Plates (183C8491) is required
			1m from Cask Surface	1.833E-02	15.09	1,000	
			1m from External Surface	1.093E-02	9.00	10	
Co-60-C	9.63E+03	1.9986	External Surface[c]	1.868E-02	180.0	200	Use of Tungsten Alloy Axial Shielding Plates (183C8491) and Cavity Spacer Plates (183C8518) are required
			1m from Cask Surface[d]	1.833E-02	370.27	1,000	
			1m from External Surface[c]	5.314E-04	5.12	10	
Cs-137	3.50E+04	0.9811	External Surface	3.188E-03	111.63	200	–
			1m from Cask Surface	4.152E-04	14.54	1,000	
			1m from External Surface[e]	2.570E-04	9.00	10	
Hf-181	4.12E+05	1.8501	External Surface	2.595E-04	107.04	200	
			1m from Cask Surface	3.413E-05	14.08	1,000	
			1m from External Surface[e]	2.182E-05	9.00	10	
Zr/Nb-95	3.50E+03	3.2000	External Surface	3.098E-02	108.44	200	
			1m from Cask Surface	4.106E-03	14.37	1,000	
			1m from External Surface[e]	2.571E-03	9.00	10	

a. *Refer to Table 5-19 for Ir-192 and Ir-194 maximum radiation levels.*

b. *Higher activity limits are permissible when transporting exclusive use. Refer to Appendix 5.5.7.*

c. *Marked dose rate values from Appendix 5.5.8.1, Table 5-46.*

d. *Dose rates based on Co-60-B configuration, assuming that only the tungsten alloy axial shielding plates survive Hypothetical Accident conditions of transport.*

e. *Dose rate/curie values from Appendix 5.5.8.2, Table 5-56.*

Table 5-16. Maximum Radiation Levels (All Isotopes Except Ir-192 and Ir-194)[a] – Model AOS-100B

Isotope[b]	Source Strength (Ci)	Photon/Bq	Location	Maximum Dose Rate/ Curie (mrem/hr/ Ci)	Peak Dose Rate (mrem/hr)	Limit (mrem/hr)	Shipping Configuration
Co-60	9.89E+00	1.9986	External Surface	9.217E+00	91.16	200	No Additional Components
			1m from Cask Surface	1.358E+00	13.43	1,000	
			1m from External Surface	9.098E-01	9.00	10	
Cs-137	5.29E+02	0.9811	External Surface	1.871E-01	98.98	200	
			1m from Cask Surface	2.515E-02	13.31	1,000	
			1m from External Surface	1.694E-02	8.96	10	
Hf-181	3.99E+03	1.8501	External Surface	2.527E-02	100.87	200	
			1m from Cask Surface	3.354E-03	13.38	1,000	
			1m from External Surface	2.256E-03	9.00	10	
Zr/Nb-95	6.65E+01	3.2000	External Surface	1.459E+00	96.95	200	
			1m from Cask Surface	2.000E-01	13.29	1,000	
			1m from External Surface	1.355E-01	9.00	10	

a. *Refer to Table 5-20 for Ir-192 and Ir-194 maximum radiation levels.*

b. *Activity limit and 1-m external surface dose rate/curie values from Appendix 5.5.8.2, Table 5-59.*

Table 5-17. Maximum Ir-192/Ir-194 Radiation Levels – Model AOS-025A

A_{194} (Ci)	A_{192} (Ci)	Location	DR_{194} (mrem/hr/Ci)	DR_{192} (mrem/hr/Ci)	Total Dose Rate (mrem/hr)	Limit (mrem/hr)	Total Thermal Power (W)	Shipping Configuration
0.5	71.52	External Surface	1.367E+01	2.421E+00	180.00	200	0.44	Use of Tungsten Alloy Liner 183C8485 is required
		1m from Cask Surface	1.920E-01	4.875E-02	3.58	1,000		
		1m from External Surface	1.734E-01	4.259E-02	3.13	10		
2.0	63.04	External Surface	1.367E+01	2.421E+00	180.00	200	0.40	
		1m from Cask Surface	1.920E-01	4.875E-02	3.46	1,000		
		1m from External Surface	1.734E-01	4.259E-02	3.03	10		
3.0	57.40	External Surface	1.367E+01	2.421E+00	180.00	200	0.37	
		1m from Cask Surface	1.920E-01	4.875E-02	3.37	1,000		
		1m from External Surface	1.734E-01	4.259E-02	2.96	10		

Table 5-18. Maximum Ir-192/Ir-194 Radiation Levels – Model AOS-050A

A_{194} (Ci)	A_{192} (Ci)	Location	DR_{194} (mrem/hr/Ci)	DR_{192} (mrem/hr/Ci)	Total Dose Rate (mrem/hr)	Limit (mrem/hr)	Total Thermal Power (W)	Shipping Configuration
10	1,009	External Surface[a b]	1.150E+00	1.669E-01	180.00	200	6.24	Use of Axial Shielding Plates 183C8519 is required
		1m from Cask Surface[c]	1.334E-01	1.042E-01	106.54	1,000		
		1m from External Surface	2.628E-02	6.286E-03	6.61	10		
20	940	External Surface[a b]	1.150E+00	1.669E-01	180.00	200	5.87	
		1m from Cask Surface[c]	1.334E-01	1.042E-01	100.69	1,000		
		1m from External Surface	2.628E-02	6.286E-03	6.44	10		
40	802	External Surface[a b]	1.150E+00	1.669E-01	180.00	200	5.13	
		1m from Cask Surface[c]	1.334E-01	1.042E-01	89.00	1,000		
		1m from External Surface	2.628E-02	6.286E-03	6.10	10		
60	665	External Surface[a b]	1.150E+00	1.669E-01	180.00	200	4.39	
		1m from Cask Surface[c]	1.334E-01	1.042E-01	77.30	1,000		
		1m from External Surface	2.628E-02	6.286E-03	5.76	10		
80	527	External Surface[a b]	1.150E+00	1.669E-01	180.00	200	3.66	
		1m from Cask Surface[c]	1.334E-01	1.042E-01	65.61	1,000		
		1m from External Surface	2.628E-02	6.286E-03	5.42	10		
100	389	External Surface[a b]	1.150E+00	1.669E-01	180.00	200	2.92	
		1m from Cask Surface[c]	1.334E-01	1.042E-01	53.91	1,000		
		1m from External Surface	2.628E-02	6.286E-03	5.08	10		

a. *Isotopes have different bounding locations (Ir-192 – Corner; Ir-194 – Side); however, the bounding location is used for each.*

b. *Dose rate values from Appendix 5.5.8 (Ir-192 – Table 5-53; Ir-194 – Table 5-46).*

c. *Dose rates calculated excluding stainless steel axial shielding plates, assuming that they do not survive Hypothetical Accident conditions of transport.*

Table 5-19. Maximum Ir-192/Ir-194 Radiation Levels – Models AOS-100A and AOS-100A-S

A_{194} (Ci)	A_{192} (Ci)	Location	DR_{194} (mrem/hr/Ci)	DR_{192} (mrem/hr/Ci)[a]	Total Dose Rate (mrem/hr)	Limit (mrem/hr)	Total Thermal Power (W)	Shipping Configuration
4,000	61,794.45	External Surface	4.502E-03	5.802E-04	53.86	200	400.00	No additional shielding is required
		1m from Cask Surface	6.536E-04	7.547E-05	7.28	1,000		
		1m from External Surface	3.871E-04	4.898E-05	4.58	10		
10,000	56,606.85	External Surface	4.502E-03	5.802E-04	77.86	200	400.00	
		1m from Cask Surface	6.536E-04	7.547E-05	10.81	1,000		
		1m from External Surface	3.871E-04	4.898E-05	6.64	10		

a. 1-m from external surface dose rate/curie values from Appendix 5.5.8.2, Table 5-56.

Table 5-20. Maximum Ir-192/Ir-194 Radiation Levels – Model AOS-100B

A_{194} (Ci)	A_{192} (Ci)	Location	DR_{194} (mrem/hr/Ci)[a]	DR_{192} (mrem/hr/Ci)[a]	Total Dose Rate (mrem/hr)	Limit (mrem/hr)	Total Thermal Power (W)	Shipping Configuration
100	2,176.85	External Surface	1.016E-01	4.084E-02	99.05	200	13.87	No additional shielding is required
		1m from Cask Surface	1.502E-02	5.431E-03	13.32	1,000		
		1m from External Surface	1.003E-02	3.674E-03	9.00	10		
230	1,821.94	External Surface	1.016E-01	4.084E-02	97.77	200	12.39	
		1m from Cask Surface	1.502E-02	5.431E-03	13.35	1,000		
		1m from External Surface	1.003E-02	3.674E-03	9.00	10		

a. 1-m from external surface dose rate/curie values from Appendix 5.5.8.2, Table 5-59.

5.5 APPENDIX

This appendix presents the following information:

- AOS Cask Isotopic Heat Load Calculations
- Isotope Values for Calculations
- MCNP6 Input and Output Files for Dose Calculations
- Cobalt-60-C Volume Source Calculation Study
- Shipments of Multiple Isotopes under *10 CFR 71.47(a)*
- Isotopes Insignificant to External Dose Rates
- *10 CFR 71.47(b) Exclusive Use Activity Limits for Models AOS-100A and AOS-100A-S*
- Evaluation of Dose Rate Tally Locations

5.5.1 AOS Cask Isotopic Heat Load Calculations

Table 5-21 provides the decay heat values generated from SCALE 6.1 ORIGEN **[5.2]** decay library *origen.rev03.decay.data* for each isotope analyzed in this chapter. This library provides a Q value, in MeV/disintegration, for each isotope. For each isotope, Table 5-21 also provides the isotope identifier and Q value in the ORIGEN decay library.

For Cs-137, it is assumed that this isotope is combined with Ba-137m (due to the short half-life of Ba-137m). As a result, the heat load for Cs-137 is calculated using the Cs-137 and Ba-137m Q-value sum.

To be consistent with the shielding evaluation supporting Zr/Nb-95, the heat load is determined by multiplying the higher Q value of the two isotopes (Zr-95 as seen in Table 5-21) by a factor of 3.2. The resulting value is 1.62E-02 W/Ci for Zr/Nb-95.

Table 5-22 summarizes the final heat load values applicable to the isotopes analyzed in this chapter. These values, along with the respective cask decay heat limits reported in Table 1-2, "*10 CFR 71.47(a) Activity Limits (All Isotopes Except Ir-192 and Ir-194) – All Models,*" Table 1-2a, "*10 CFR 71.47(a) Ir-192 and Ir-194 Activity Limits – All Models,*" and Table 1-2b, "*10 CFR 71.47(b) Activity Limits – Model AOS-100A and AOS-100A-S,*" are used to calculate activity limits based on heat loads. The heat load presented in Table 5-22 for each isotope is calculated as shown in Equation 5-8. Refer to Appendix 5.5.5 for the heat load calculations that are to be used for shipping multiple isotopes in Models AOS-100A and AOS-100A-S.

$$\text{Heat Load}\left[\frac{\text{W}}{\text{Ci}}\right] = \text{Q}\left[\frac{\text{MeV}}{\text{disintegration}}\right] * 1.60217 * 10^{-13}\left[\frac{\text{J}}{\text{MeV}}\right] * 3.7 * 10^{10}\left[\frac{\frac{\text{disintegrations}}{\text{s}}}{\text{Ci}}\right] \tag{5-8}$$

Table 5-21. AOS Cask Isotopic Heat Loads (Reference [5.2])

Isotope	Library Isotope Identifier *(origen.rev03.decay.data)*	Q Value (MeV/disintegration)
Co-60	270600	2.6006E+00
Cs-137	551370	1.7945E-01
Ba-137m	561371	6.6140E-01
Hf-181	721810	7.3010E-01
Ir-192	771920	1.0334E+00
Ir-194	771940	8.9387E-01
Zr-95	400950	8.5013E-01
Nb-95	410950	8.0900E-01
Yb-169	701690	4.3013E-01

Table 5-22. AOS Cask Isotopic Heat Load Results

Isotope	Heat Load (W/Ci)
Co-60	1.55E-02
Cs-137	4.99E-03
Hf-181	4.33E-03
Ir-192	6.13E-03
Ir-194	5.30E-03
Zr/Nb-95	1.62E-02
Yb-169	2.55E-03

5.5.2 Isotope Values for Calculations

Table 5-23. Isotope Photon per Decay – All Models

Isotope	Photons/Decay	Model		
		AOS-025	AOS-050	AOS-100
Co-60	1.9986	✔	✔	✔
Cs-137	0.9811	✔	✔	✔
Hf-181	1.8501		✔	✔
Ir-192	2.3591	✔	✔	✔
Ir-194	0.2141	✔	✔	✔
Zr/Nb-95	3.2000		✔	✔
Yb-169	3.7623	✔	✔	

Table 5-24. Co-60 Gamma Spectra Used in Shielding Models – All Models

Energy (MeV)	Absolute Probability of Emission per Decay	Model		
		AOS-025	AOS-050	AOS-100
7.5100E-04	1.6946E-06	✔	✔	✔
8.5234E-04	8.0550E-07			
8.7689E-04	1.3826E-08			
8.8364E-04	5.6638E-07			
7.4178E-03	3.1894E-05			
7.4358E-03	6.2286E-05			
8.2223E-03	3.9005E-06			
8.2246E-03	7.6481E-06			
8.2879E-03	3.3435E-09			
8.2881E-03	4.8594E-09			
3.4714E-01	7.5000E-05			
8.2610E-01	7.6000E-05			
1.1732E+00	9.9850E-01			
1.3325E+00	9.9983E-01			
2.1586E+00	1.2000E-05			
2.5057E+00	2.0000E-08			

Table 5-25. Cs-137 Gamma Spectra Used in Shielding Models – All Models

Energy (MeV)	Absolute Probability of Emission per Decay	Model		
		AOS-025	AOS-050	AOS-100
4.4700E-03	9.6595E-03	✔	✔	✔
3.1817E-02	2.1043E-02			
3.2194E-02	3.8387E-02			
3.6304E-02	3.6743E-03			
3.6378E-02	7.0939E-03			
3.7255E-02	2.2441E-03			
6.6166E-01	8.9900E-01			

Table 5-26. Hf-181 Gamma Spectra Used in Shielding Models – All Models

Energy (MeV)	Absolute Probability of Emission per Decay	Model		
		AOS-025	AOS-050	AOS-100
7.5803E-03	3.1170E-03	✔	✔	✔
8.1315E-03	3.7431E-02			
9.4239E-03	3.0249E-02			
1.0926E-02	4.5632E-03			
5.6402E-02	9.0128E-02			
5.7686E-02	1.5707E-01			
6.5104E-02	1.6811E-02			
6.5381E-02	3.2483E-02			
6.5763E-02	3.5211E-04			
6.5823E-02	4.4618E-04			
6.7104E-02	3.8016E-03			
6.7168E-02	7.3649E-03			
6.7323E-02	8.3999E-05			
6.7334E-02	1.0591E-04			
6.3000E-03	1.1511E-04			
1.3302E-01	4.3309E-01			
1.3626E-01	5.8523E-02			
1.3686E-01	8.6135E-03			
3.4593E-01	1.5118E-01			
4.7599E-01	7.0276E-03			
4.8218E-01	8.0500E-01			
6.1517E-01	2.3345E-03			
6.1866E-01	2.5035E-04			

Table 5-27. Ir-192 Gamma Spectra Used in Shielding Models – All Models

Energy (MeV)	Absolute Probability of Emission per Decay	Model		
		AOS-025	AOS-050	AOS-100
8.3025E-03	6.6719E-04	✔	✔	✔
8.8986E-03	7.6141E-03			
9.0571E-03	1.8748E-03			
9.4295E-03	1.9970E-02			
1.0425E-02	6.3780E-03			
1.1127E-02	1.8272E-02			
1.2198E-02	1.0622E-03			
1.3025E-02	3.1858E-03			
6.1642E-02	1.2211E-02			
6.3189E-02	2.1041E-02			
6.5302E-02	2.6539E-02			
6.7048E-02	4.5551E-02			
7.1276E-02	2.2846E-03			
7.1614E-02	4.4158E-03			
7.2021E-02	5.2499E-05			
7.2095E-02	6.5560E-05			
7.3520E-02	5.2604E-04			
7.3600E-02	1.0228E-03			
7.3769E-02	1.3000E-05			
7.3784E-02	1.6170E-05			
7.5593E-02	5.0098E-03			
7.5978E-02	9.6917E-03			
7.6403E-02	1.2217E-04			
7.6486E-02	1.5101E-04			
7.8011E-02	1.1680E-03			
7.8103E-02	2.2787E-03			
7.8282E-02	3.1008E-05			
7.8299E-02	3.8202E-05			
1.1040E-01	1.2200E-04			
1.3634E-01	1.9900E-03			
1.7698E-01	4.3000E-05			
2.0131E-01	4.7300E-03			
2.0579E-01	3.3400E-02			
2.8027E-01	9.0001E-05			

Table 5-27. Ir-192 Gamma Spectra Used in Shielding Models – All Models (Continued)

Energy (MeV)	Absolute Probability of Emission per Decay	Model		
		AOS-025	AOS-050	AOS-100
2.8327E-01	2.6600E-03	✔	✔	✔
2.9596E-01	2.8720E-01			
3.0846E-01	2.9680E-01			
3.1651E-01	8.2711E-01			
3.2917E-01	1.7400E-04			
3.7449E-01	7.2600E-03			
4.1647E-01	6.6900E-03			
4.2052E-01	6.9000E-04			
4.6807E-01	4.7810E-01			
4.8458E-01	3.1870E-02			
4.8530E-01	2.3000E-05			
4.8906E-01	4.3800E-03			
5.8858E-01	4.5170E-02			
5.9349E-01	4.2100E-04			
5.9941E-01	3.9000E-05			
6.0441E-01	8.2001E-02			
6.1246E-01	5.3400E-02			
7.0387E-01	5.3000E-05			
7.6580E-01	1.3000E-05			
8.8454E-01	2.9100E-03			
1.0615E+00	5.3000E-04			
1.0899E+00	1.2000E-05			
1.3782E+00	1.2000E-05			

Table 5-28. Ir-194 Gamma Spectra Used in Shielding Models – All Models

Energy (MeV)	Absolute Probability of Emission per Decay	Model		
		AOS-025	AOS-050	AOS-100
9.0557E-03	1.7306E-04	✔	✔	✔
9.4295E-03	1.8464E-03			
1.1127E-02	1.6826E-03			
1.3024E-02	2.9287E-04			
6.5302E-02	2.5064E-03			
6.7048E-02	4.2842E-03			
7.5593E-02	4.6947E-04			
7.5978E-02	9.0788E-04			
7.6403E-02	1.1443E-05			
7.6486E-02	1.4144E-05			
7.8011E-02	1.0940E-04			
7.8103E-02	2.1343E-04			
7.8282E-02	2.9043E-06			
7.8299E-02	3.5780E-06			
1.1140E-01	1.7030E-05			
2.0291E-01	3.0130E-05			
2.4483E-01	7.7290E-05			
2.9354E-01	2.5152E-02			
3.0074E-01	3.4846E-03			
3.2845E-01	1.3100E-01			
3.6487E-01	4.1134E-04			
4.8286E-01	4.5588E-04			
5.3017E-01	1.5851E-04			
5.8918E-01	1.4017E-03			
5.9429E-01	6.2487E-04			
6.0761E-01	3.9300E-05			
6.2129E-01	9.5630E-05			
6.2197E-01	3.3405E-03			
6.4515E-01	1.1751E-02			
6.9950E-01	2.4890E-05			
7.0055E-01	2.6200E-04			
8.1066E-01	2.4890E-05			
8.5712E-01	7.0740E-05			
8.5945E-01	1.7030E-05			

Table 5-28. Ir-194 Gamma Spectra Used in Shielding Models – All Models (Continued)

Energy (MeV)	Absolute Probability of Emission per Decay	Model		
		AOS-025	AOS-050	AOS-100
8.8998E-01	5.0566E-04	✔	✔	✔
9.2526E-01	1.2576E-04			
9.3869E-01	5.9867E-03			
1.0001E+00	4.6505E-04			
1.0486E+00	2.6069E-04			
1.1041E+00	2.6069E-04			
1.1508E+00	6.0129E-03			
1.1566E+00	1.8340E-05			
1.1754E+00	6.0522E-04			
1.1835E+00	3.0654E-03			
1.1864E+00	8.3840E-05			
1.2188E+00	5.6330E-04			
1.2937E+00	4.5981E-04			
1.3082E+00	1.2969E-05			
1.3422E+00	3.7990E-04			
1.4215E+00	6.2880E-06			
1.4314E+00	2.2270E-05			
1.4325E+00	1.1397E-05			
1.4418E+00	1.4934E-05			
1.4502E+00	1.6375E-05			
1.4635E+00	5.8950E-05			
1.4689E+00	1.9257E-03			
1.4870E+00	1.7030E-04			
1.4922E+00	1.4541E-05			
1.5120E+00	2.3580E-04			
1.5122E+00	1.3231E-04			
1.5188E+00	1.6637E-05			
1.5652E+00	2.0829E-04			
1.5958E+00	1.6244E-05			
1.6019E+00	1.9519E-05			
1.6222E+00	6.4190E-04			
1.6707E+00	5.7640E-05			
1.7153E+00	1.3100E-05			
1.7245E+00	7.5980E-06			

Table 5-28. Ir-194 Gamma Spectra Used in Shielding Models – All Models (Continued)

Energy (MeV)	Absolute Probability of Emission per Decay	Model		
		AOS-025	AOS-050	AOS-100
1.7354E+00	2.4890E-05	✔	✔	✔
1.7573E+00	4.1920E-06			
1.7807E+00	5.2400E-05			
1.7857E+00	4.0217E-05			
1.7975E+00	1.7554E-04			
1.8058E+00	3.2488E-04			
1.8126E+00	4.4540E-06			
1.8296E+00	1.9257E-05			
1.9244E+00	1.8340E-05			
2.0437E+00	7.0740E-05			
2.1142E+00	2.6069E-05			

Table 5-29. Zr/Nb-95 Gamma Spectra Used in Shielding Models – All Models

Energy (MeV)	Absolute Probability of Emission per Decay	Model		
		AOS-025	AOS-050	AOS-100
7.6600E-01	3.2000E+00		✔	✔

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Table 5-31. Yb-169 Gamma Spectra Used in Shielding Models – All Models

Energy (MeV)	Absolute Probability of Emission per Decay	Model		
		AOS-025	AOS-050	AOS-100
6.4053E-03	1.8357E-02	✔	✔	
7.1637E-03	2.1264E-01			
8.1831E-03	1.8668E-01			
9.5498E-03	2.9349E-02			
4.9859E-02	5.2762E-01			
5.0850E-02	9.3274E-01			
5.7413E-02	9.7740E-02			
5.7623E-02	1.8890E-01			
5.7972E-02	1.7927E-03			
5.8018E-02	2.3136E-03			
5.9117E-02	2.1696E-02			
5.9164E-02	4.1962E-02			
5.9301E-02	4.1114E-04			
5.9310E-02	5.2762E-04			
8.4102E-03	3.5930E-03			
2.0752E-02	1.9797E-03			
4.2760E-02	1.2575E-03			
4.5940E-02	5.3895E-05			
5.0610E-02	2.6947E-03			
5.0860E-02	2.6947E-03			
5.1510E-02	8.9825E-05			
6.3010E-02	1.0779E-02			
6.3120E-02	4.3619E-01			
6.5860E-02	5.2099E-05			
7.2028E-02	1.7965E-05			
8.5090E-02	1.4372E-05			
9.3614E-02	2.5798E-02			
9.5700E-02	1.0779E-05			
9.5850E-02	1.0779E-05			
9.8010E-02	8.9825E-06			
1.0141E-01	3.5930E-05			
1.0519E-01	2.5870E-05			
1.0978E-01	1.7387E-01			
1.1362E-01	5.3895E-05			

Table 5-31. Yb-169 Gamma Spectra Used in Shielding Models – All Models (Continued)

Energy (MeV)	Absolute Probability of Emission per Decay	Model		
		AOS-025	AOS-050	AOS-100
1.1398E-01	4.3116E-05	✔	✔	
1.1738E-01	3.9882E-04			
1.1819E-01	1.8741E-02			
1.2994E-01	2.6947E-03			
1.3052E-01	1.1383E-01			
1.5672E-01	9.8807E-05			
1.7388E-01	1.4372E-05			
1.7721E-01	2.2280E-01			
1.9315E-01	7.5453E-05			
1.9796E-01	3.5930E-01			
1.9977E-01	1.6169E-04			
2.0599E-01	3.3774E-05			
2.1394E-01	2.9103E-05			
2.2630E-01	2.5151E-06			
2.2871E-01	1.9762E-06			
2.4033E-01	1.1390E-03			
2.6108E-01	1.6794E-02			
2.9119E-01	4.3116E-05			
2.9454E-01	9.7011E-06			
3.0173E-01	2.3354E-05			
3.0683E-01	8.9825E-04			
3.0752E-01	2.5151E-03			
3.0774E-01	1.0046E-01			
3.3396E-01	1.7426E-05			
3.3662E-01	9.4496E-05			
3.5674E-01	1.4085E-06			
3.7085E-01	8.8029E-06			
3.7928E-01	4.0601E-06			
3.8667E-01	3.3487E-06			
4.5262E-01	1.7606E-07			
4.6470E-01	3.5930E-08			
4.6565E-01	1.9043E-06			
4.6670E-01	1.9402E-07			
4.7497E-01	1.9438E-06			

Table 5-31. Yb-169 Gamma Spectra Used in Shielding Models – All Models (Continued)

Energy (MeV)	Absolute Probability of Emission per Decay	Model		
		AOS-025	AOS-050	AOS-100
4.9436E-01	1.4731E-05	✔	✔	
5.0035E-01	8.8388E-08			
5.0780E-01	1.4731E-08			
5.1510E-01	4.1715E-05			
5.2857E-01	1.1965E-06			
5.4616E-01	1.4731E-08			
5.6241E-01	1.1893E-06			
5.7089E-01	1.1138E-06			
5.7985E-01	1.9258E-05			
6.0060E-01	1.1390E-05			
6.2488E-01	4.9224E-05			
6.3332E-01	6.8986E-08			
6.4287E-01	7.6531E-07			
6.6360E-01	1.9330E-06			
6.9346E-01	8.6951E-08			
7.1035E-01	3.4134E-07			
7.3942E-01	1.8324E-08			
7.6024E-01	8.2639E-09			
7.7339E-01	2.0875E-06			
7.8164E-01	3.0181E-08			

5.5.3 MCNP6 Input and Output Files for Dose Calculations

Submitted separately.

5.5.4 Cobalt-60-C Volume Source Calculation Study

This appendix provides a study that considers a volume source for Co-60-C in the Model AOS-100A/AOS-100A-S shipping casks for a minimum activity of 19,000 Ci. The results of this study are used as the basis for the volume source geometry for the Co-60-C dose rate calculations in Appendix 5.5.7. The first step for using a bounding volume source is to determine a minimum volume that the source will occupy. For Co-60, there is a practical specific activity limit of 350 Ci/g, meaning that the maximum activity that any single gram of Cobalt may contain is 350 Ci. This 350 Ci/g limit is used to determine the minimum volume that a given activity of Cobalt will occupy. Any reduction in the specific activity would result in a larger volume of Cobalt. At a specific activity of 350 Ci/g, the desired activity limit of at least 19,000 Ci Co-60 would result in a minimum mass of 54.29g of Cobalt. With a density of 8.9g/cm^3, this mass of Cobalt takes up a volume of 6.1 cm^3. So, at a specific activity of 350 Ci/g or less, any activity of Co-60 greater than or equal to 19,000 Ci will occupy a volume of at least 6.1 cm^3. As long as the calculated minimum activity is greater than 19,000 Ci, a volume of 6.1 cm^3 is bounding because a greater activity will only result in a larger volume.

In addition to determining the minimum volume that the source will occupy, it must be determined what geometry distribution of this volume would result in the highest dose rate. To make this determination, it is considered that the sources will either accumulate into one of two geometries – either a lumped **cylinder** or an **arc segment** within the cask's top corner. Figure 5-8 illustrates these two geometries, as follows:

- **Transparent blue cell** – Usable cask cavity
- **Solid blue and yellow cells** – Axial shielding plates
- **Solid green cell** – Source volume

Table 5-32 lists the variations of the cylinder and arc segment geometries to determine the most limiting geometry of each. Table 5-33 lists the results for this analysis. Because the arc segment geometry with r_i = 6.0 cm and θ = 80° results in the most restrictive activity limit, this is considered to be the bounding geometry for the Co-60-C isotope for the Model AOS-100A/AOS-100A-S shipping casks.

Table 5-32. Volume Source Analysis – Source Geometry Dimensions

Geometry	Case		h (cm)	r[a] (cm)	θ (°)	V (cm^3)
Cylinder	H = D		1.98	0.99	360	6.1
	H = 2D		3.15	0.785	360	6.1
	2H = D		1.25	1.245	360	6.1
Arc Segment	ID = 5.75 in.	θ = 80°	0.5936	7.3025	80	6.1
	ID = 5.75 in.	θ = 90°	0.5276	7.3025	90	6.1
	ID = 5.75 in.	θ = 100°	0.4748	7.3025	100	6.1
	ID = 6.00 in.	θ = 80°	0.8753	7.6200	80	6.1
	ID = 6.00 in.	θ = 90°	0.7781	7.6200	90	6.1
	ID = 6.00 in.	θ = 100°	0.7002	7.6200	100	6.1
	ID = 6.25 in.	θ = 80°	1.7329	7.9375	80	6.1
	ID = 6.25 in.	θ = 90°	1.5403	7.9375	90	6.1
	ID = 6.25 in.	θ = 100°	1.3863	7.9375	100	6.1

a. For the Cylinder geometry, the radius dimension refers to the cylinder's radius.
For the Arc Segment geometry, the radius refers to the arc's inner radius because the arc's outer radius is equal to the cask cavity's radius.

Table 5-33. Volume Source Analysis – Results

Geometry	Case		Surface Dose Rate (mrem/hr/Ci)	Transport Index 1m Dose Rate (mrem/hr/Ci)
Cylinder	H = D		3.986E-03	3.011E-04
	H = 2D		4.209E-03	3.170E-04
	2H = D		3.627E-03	2.783E-04
Arc Segment	ID = 5.75 in.	θ = 80°	3.783E-03	3.997E-04
	ID = 5.75 in.	θ = 90°	3.707E-03	3.941E-04
	ID = 5.75 in.	θ = 100°	3.690E-03	3.912E-04
	ID = 6.00 in.	θ = 80°	3.947E-03	4.452E-04
	ID = 6.00 in.	θ = 90°	3.999E-03	4.379E-04
	ID = 6.00 in.	θ = 100°	3.996E-03	4.307E-04
	ID = 6.25 in.	θ = 80°	3.695E-03	3.796E-04
	ID = 6.25 in.	θ = 90°	3.560E-03	3.914E-04
	ID = 6.25 in.	θ = 100°	3.659E-03	4.135E-04
Maximum Dose Rate (mrem/hr/Ci)			4.209E-03	4.452E-04
Resulting A_{limit}[Ci][a]			**42,763**	**20,214**

a. Refer to Equation 5-5.

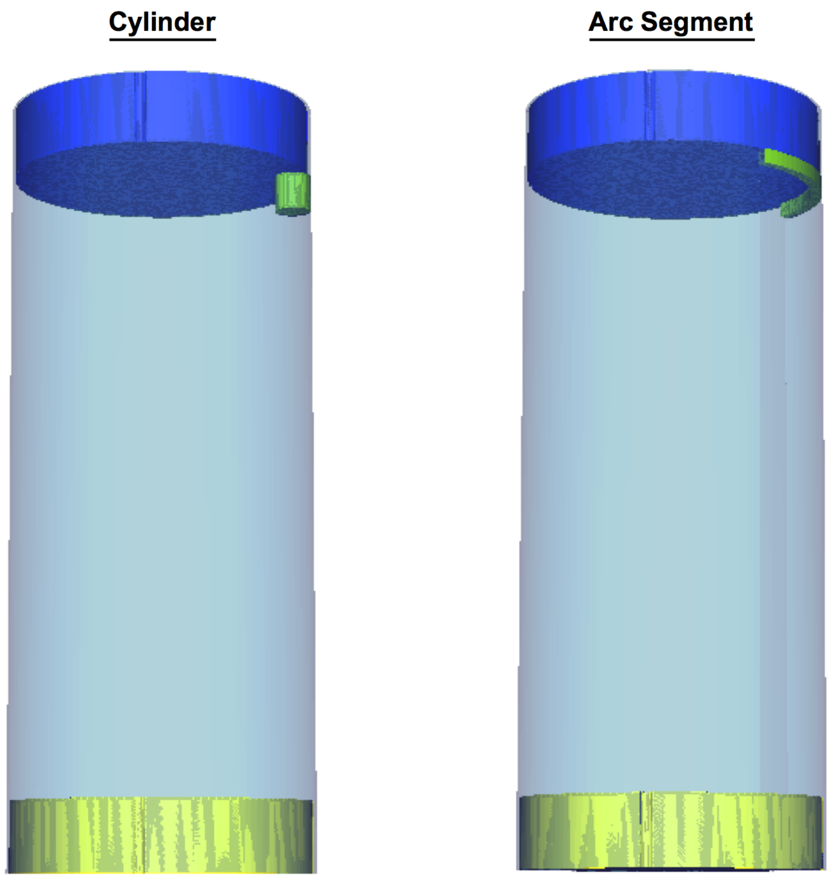

Figure 5-8. MCNP6 Volume Source Location/Geometries

5.5.5 Shipments of Multiple Isotopes under *10 CFR 71.47(a)*

This appendix documents the method that is used to demonstrate external dose rate and decay heat requirement compliance when mixing multiple isotopes within a single shipping cask's contents. Table 5-34 lists the equations that are used to calculate the total dose rate and decay heat from multiple isotopes. These equations are based on the dose rate acceptance criteria, as identified in Subsection 5.4.4 and the decay heat limit of the respective shipping cask model (for example, 400W for the Model AOS-100).

Table 5-34. *10 CFR 71.47(a)*[a] Dose Rate Acceptance Criteria for Multiple Isotopes

Criteria	Value
Transport Package Surface (External Surface)	$\sum_{i}^{n} A_i \times R_{Si} \leq 180$ mrem/hr
Transport Index (1m from External Surface)	$\sum_{i}^{n} A_i \times R_{1mPi} \leq 9$ mrem/hr
1-m HAC (1m from Shipping Cask Surface)	$\sum_{i}^{n} A_i \times R_{1mCi} \leq 900$ mrem/hr
Decay Heat	$\sum_{i}^{n} A_i \times Q_i \leq Q_{Limit}$

a. Reference **[5.1]**.

where:

A_i = Isotope *i* activity within the shipping cask contents (Ci)

n = Quantity of isotopes within the shipping cask contents

R_{Si} = External surface dose rate/curie for isotope *i* within the shipping cask contents (mrem/hr/Ci)

R_{1mCi} = 1m from the shipping cask surface dose rate/curie for isotope *i* within the shipping cask contents (mrem/hr/Ci)

R_{1mPi} = 1m from the external surface dose rate/curie for isotope *i* within the shipping cask contents (mrem/hr/Ci)

Q_i = Isotope *i* decay/curie within the shipping cask contents (W/Ci)

Q_{Limit} = AOS shipping cask decay heat limit (for example, 400W for Models AOS-100A and AOS-100A-S)

For each of the AOS shipping cask models, the total external dose rates at each regulatory location and total decay heat are calculated using each isotope's activity within the shipping cask contents and their respective reference values. These reference values for each of the AOS shipping casks are listed Table 5-35 through Table 5-35c. For Models AOS-100A and AOS-100A-S, an isotope that does not appear in Table 5-35 or fall within one of the categories addressed in Appendix 5.5.6 (that is, low-energy gamma and/or beta emitters) is **not** acceptable for shipment. For isotopes that fall within the criteria specified in Appendix 5.5.6, that are insignificant to external dose rates but must be accounted for in decay heat calculations, the decay heat for each of those isotopes and their progeny shall be calculated using Equation 5-8 and the isotope Q-value from the SCALE 6.1 ORIGEN (Reference **[5.2]**) decay library *origen.rev03.decay.data*. The radioactive contents of the other AOS shipping cask models are limited to the isotopes listed in their respective tables – Table 5-35a, Table 5-35b, and Table 5-35c for Models AOS-025A, AOS-050A, and AOS-100B, respectively. For any mixture of isotopes in which the Co-60-B or Co-60-C dose rate/curie values are used, the required axial shielding and cavity spacer plate components shall be used. For isotopes other than Co-60 (that is, those for which the axial shielding and cavity spacer plates were not analyzed), the added use of these components will decrease external dose rates, thereby providing additional margin to the values listed in Table 5-35. For any mixtures within the Model AOS-050A in which the Ir-192 or Ir-194 dose rate/curie values are used, the required axial shielding plates shall be used.

Table 5-35. Multiple Isotope Calculation Reference Value Summary – Models AOS-100A and AOS-100A-S

Isotope	Dose Rate Location[a] (mrem/hr/Ci)			Decay Heat Q_i[b] (W/Ci)
	External Surface R_{Si}	1m from External Surface R_{1mPi}	1m from Shipping Cask Surface R_{1mCi}	
Co-60	3.912E-01	3.292E-02	5.545E-02	1.55E-02
Co-60-B[c]	1.139E-01	1.093E-02	1.833E-02	1.55E-02
Co-60-C[d]	1.868E-02	5.314E-04	1.833E-02	1.55E-02
Cs-137	3.188E-03	2.570E-04	4.152E-04	4.99E-03
Hf-181	2.595E-04	2.182E-05	3.413E-05	4.33E-03
Ir-192	5.802E-04	4.898E-05	7.547E-05	6.13E-03
Ir-194	4.502E-03	3.871E-04	6.536E-04	5.30E-03
Zr/Nb-95	3.098E-02	2.571E-03	4.106E-03	1.62E-02

a. Dose rates in units of mrem/hr/Ci, from Table 5-19 (Ir-192 and Ir-194 only) and Table 5-15 (all others).

b. Decay heat in units of W/Ci, from Table 5-22.

c. Use of tungsten alloy axial shielding plates 183C8491 is required.

d. Use of tungsten alloy axial shielding plates 183C8491 and stainless steel –or– aluminum cavity spacer plates 183C8518 is required.

Table 5-35a. Multiple Isotope Calculation Reference Value Summary – Model AOS-025A

Isotope[a]	Dose Rate Location[b] (mrem/hr/Ci)			Decay Heat Q_i[c] (W/Ci)
	External Surface R_{Si}	1m from External Surface R_{1mPi}	1m from Shipping Cask Surface R_{1mCi}	
Co-60	1.355E+03	1.713E+01	1.879E+01	1.55E-02
Cs-137	1.800E+01	2.835E-01	3.252E-01	4.99E-03
Ir-192	2.421E+00	4.259E-02	4.875E-02	6.13E-03
Ir-194	1.367E+01	1.734E-01	1.920E-01	5.30E-03
Yb-169	1.131E-03	1.995E-05	2.307E-05	2.55E-03

a. *Use of tungsten alloy shielding liner 183C8485 is required for all isotopes.*

b. *Dose rates in units of mrem/hr/Ci, from Table 5-17 (Ir-192 and Ir-194 only) and Table 5-13 (all others).*

c. *Decay heat in units of W/Ci, from Table 5-22.*

Table 5-35b. Multiple Isotope Calculation Reference Value Summary – Model AOS-050A

Isotope	Dose Rate Location[a] (mrem/hr/Ci)			Decay Heat Q_i[b] (W/Ci)
	External Surface R_{Si}	1m from External Surface R_{1mPi}	1m from Shipping Cask Surface R_{1mCi}	
Co-60	2.410E+02	8.837E+00	1.178E+01	1.55E-02
Cs-137	1.044E+01	2.933E-01	3.926E-01	4.99E-03
Hf-181	2.349E+00	5.774E-02	7.598E-02	4.33E-03
Ir-192[c]	1.669E-01	6.286E-03	1.042E-01	6.13E-03
Ir-194[c]	1.150E+00	2.628E-02	1.334E-01	5.30E-03
Zr/Nb-95	6.768E+01	2.068E+00	2.755E+00	1.62E-02
Yb-169	2.317E-02	5.804E-04	7.277E-04	2.55E-03

a. *Dose rates in units of mrem/hr/Ci, from Table 5-18 (Ir-192 and Ir-194 only) and Table 5-14 (all others).*

b. *Decay heat in units of W/Ci, from Table 5-22.*

c. *Use of stainless steel axial shielding plates 183C8519 is required.*

Table 5-35c. Multiple Isotope Calculation Reference Value Summary – Model AOS-100B

Isotope	Dose Rate Location[a] (mrem/hr/Ci)			Decay Heat Q_i[b] (W/Ci)
	External Surface R_{Si}	1m from External Surface R_{1mPi}	1m from Shipping Cask Surface R_{1mCi}	
Co-60	9.217E+00	9.098E-01	1.358E+00	1.55E-02
Cs-137	1.871E-01	1.694E-02	2.515E-02	4.99E-03
Hf-181	2.527E-02	2.256E-03	3.354E-03	4.33E-03
Ir-192	4.084E-02	3.674E-03	5.431E-03	6.13E-03
Ir-194	1.016E-01	1.003E-02	1.502E-02	5.30E-03
Zr/Nb-95	1.459E+00	1.355E-01	2.000E-01	1.62E-02

a. *Dose rates in units of mrem/hr/Ci, from Table 5-20 (Ir-192 and Ir-194 only) and Table 5-16 (all others).*

b. *Decay heat in units of W/Ci, from Table 5-22.*

5.5.6 Isotopes Insignificant to External Dose Rates

This appendix addresses isotopes that are considered insignificant to external dose rates by defining the requirements and minimum gamma emission energy at which the effect on external dose rates is considered significant. Additionally, W/Ci values are provided for multiple low-energy gamma and beta emitter isotopes as examples of typical values that are necessary for calculating the decay heat of each isotope.

To determine the minimum gamma emission energy at which the effect on external dose rates is considered significant, multiple additional MCNP cases were run to calculate external dose rates for low-energy gammas for the Model AOS-100A and AOS-100A-S configurations. These additional MCNP cases are identical to the MCNP cases defined in Section 5.3, with only the source spectra changed. Top, side, and corner dose rate cases are analyzed with identical model materials and geometry (refer to Paragraph 5.3.1.1) and tallies (refer to Paragraph 5.3.1.4). For each case analyzed within this appendix, the only change was the source energy, from an isotope spectrum to a single emission energy of either 0.2 or 0.3 MeV.

Only Models AOS-100A and AOS-100A-S without their axial shielding or cavity spacer plates are being analyzed for low-energy gamma emissions. Thus, the determined minimum significant gamma energy is applicable only to the Model AOS-100A and AOS-100A-S configurations, and no exclusion criteria for low-energy gamma emitters is set for the other AOS shipping cask variants. This refers to the Model AOS-100A and AOS-100A-S in any configuration (that is, with or without axial shielding or cavity spacer plates) because the configurations with the axial shielding or cavity spacer plates are bounded by the bare cask cavity configuration without these plates. Table 5-36 presents a summary of the calculated values.

Table 5-36. Low-Energy Gamma External Dose Rates – Models AOS-100A and AOS-100A-S

Gamma Energy (MeV)	Direction	Dose Rates					
		External Surface		1m from External Surface		1m from Shipping Cask Surface	
		(mrem/hr/Ci)[a]	(mrem/hr)[b]	(mrem/hr/Ci)[a]	(mrem/hr)[b]	(mrem/hr/Ci)[a]	(mrem/hr)[b]
0.2	Top	1.774E-12	5.985E-07	3.065E-13	1.034E-07	4.747E-13	1.601E-07
	Side	5.425E-15	1.831E-09	3.706E-16	1.250E-10	5.233E-16	1.766E-10
	Corner	2.087E-09	7.042E-04	1.623E-10	5.478E-05	2.679E-10	9.038E-05
0.3	Top	4.464E-09	1.005E-03	7.397E-10	1.664E-04	1.137E-09	2.559E-04
	Side	1.466E-11	3.299E-06	1.267E-12	2.851E-07	1.716E-12	3.862E-07
	Corner	2.379E-06	5.353E-01	1.869E-07	4.206E-02	3.056E-07	6.876E-02
Maximum Location Dose Rate[c]		180.54 mrem/hr		9.04 mrem/hr		900.07 mrem/hr	

a. Dose rates in units of mrem/hr/Ci, based on 1 γ/decay (MCNP output).

b. Maximum dose rate contribution based on limiting activity from decay heat limit (3.374E5 Ci for 0.2 MeV and 2.249E5 for 0.3 MeV).

c. Based on the maximum allowable dose rate at each location plus the maximum dose rate that accounts for 400W of 0.3-MeV gammas (that is, the maximum possible dose rate that accounts for the maximum quantity of 0.3-MeV gammas).

The flux values calculated in MCNP have been converted to dose rates, using the ANSI/ANS-6.1.1 1977 (Reference **[5.5]**) dose conversion factors (refer to Subsection 5.4.3) and a 3.7E10 multiplier (refer to Subsection 5.4.4). Thus, the dose rates listed in Table 5-36 can be considered for 1 Ci of an isotope that emits one gamma/decay. For a source that emits gammas at an energy of 0.2 or 0.3 MeV, the limiting activity (assuming 1 γ/decay) based on the Model AOS-100A and AOS-100A-S shipping cask's 400-W decay heat limit is calculated as follows:

- **0.2-MeV gammas** – $400\,\frac{J}{s} \times \frac{1\text{ eV}}{1.602167\text{E-}19\text{J}} \times \frac{1\gamma}{0.2\text{E6 eV}} \times \frac{1\text{ Ci}}{3.7\text{E}10\frac{\gamma}{s}} = 3.374\text{E5 Ci}$
- **0.3-MeV gammas** – $400\,\frac{J}{s} \times \frac{1\text{ eV}}{1.602167\text{E-}19} \times \frac{1\gamma}{0.3\text{E6 eV}} \times \frac{1\text{ Ci}}{3.7\text{E}10\frac{\gamma}{s}} = 2.249\text{E5 Ci}$

Note that although the isotopes might emit more or fewer gammas/decay, thereby resulting in a different activity that is equivalent to a 400-W decay heat, the total quantity of gammas/sec emitted is the same. Thus, the maximum dose rate values listed in Table 5-36 are bounding, regardless of the isotope's actual gammas/decay quantity when the limiting activity is based on the decay heat. It should also be considered that these calculated activities equivalent to the 400-W decay heat limit do not consider any electron emissions that are characteristic of low-energy gamma isotopes. If electron emissions were accounted for as well, the total quantity of gammas/sec would be decreased, thereby also decreasing the calculated maximum dose rate.

The maximum dose rate at each regulatory location based on this activity limit is provided in Table 5-36. Based on the statistical convergence information in each MCNP output (that is, statistical checks, tally fluctuation charts, fractional standard deviations, and probability density function plots), it was determined that all tallies are sufficiently converged, and that the reported dose rate results are accurate. Because there is a 10% margin built into all external dose rate limits per Subsection 5.1.2, the regulatory dose rate limits would not be exceeded even if these neglected low-energy gamma isotopes were accounted for. Evaluating the Maximum Location Dose Rate row in Table 5-36 shows that in the worst-case scenario for all dose rate locations, the remaining margin to the regulatory dose rate limit would still be greater than 9.5%. Additionally, it should be noted that although the total allowable activity based on the 400-W decay heat increases with lower gamma energy emissions, the maximum resulting dose rates decrease because the reduction in dose rate/curie is greater than the increase in activity for lower energies (comparison of 0.2 and 0.3MeV maximum dose rate results in Table 5-36). Thus, based on the results of this additional calculation, Models AOS-100A and AOS-100A-S in any configuration (with or without axial shielding and cavity spacer plates) may transport any isotope with all gamma emissions below 0.3 MeV without accounting for its contribution to external dose rates. Some examples of isotopes that fall within this category are Fe-55, V-49, and I-125.

For all AOS shipping cask variants, beta particles cannot sufficiently penetrate an AOS shipping cask's shielding to contribute to external dose rates. The only concern for external dose rates is from the secondary radiation of the beta particles (i.e., bremsstrahlung). However, the bremsstrahlung gamma energy cannot exceed the source electron energy. Thus, for the Model AOS-100A and AOS-100A-S variants, all beta emissions for these "low-energy beta emitters" and their progeny must be less than 0.3 MeV because it has already been determined that 0.3-MeV gammas will **not** significantly contribute to external dose rates. For the Model AOS-025A, AOS-050A, and AOS-100B variants, low-energy beta emitters are currently **not** acceptable for shipment because they remain unanalyzed. Note that although the term "beta particles" specifically refers to electrons that are emitted through beta decay, in this context, beta particles refers to any electron that is emitted from an isotope regardless of decay mode (that is, including electrons emitted by way of other decay modes, such as internal conversion of the auger effect). Some common examples of low-energy beta emitters are H-3, C-14, and Ni-63.

As determined earlier in this appendix, low-energy gamma and beta emitters (that is, all emitted gammas and betas that are less than 0.3 MeV) do not need to be accounted for in the Model AOS-100A and AOS-100A-S dose rate calculations. To clarify, this requirement applies to the full beta spectrum not the average beta energy (i.e. $E_{max,\beta} \le 0.3$). However, the decay heat from these isotopes and their progeny must be accounted for when calculating the shipping cask content's total decay heat output. The method defined in Appendix 5.5.1 can be used to determine any isotope's decay heat value (in units of W/Ci), using reference decay heat Q-values from the SCALE 6.1 ORIGEN (Reference **[5.2]**) decay library *origen.rev03.decay.data*. The decay heat contribution of all radioisotopes within the shipping cask contents must be accounted for, regardless of whether they contribute to external dose rates. Table 5-37 provides calculated decay heat values for some example isotopes that would not be included in dose rate calculations, but must be considered for decay heat calculations. It should be noted that Table 5-37 is not a comprehensive list of all low-energy gamma and beta emitters, but provides examples of some typical isotopes. These calculated decay heat values can be used along with the decay heat values provided in Table 5-35 to determine the decay heat of shipping cask contents that have a mixture of isotopes, as defined in Appendix 5.5.5 and Appendix 5.5.7.

Table 5-37. Example Low-Energy Gamma and Beta Emitter Decay Heat Values

Isotope	$E_{max,\gamma}$ [a] (MeV)	$E_{max,\beta}$ [a] (MeV)	Library Isotope Identifier[b]	Q_{Value} (MeV/ Disintegration)	Decay Heat (W/Ci)
H-3	–	0.019	10030	5.6900E-03	3.38E-05
C-14	–	0.157	60140	4.9470E-02	2.94E-04
V-49	0.005	0.005	230490	4.4514E-03	2.64E-05
Fe-55	0.126	0.125	260550	5.8421E-03	3.47E-05
Ni-63	–	0.067	280630	1.7425E-02	1.04E-04
I-125	0.036	0.036	531250	6.0467E-02	3.59E-04

a. *Based on ICRP-107 data (Reference* **[5.7]***).*

b. *From the SCALE 6.1 ORIGEN (Reference* **[5.2]***) decay library origen.rev03.decay.data.*

5.5.7 *10 CFR 71.47(b)* Exclusive Use Activity Limits for Models AOS-100A and AOS-100A-S

This appendix analyzes Models AOS-100A and AOS-100A-S under the conditions permitted for Exclusive Use shipments and establishes applicable activity limits. The activity limits established in Subsection 5.4.4 for all AOS shipping cask models are based on compliance with *10 CFR 71.47(a)* and *71.51(a)(2)* (Reference **[5.1]**) for NCT and HAC, respectively. However, *10 CFR 71.47(b)* (Reference **[5.1]**) allows for the use of alternative dose rate limits if *10 CFR 71.47(a)* dose rate limits are exceeded. Thus, if the activity limits established in Subsection 5.4.4 are exceeded, the shipping cask contents may still be acceptable for shipment under *10 CFR 71.47(b)* requirements, as long as the shipment is exclusive use. For simplicity within this appendix, however, *10 CFR 71.47(a)* requirements are referred to as "non-exclusive use" limits, and *10 CFR 71.47(b)* requirements are referred to as "exclusive use" limits.

The Subsection 5.4.4 activity limits that are based on non-exclusive use dose rate limits that are usually limited by the 1m from external surface (TI) dose rate limit. However, when shipping exclusive use, the TI limit may be neglected, thus allowing for higher activity limits. Per *10 CFR 71.47(b)*, there are additional dose rate limits for exclusive use, for 2m from the transport vehicle trailer's outer lateral surfaces and any normally occupied space (that is, the driver cab). Applying a 10% margin to all regulatory dose rate limits results in the additional exclusive use shipment activity limits listed in Table 5-38. These additional activity limits are calculated only for the Model AOS-100A shipping cask variant and are also applicable to the Model AOS-100A-S shipping cask variant.

Table 5-38. Additional Exclusive Use Dose Rate Locations and Activity Limits – Models AOS-100A and AOS-100A-S

Conditions of Transport	Dose Rate Location	Limit Value (mrem/hr)
NCT	Transport Package Surface	180
	2m from Trailer Surface	9
	Driver Cab	1.8
HAC	1m from Shipping Cask Surface	900

The NCT external surface and HAC 1m from shipping cask surface dose rates for each isotope are already calculated in Subsection 5.4.4 for each isotope. Thus, to allow for higher activity limits for exclusive use transport, the NCT 2m from trailer surface and driver cab dose rates for each isotope must be determined. The Model AOS-100A and AOS-100A-S shipping casks are always transported in the upright position; thus, the NCT 2m from trailer surface and driver cab dose rates are applicable only to the shipping cask's lateral (radial) direction. Additionally, the following requirements are set for exclusive use shipments to support these additional dose rate location calculations:

- Only one transport package may be shipped per trailer
- Trailer used for transporting the transport package must be standard width (8-ft. wide), at minimum
- Transport package must be secured to the trailer's center (side-to-side), at least 4 ft. forward from the back of the trailer, and at least 20 ft. back from the driver cab (transport package centerline to driver cab)

With these parameters set, the lateral distances from the shipping cask's centerline to the NCT 2m from trailer surface and driver cab dose rate locations are determined as follows:

- **NCT 2m from trailer surface location** – Shipping cask centerline to the outer lateral vehicle surfaces (4 ft) + 2-m tally distance

$$4 \text{ ft.} \times \frac{30.48 \text{ cm}}{1 \text{ ft.}} + 2\text{m} \times \frac{100 \text{ cm}}{1\text{m}} = 321.92 \text{ cm}$$

- **NCT Driver cab location** – Shipping cask centerline to the driver's cab (20 ft.)

$$20 \text{ ft.} \times \frac{30.48 \text{ cm}}{1 \text{ ft.}} = 609.6 \text{ cm}$$

For the additional exclusive use dose rate calculations, the same MCNP model as defined in Paragraph 5.3.1.1 was used with the spacer components defined in Paragraph 5.3.1.2 for the relevant configurations (that is, Co-60-B and Co-60-C). The source is modeled as a point source in the top corner of the available cask cavity, as defined in Paragraph 5.3.1.3, to allow for streaming around the tungsten alloy axial shielding plates and provide bounding calculated dose rates. The exception to this is the Co-60-C calculation, where the source is modeled as a small volume. Per the results provided in Table 5-33, the most restrictive source geometry is an arc segment with an ID = 6.00 in. and inner angle of $\theta = 80°$. Thus, this source geometry is used for the Co-60-C configuration's exclusive use dose rate calculations. In Table 5-33, the tallies at each lateral distance are divided into a column of small tally cells so that the flux is not averaged over too large a volume. Note that the tally cells do not curve in the same way as the tallies shown in Figure 5-7. Instead, the tally cells form a single column because the new dose rate locations are applicable only in the lateral direction. For reference, the arrangement of the tally cells is illustrated in Figure 5-9. The cell tally at the maximum calculated dose rate's axial location is used as the dose rate for each of those locations.

Table 5-39 summarizes the exclusive use MCNP calculation results, which include each regulatory dose rate location's maximum dose rate and each isotope's W/Ci factor. Based on these values, each isotope's maximum activity limit is determined based on the limiting dose rate location or decay heat. A review of the statistical convergence information in each MCNP output (that is, statistical checks, tally fluctuation charts, fractional standard deviations, and probability density function plots) indicates that all tallies are sufficiently converged, and that the reported dose rate results are accurate. It should be noted in Table 5-39 that for the Co-60-C isotope, the "External Surface" location is considered to be that of the enclosure surface for a closed transport vehicle, with the shipping cage being the enclosure. As such, use of the dose rate at the radial distance of the deformed impact limiter surface for the enclosure surface location is bounding. Based on the transport package surface dose rate from Table 5-46 (1.868E-02 mrem/hr/Ci) and the activity limit from Table 5-39 (25,806.4 Ci), the maximum transport package surface dose rate is 428 mrem/hr, which is well below the closed transport limit of 1,000 mrem/hr. However, this also means that the *10 CFR 71.47(b)(1)(i) through (iii)* (Reference **[5.1]**) requirements apply to Co-60-C Exclusive Use shipments as well.

Table 5-39. Exclusive Use Activity Limit Maximum Dose Rates and Decay Heat – Models AOS-100A and AOS-100A-S[a]

Isotope	Dose Rate Location (mrem/hr/Ci)				Decay Heat[b] (W/Ci)	Exclusive Use Activity Limit (Ci)
	NCT			HAC		
	External Surface[c]	2m from Trailer Surface	Driver Cab	1m from Shipping Cask Surface[c]		
Co-60	3.912E-01	2.457E-03	5.011E-04	5.545E-02	1.55E-02	460.2
Co-60-B[d]	1.139E-01	4.973E-04	7.277E-05	1.833E-02	1.55E-02	1,580.3
Co-60-C[e f]	5.452E-03	5.577E-05	1.534E-05	1.833E-02	1.55E-02	25,806.4
Cs-137	3.188E-03	1.152E-05	2.240E-06	4.152E-04	4.99E-03	56,460.4
Hf-181	2.595E-04	7.384E-07	1.416E-07	3.413E-05	4.33E-03	92,378.7
Ir-192	5.802E-04	2.065E-06	3.957E-07	7.547E-05	6.13E-03	65,252.9
Ir-194	4.502E-03	3.130E-05	6.375E-06	6.536E-04	5.30E-03	39,982.4
Zr/Nb-95	3.098E-02	1.264E-04	2.471E-05	4.106E-03	1.62E-02	5,811.0

a. *Maximum allowable activity at which all dose rate locations do not exceed exclusive use dose rate limits, and the decay heat does not exceed 400W.*

b. *Decay heat in units of W/Ci, from Table 5-22.*

c. *Dose rates in units of mrem/hr/Ci, from Table 5-19 (Ir-192 and Ir-194 only), Table 5-44 (Co-60-C), and Table 5-15 (all others).*

d. *Use of tungsten alloy axial shielding plates 183C8491 is required.*

e. *Use of tungsten alloy axial shielding plates 183C8491 and stainless steel –or– aluminum cavity spacer plates 183C8518 is required.*

f. *For Co-60-C quantities, the maximum allowable specific activity is 350 Ci/g (that is, no more than 350 Ci of Co-60 in a gram of Cobalt).*

Based on the Table 5-39 isotope activity limits, the Table 5-40 results show the dose rate at each exclusive use regulatory dose rate location and the total decay heat. Each isotope's limiting value is **bolded**. It can be noted from the Table 5-40 results that all activity limits are based on either the external surface dose rate location or decay heat. Neither of the exclusive use regulatory locations (that is, 2m from trailer surface or driver cab dose rate location) are close to the respective regulatory dose rate limit. For all isotopes, there is a significant margin between the maximum dose rates at the NCT 2m from trailer surface or driver cab locations and their respective regulatory limits. The activity increase is solely due to the removal of the non-exclusive use, NCT 1m from external surface activity limit.

Table 5-40. Exclusive Use Maximum Activity Dose Rates and Decay Heat – Models AOS-100A and AOS-100A-S

Isotope	Dose Rate Location[a] (mrem/hr)				Decay Heat[b] (W)
	NCT			HAC	
	External Surface	2m from Trailer Surface	Driver Cab	1m from Shipping Cask Surface	
Co-60	**180.00**	1.13	0.23	25.52	7.13
Co-60-B[c]	**180.00**	0.79	0.11	28.96	24.49
Co-60-C[d]	101.87	1.44	0.40	472.93	**400.00**
Cs-137	**180.00**	0.65	0.13	23.44	281.74
Hf-181	23.97	0.07	0.01	3.15	**400.00**
Ir-192	37.86	0.13	0.03	4.92	**400.00**
Ir-194	**180.00**	1.25	0.25	26.13	211.91
Zr/Nb-95	**180.00**	0.73	0.14	23.86	94.14

a. Calculated based on Table 5-39 exclusive use activity limit and dose rate/curie values.

b. Calculated based on Table 5-39 exclusive use activity limit and watt/curie (W/Ci) values.

c. Use of tungsten alloy axial shielding plates 183C8491 is required.

d. Use of tungsten alloy axial shielding plates 183C8491 and stainless steel –or– aluminum cavity spacer plates 183C8518 is required.

It is acceptable to transport mixtures of analyzed isotopes when shipping the Model AOS-100A and AOS-100A-S exclusive use with the following method. Using the dose rate equations for the NCT external transport surface, NCT 2m from trailer surface, NCT driver cab, and HAC 1-m locations provided in Table 5-40a, the total dose rates and decay heat for the isotope mixture within the shipping cask contents can be calculated. To complete these calculations, the transport package's user needs each isotope's activity within the mixture and the dose rate/curie values listed in Table 5-41. Isotope mixtures are limited to the radionuclides listed in Table 5-41 and low-energy gamma and beta emitters, as defined in Appendix 5.5.6. Note that for low-energy gamma and beta emitters, the decay heat from these isotopes and their progeny must be accounted for when calculating the shipping cask content's total decay heat output. For any isotope mixtures in which the Co-60-B or Co-60-C dose rate/curie values are used, axial shielding and cavity spacer plates shall be used.

Table 5-40a. ***10 CFR 71.47(b)*[a] Dose Rate Acceptance Criteria for Multiple Isotopes**

Criteria	Value
External Surface (Transport Package or Enclosure Surface)[b]	$\sum_{i}^{n} A_i \times R_{Si} \leq 180$ mrem/hr
2-m Dose Rate (2m from Lateral Trailer Side or Rear)	$\sum_{i}^{n} A_i \times R_{2mi} \leq 9$ mrem/hr
Driver Cab Dose Rate (Shipping Cask Centerline, at Least 20 ft. from Driver Cab)	$\sum_{i}^{n} A_i \times R_{Cabi} \leq 1.8$ mrem/hr
1-m HAC (1m from Shipping Cask Surface)	$\sum_{i}^{n} A_i \times R_{1mCi} \leq 900$ mrem/hr
Decay Heat	$\sum_{i}^{n} A_i \times Q_i \leq \mathrm{Q}_{\mathrm{Limit}}$

a. Reference **[5.1]**.

b. Enclosure surface for Co-60-C. Transport package surface for all others.

where:

A_i = Isotope *i* activity within the shipping cask contents (Ci)

n = Quantity of isotopes within the shipping cask contents

R_{Si} = Transport surface dose rate/curie for isotope *i* within the shipping cask contents (mrem/hr/Ci)

R_{2mi} = 2m from the lateral trailer side of rear dose rate/curie for isotope *i* within the shipping cask contents (mrem/hr/Ci)

R_{Cabi} = Driver cab dose rate/curie for isotope *i* within the shipping cask contents (mrem/hr/Ci)

R_{1mCi} = 1m from the external surface dose rate/curie for isotope *i* within the shipping cask contents (mrem/hr/Ci)

Q_i = Isotope *i* decay/curie within the shipping cask contents (W/Ci)

$\mathrm{Q}_{\mathrm{Limit}}$ = AOS shipping cask decay heat limit (400W for Models AOS-100A and AOS-100A-S)

Table 5-41. Multiple Isotope Exclusive Use Calculation Reference Values – Models AOS-100A and AOS-100A-S

Isotope	Dose Rate Location[a] (mrem/hr/Ci)				Decay Heat Q_i[b] (W/Ci)
	NCT			HAC	
	External Surface R_{Si}	2m from Trailer Surface R_{2mi}	Driver Cab R_{Cabi}	1m from Shipping Cask Surface R_{1mCi}	
Co-60	3.912E-01	2.457E-03	5.011E-04	5.545E-02	1.55E-02
Co-60-B[c]	1.139E-01	4.973E-04	7.277E-05	1.833E-02	1.55E-02
Co-60-C[d e f]	5.452E-03	5.577E-05	1.534E-05	1.833E-02	1.55E-02
Cs-137	3.188E-03	1.152E-05	2.240E-06	4.152E-04	4.99E-03
Hf-181	2.595E-04	7.384E-07	1.416E-07	3.413E-05	4.33E-03
Ir-192	5.802E-04	2.065E-06	3.957E-07	7.547E-05	6.13E-03
Ir-194	4.502E-03	3.130E-05	6.375E-06	6.536E-04	5.30E-03
Zr/Nb-95	3.098E-02	1.264E-04	2.471E-05	4.106E-03	1.62E-02

a. *Maximum dose rates in units of mrem/hr/Ci, from Table 5-39.*

b. *Decay heat in units of W/Ci, from Table 5-39.*

c. *Use of tungsten alloy axial shielding plates 183C8491 is required.*

d. *Use of tungsten alloy axial shielding plates 183C8491 and stainless steel –or– aluminum cavity spacer plates 183C8518 is required.*

e. *For shipments including Co-60-C, 10 CFR 71.47(b)(1)(i) through (iii) (Reference [5.1]) requirements apply.*

f. *For Co-60-C quantities, the maximum allowable specific activity is 350 Ci/g (that is, no more than 350 Ci of Co-60 in a gram of Cobalt).*

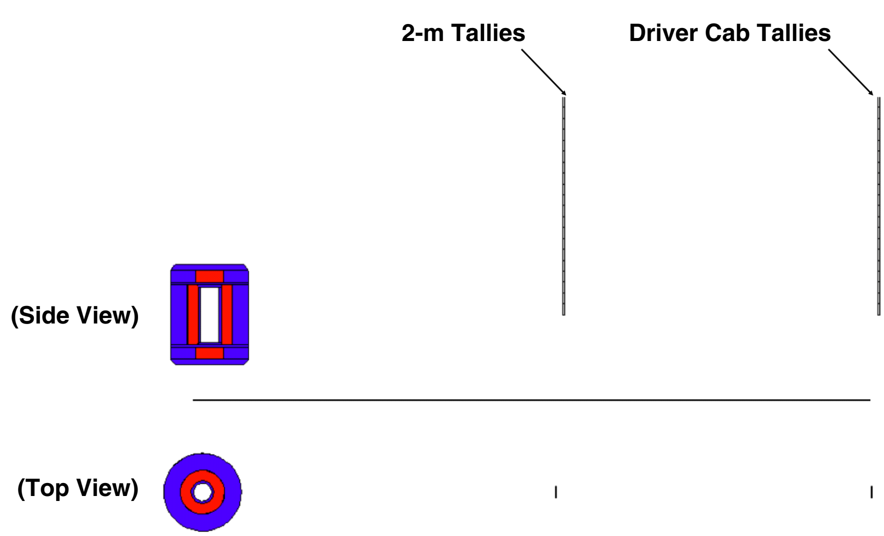

Figure 5-9. Exclusive Use MCNP Tally Locations

5.5.8 Evaluation of Dose Rate Tally Locations

This appendix presents the following information:

- Assessment of Gap between Upper and Lower Impact Limiters on External Dose Rates
- Assessment of Recessed Region within Upper and Lower Impact Limiters Effect on External Dose Rates

5.5.8.1 Assessment of Gap between Upper and Lower Impact Limiters on External Dose Rates

This appendix addresses dose rates out the Model AOS-050 and AOS-100 transport package sides, in the gap between the upper and lower impact limiters. Because the dose rates listed in Subsection 5.4.4 are solely for the bounding location (out the shipping cask's corner), this appendix assesses the side location to consider the side's potential for becoming the limiting dose rate location if the impact limiter offset is not considered out the transport package's side. The appendix is specific to the *10 CFR 71.47(a)* (Reference **[5.1]**) dose rate calculations presented in Subsection 5.4.4, where the offset provided by the shipping cage cannot be credited.

An approximation of the dose rate increase that occurs from moving the dose rate location from the deformed impact limiter to the shipping cask surface can be made due to the simplicity of the source/shield geometry for the side dose rate location. Because the source is modeled as a point source at the cask cavity wall and there are no abnormalities (such as voids, streaming paths, and so forth) in the radial shield, approximate dose rates can be calculated using a 1D point source geometry, as illustrated in Figure 5-10. The approximate dose rate increase from moving the dose rate location from the deformed impact limiter to the shipping cask surface can be calculated as the particle flux ratio at the two locations. For the particle flux calculation at both locations, the source (S) and shielding ($Be^{-\mu t}$) are identical. Thus, the ratio can be simplified to show that the flux at the shipping cask surface (ϕ_2) can be calculated based on the flux at the deformed impact limiter surface (ϕ_1), as follows:

$$\frac{\phi_2}{\phi_1} = \frac{\dfrac{SBe^{-\mu t}}{4\pi r_2^{\,2}}}{\dfrac{SBe^{-\mu t}}{4\pi r_1^{\,2}}} \rightarrow \phi_2 = \phi_1 \frac{r_1^{\,2}}{r_2^{\,2}}$$

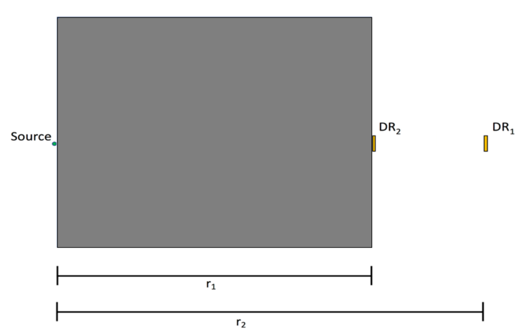

Figure 5-10. Simplified 1D Dose Rate Calculations

As long as the margin between the maximum side dose rates and regulatory limit is significantly larger than the approximate dose rate increase calculated from moving the point source location (that is, r_1^2 / r_2^2), it can be determined that the external dose rates would not be exceeded by moving the side locations to be based on the exposed shipping cask surface and not the deformed impact limiter. The approximate factor by which the side transport package surface dose rates are expected to increase by moving the side location are shown in Table 5-42 to be approximately 2.5.

Table 5-42. Approximate Change in Side Dose Rates – Models AOS-050 and AOS-100

Transport Package Surface Location	Model	
	AOS-050	**AOS-100**
r_1 (cm)	21.6625	44.375
r_2 (cm)	13.6525	27.305
r_1^2 / r_2^2	2.52	2.64

Table 5-43, Table 5-44, and Table 5-45 list the Model AOS-050A, AOS-100A and AOS-100A-S, and AOS-100B side dose rate/curie values, respectively, in the gap between the upper and lower impact limiters for the transport package surface and 1-m TI locations, with both a point source in the top corner of the shipping cask cavity and a source on the side wall. (Refer to Figure 5-11 and Figure 5-12.) For each case, the 1-m TI dose rates listed are based on the HAC dose rates that are calculated as described in Paragraph 5.3.1.4 (that is, 1m from the shipping cask surface). Because the HAC 1-m dose rates are from the shipping cask surface (neglecting the impact limiters), this tally is representative of the side 1-m TI location at the exposed shipping cask surface. Thus, for this location, as long as the factor of safety listed is greater than 1, the limit will not be exceeded at the side 1-m TI location. Based on the Table 5-42 results, as long as the factor of safety listed for the side transport package surface is significantly greater than 2.5, the limit will not be exceeded for the side transport package surface location. For this comparison, a factor of 3 is considered to be sufficiently large to bound this increase in side dose rates. In Table 5-43, Table 5-44, and Table 5-45, the results are listed for both the side source (minimizing distance) and corner source (maximizing streaming around the radial shield) locations.

Figure 5-11 (Model AOS-050A) and Figure 5-12 (Models AOS-100A, AOS-100A-S, and AOS-100B) illustrate the source locations (**green** point) and tallies within the upper and lower impact limiter gap (highlighted **red**). Although Figure 5-11 and Figure 5-12 do not show the Ir-192 and Ir-194 isotope (Model AOS-050A) and Co-60-B and Co-60-C isotope (Model AOS-100A and AOS-100A-S) spacer and shielding components, the MCNP models include these components for the respective cases. All listed results are from calculations outlined in Section 5.4. However, the maximum dose rates listed are from the maximum tally location in the side impact limiter gap, not across the entire tally.

From the comparison provided in Table 5-43, it is clear that when the Model AOS-050A side dose rates are from the exposed shipping cask surface (gap) between the impact limiters, only the Ir-194 isotope would result in exceeded external dose rates. This is a result of the additional spacing and shielding, along with the Ir-194 isotope's higher gamma energy, which causes the corner location to be bounded by a much-smaller margin than the other isotope configurations. Thus, an additional case is required to calculate the dose rate on the Model AOS-050A exposed side shipping cask surface for Ir-194.

From the comparison provided in Table 5-44, it is clear that when the Model AOS-100A and AOS-100A-S side dose rates are from the exposed shipping cask surface (gap) between the impact limiters, only the Co-60-C case would result in exceeded external dose rates. This is a result of the Co-60-C configuration's additional spacing and shielding, which causes the corner location to be bounded by a much-smaller margin than the other isotope configurations. Thus, an additional case is required to calculate the dose rate on the Model AOS-100A and AOS-100A-S exposed side shipping cask surface for Co-60-C.

From the comparison provided in Table 5-45, it is clear that when the Model AOS-100B side dose rates are from the exposed shipping cask surface (gap) between the impact limiters, no external dose rates would be exceeded. This is a result of the difference in shielding configuration for this shipping cask design. Instead of tungsten alloy, the radial and axial shields are composed of carbon steel, which has a gamma shielding effectiveness that is near-equivalent to the stainless steel that is used for the shipping cask body. With no difference in shielding material, the shipping cask side provides almost 3 in. of additional shielding when compared to the shipping cask top/bottom.

Based on the comparisons made in this appendix, the Ir-194 isotope in the Model AOS-050A and Co-60-C isotope configuration in Models AOS-100A and AOS-100A-S are the only isotopes for which external dose rates would be exceeded with the side dose rates based on the exposed shipping cask surface. To account for this, two additional MCNP calculations were performed for the side transport package surface dose rate location being moved to the exposed shipping cask side. (Refer to Figure 5-13.) The results of these calculations are provided in Table 5-46. These new dose rate/curie values are used to update the results provided in Subsection 5.4.4 to account for relocating the side dose rate locations and allow for these isotopes to be transported as non-exclusive use under the new activity limits.

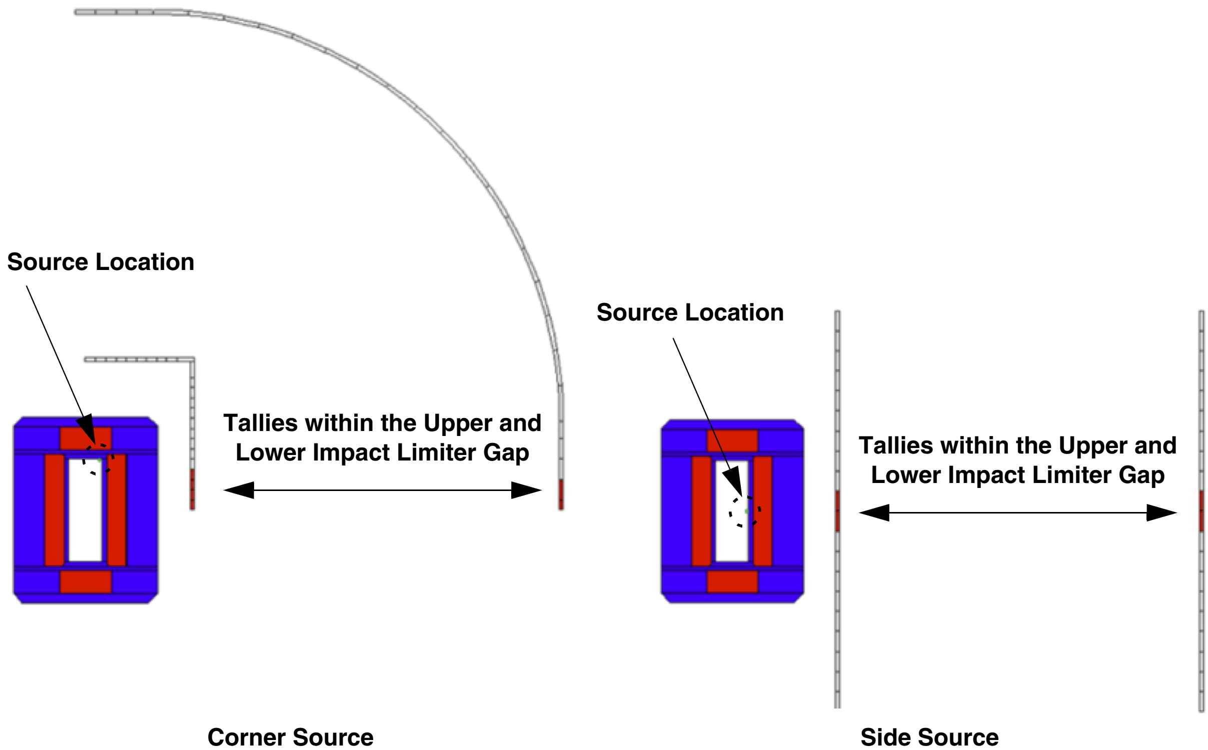

Figure 5-11. Impact Limiter Gap Dose Rate Locations – Model AOS-050A

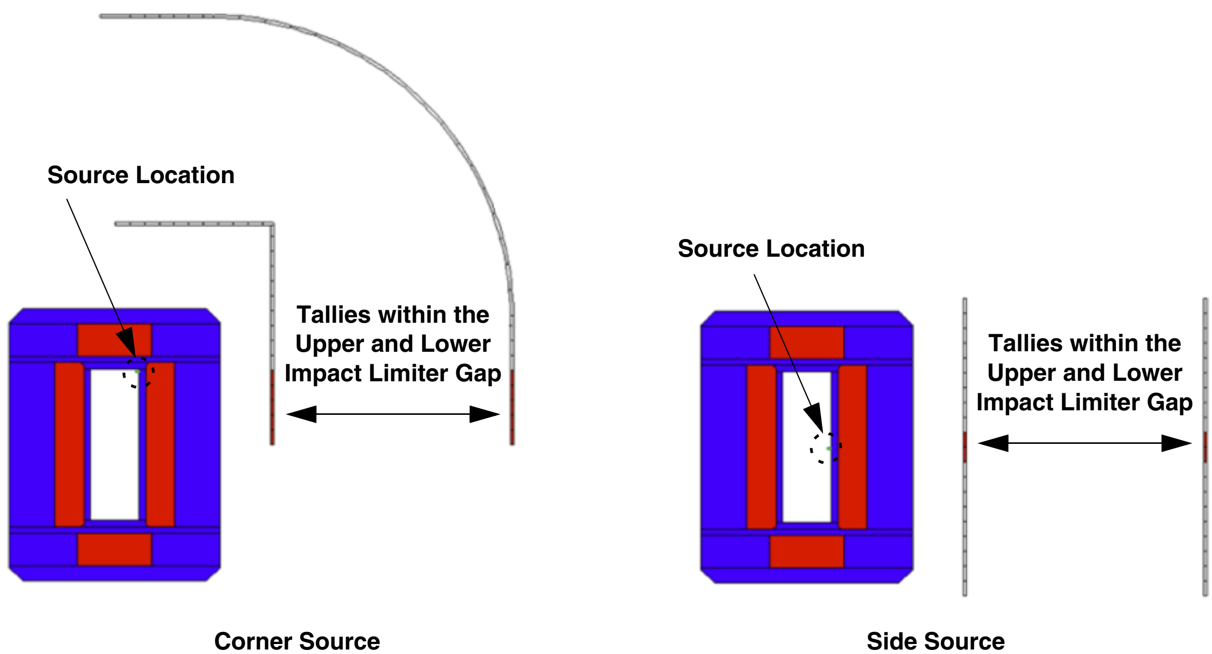

Figure 5-12. Impact Limiter Gap Dose Rate Locations – Models AOS-100A, AOS-100A-S, and AOS-100B

Table 5-43. Side Dose Rates – Model AOS-050A

Isotope	Location	Corner Source Dose Rate/Ci (mrem/hr/Ci)	Side Source Dose Rate/Ci (mrem/hr/Ci)	Maximum Dose Rate[a] (mrem/hr)	Safety Factor[b]
Co-60	1-m TI	2.844E+00	1.407E+00	2.13	4.2
	Side Surface	5.735E+01	4.191E+01	43.02	4.2
Cs-137	1-m TI	7.348E-02	4.299E-03	1.42	6.4
	Side Surface	1.122E+00	1.417E-01	21.62	8.3
Hf-181	1-m TI	1.377E-02	6.763E-05	1.27	7.1
	Side Surface	1.934E-01	2.620E-03	17.84	10.1
Zr/Nb-95	1-m TI	5.359E-01	7.002E-02	1.56	5.8
	Side Surface	8.542E+00	2.252E+00	24.78	7.3
Yb-169	1-m TI	9.848E-05	3.527E-07	0.93	9.7
	Side Surface	1.372E-03	1.242E-05	12.95	13.9
Ir-192	1-m TI	9.294E-04	6.741E-04	1.08	8.4
	Side Surface	2.601E-02	2.138E-02	30.11	6.0
Ir-194	1-m TI	1.569E-02	1.478E-02	4.55	2.0
	Side Surface	4.695E-01	4.385E-01	136.03	1.3

a. *Calculated as the dose rate/Ci value listed times the isotope activity limit based on the corner location, as calculated in Subsection 5.4.4.*

b. *Calculated as the dose rate limit for the respective location (180 or 9 mrem/hr) divided by the maximum dose rate listed.*

Table 5-44. Side Dose Rates – Models AOS-100A and AOS-100A-S

Isotope	Location	Corner Source Dose Rate/Ci (mrem/hr/Ci)	Side Source Dose Rate/Ci (mrem/hr/Ci)	Maximum Dose Rate[a] (mrem/hr)	Safety Factor[b]
Co-60	1-m TI	4.673E-03	5.319E-04	1.28	7.0
	Side Surface	2.767E-02	5.467E-03	7.57	23.8
Co-60-B	1-m TI	6.992E-04	5.303E-04	0.58	15.6
	Side Surface	6.325E-03	5.453E-03	5.21	34.6
Co-60-C	1-m TI	3.471E-04	5.314E-04	10.74	0.8
	Side Surface	3.228E-03	5.452E-03	110.20	1.6
Cs-137	1-m TI	2.134E-05	1.750E-08	0.76	11.9
	Side Surface	1.354E-04	1.773E-07	4.81	37.4
Hf-181	1-m TI	1.261E-06	1.931E-10	0.55	16.5
	Side Surface	8.292E-06	1.220E-09	3.59	50.1
Zr/Nb-95	1-m TI	2.400E-04	9.879E-07	0.87	10.4
	Side Surface	1.470E-03	1.098E-05	5.31	33.9
Ir-192	1-m TI	3.919E-06	3.741E-08	0.76	11.8
	Side Surface	2.358E-05	3.934E-07	4.60	39.2
Ir-194	1-m TI	5.873E-05	9.548E-06	1.37	6.6
	Side Surface	3.548E-04	9.458E-05	8.25	21.8

a. Calculated as the dose rate/Ci value listed times the isotope activity limit based on the corner location, as calculated in Subsection 5.4.4.

b. Calculated as the dose rate limit for the respective location (180 or 9 mrem/hr) divided by the maximum dose rate listed.

Table 5-45. Side Dose Rates – Model AOS-100B

Isotope	Location	Corner Source Dose Rate/Ci (mrem/hr/Ci)	Side Source Dose Rate/Ci (mrem/hr/Ci)	Maximum Dose Rate[a] (mrem/hr)	Safety Factor[b]
Co-60	1-m TI	9.753E-02	9.924E-02	1.08	8.3
	Side Surface	9.571E-01	9.666E-01	10.52	17.1
Cs-137	1-m TI	7.345E-04	7.285E-04	0.43	21.1
	Side Surface	7.738E-03	7.839E-03	4.56	39.5
Hf-181	1-m TI	5.412E-05	5.457E-05	0.24	37.6
	Side Surface	6.112E-04	6.035E-04	2.68	67.1
Zr/Nb-95	1-m TI	7.510E-03	7.370E-03	0.55	16.4
	Side Surface	7.504E-02	7.762E-02	5.67	31.7
Ir-192	1-m TI	1.312E-04	1.304E-04	0.35	25.5
	Side Surface	1.347E-03	1.398E-03	3.76	47.9
Ir-194	1-m TI	1.182E-03	1.182E-03	1.17	7.7
	Side Surface	1.114E-02	1.126E-02	11.12	16.2

a. *Calculated as the dose rate/Ci value listed times the isotope activity limit based on the corner location, as calculated in Subsection 5.4.4.*

b. *Calculated as the dose rate limit for the respective location (180 or 9 mrem/hr) divided by the maximum dose rate listed.*

Table 5-46. New Isotopic Dose Rates and Limits – Models AOS-050A, AOS-100A, and AOS-100A-S

Transport Package	Isotope (A_{limit})	Location	Dose Rate/Ci (mrem/hr/Ci)	Dose Rate (mrem/hr)
AOS-050A	Ir-194 (156.5 Ci)	1-m TI	2.628E-02[a]	4.11
		Transport Package Surface	1.150E+00	180.00
AOS-100A AOS-100A-S	Co-60-C (9,634.4 Ci)	1-m TI	5.314E-04	5.12
		Transport Package Surface	1.868E-02	180.00

a. *The 1-m TI for this isotope is still limited by corner dose rate location.*

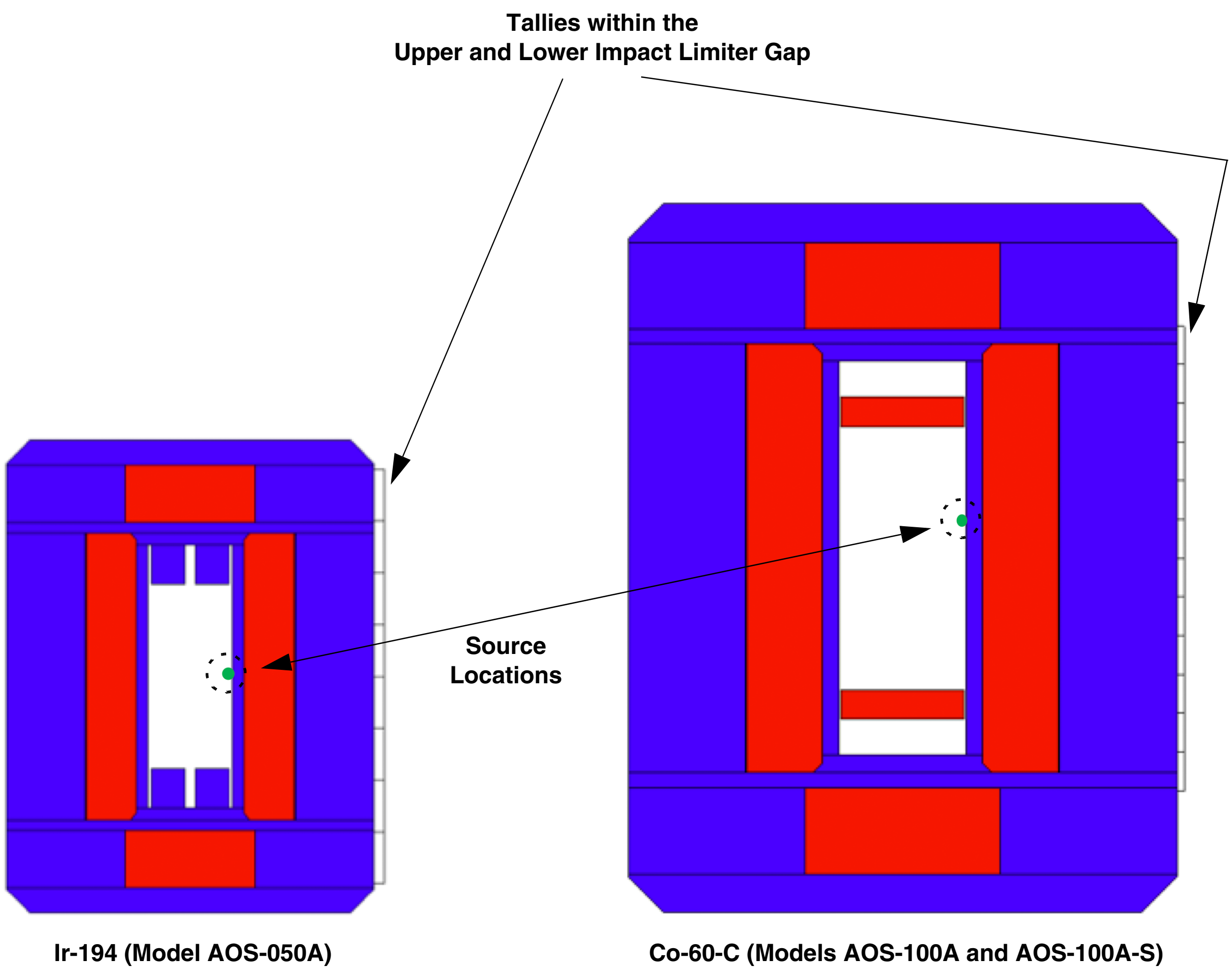

Figure 5-13. Impact Limiter Gap Dose Rate Locations – Ir-194 (Model AOS-050A) and Co-60-C (Models AOS-100A and AOS-100A-S)

5.5.8.2 Assessment of Recessed Region within Upper and Lower Impact Limiters Effect on External Dose Rates

In the original AOS shipping cask shielding analysis, the recessed region within the upper and lower impact limiters was not considered because this region is inaccessible due to the shipping cage that is required for transporting all transport packages. Neglecting the shipping cage, because it is not defined as being part of the transport package, the impact limiter recessed regions provide an area in which the transport package surface dose rate location offset provided by the impact limiters is smaller than the offset in the MCNP models, which accounts only for NCT deformations. Figure 5-14 illustrates a cross-sectional view of an AOS shipping cask that shows the recessed region within the upper and lower impact limiters.

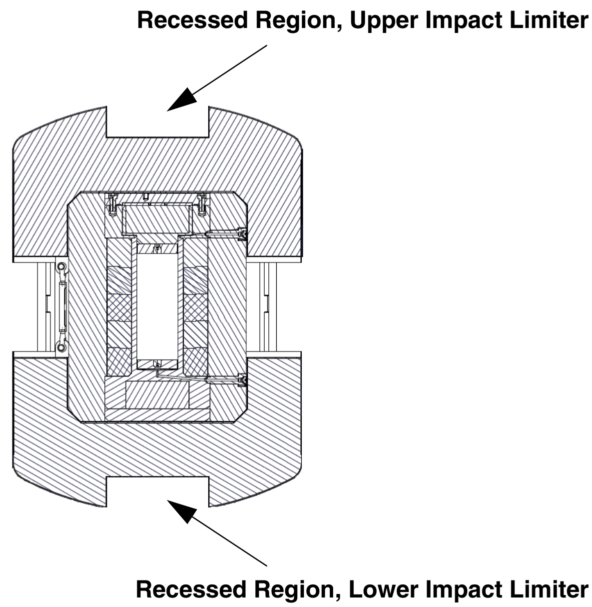

Figure 5-14. Example Cross-Sectional View Showing Impact Limiter Recessed Regions – Models AOS-100A and AOS-100B Shown

Table 5-47 lists the calculated differences in the axial offset to the transport package surface dose rate location between the MCNP models, based on the NCT drop deformation, and the offset to the recessed region within the upper and lower impact limiters. The effect on external dose rates of considering this recessed region is different for each AOS shipping cask variant due to the difference in shielding components and the limiting dose rate location of each. To consider these effects, each shipping cask variant is analyzed below.

Table 5-47. Impact Limiter Offset Distance Differences – All Models

Parameter	Model					
	AOS-025		AOS-050		AOS-100	
	cm	in.	cm	in.	cm	in.
Impact Limiter Offset	9.21	3.63	17.35	6.83	34.70	13.66
NCT Drop Deformation	1.52	0.60	3.81	1.50	6.60	2.60
Modeled Offset	7.68	3.03	13.54	5.33	28.09	11.06
Recess Depth	3.10	1.22	6.32	2.49	12.62	4.97
Recessed Offset	6.11	2.41	11.02	4.34	22.07	8.69
Δ_{Offset}	1.57	0.62	2.51	0.99	6.02	2.37

The approximate difference in the external dose rates based on the change in the axial tally offset when considering the recessed region within the upper and lower impact limiters is calculated in the same manner as the gap between the upper and lower impact limiters, as discussed in Appendix 5.5.8.1. The calculations listed in Table 5-47 are used to calculate the approximate dose rate increase from moving the tally location for the transport package surface and 1-m TI locations in Table 5-48. Table 5-48 shows that the expected external dose rate increase from considering the reduced offset within the recessed region of the upper and lower impact limiters would be approximately 25 to 30% for the transport package surface, and approximately 3 to 9% for the 1-m TI, depending on the shipping cask variant. These dose rate increases do not account for the spacer/shielding components in the Model AOS-050A (for Ir-192 and Ir-194) or Models AOS-100A and AOS-100A-S (for Co-60-B and Co-60-C). These components equally increase the distance between the source and dose rate location, both modeled and within the recessed region, thereby resulting in a lower distance ratio (r_1^2 / r_2^2). Thus, it is acceptable to neglect these components because including them would result in a smaller predicted dose rate increase within the recessed region of the upper and lower impact limiters.

Based on the Table 5-13 and Table 5-17 results, the Model AOS-025A's limiting dose rate location is the transport package surface, and there is nearly a 200% or more margin for the 1-m TI location for each isotope. Thus, an approximate 25% increase is considered for the transport package surface dose rate within the recessed region of the upper and lower impact limiters, and the 1-m TI location is not considered an issue due to the large margin.

Based on the Table 5-14 and Table 5-18 results, the Model AOS-050A's limiting dose rate location is the transport package surface, and there is nearly a 40 to 70% margin for the 1-m TI location depending on the isotope. Thus, an approximate 25% increase is considered for the transport package surface dose rate within the recessed region of the upper and lower impact limiters, and the 1-m TI location is not considered an issue due to the large margin.

Based on the Table 5-15 and Table 5-19 (Models AOS-100A and AOS-100A-S), and Table 5-16 and Table 5-20 (Model AOS-100B) results, the Model AOS-100A, AOS-100A-S, and AOS-100B's limiting dose rate location is always the 1-m TI location, and there is a 60 to 90% margin for the transport package surface location depending on the isotope. The only exception is Co-60-C in Models AOS-100A and AOS-100A-S, which is bounded by the exposed shipping cask side surface, as discussed in Appendix 5.5.8.1. Not considering Co-60-C, the highest transport package surface dose rate for the Model AOS-100A, AOS-100A-S, and AOS-100B transport packages is for Cs-137 in Models AOS-100A and AOS-100A-S. With a maximum transport package surface dose rate of 111.63 mrem/hr (refer to Table 5-15), a 30% dose rate increase would result in a dose rate of 147.8 mrem/hr, which is still well below the limit. Thus, an approximate 9% increase is considered for the 1-m TI dose rate within the recessed region of the upper and lower impact limiters, and the transport package surface location is not considered an issue due to the large margin.

Table 5-48. Projected Dose Rate Increase within Recessed Regions of Upper and Lower Impact Limiters – All Models

Axial Location		Model		
		AOS-025	AOS-050	AOS-100
MCNP Source		4.19	12.69	25.39
Transport Package Surface	MCNP Tally	19.11	36.42	73.81
	Recessed Region	17.54	33.91	67.80
	r_1^2 / r_2^2	1.249	1.251	1.304
	Approximate Percentage Increase	24.9%	25.1%	30.4%
1-m TI	MCNP Tally	119.11	136.42	173.81
	Recessed Region	117.54	133.91	167.80
	r_1^2 / r_2^2	1.028	1.042	1.086
	Approximate Percentage Increase	2.8%	4.2%	8.6%

5.5.8.2.1 Model AOS-025A

The Model AOS-025A's limiting dose rate is for a source that is located in the cask cavity's top corner, out the side of the transport package, on the deformed impact limiter. Figure 5-15 illustrates the Model AOS-025A transport package surface dose rate calculation's tally configuration. For the transport package surface, the tally cells wrap from the top to the side of the transport package, and are numbered 1701 to 1713. The maximum dose rate location tally cell (1712) of every isotope is highlighted in **red**. Table 5-49 lists the MCNP calculation transport package surface dose rate results for each isotope. When compared to tally cell locations 1701 and 1702 within the recessed region of the upper and lower impact limiters, the Table 5-49 results show that the side surface bounds by a significant margin.

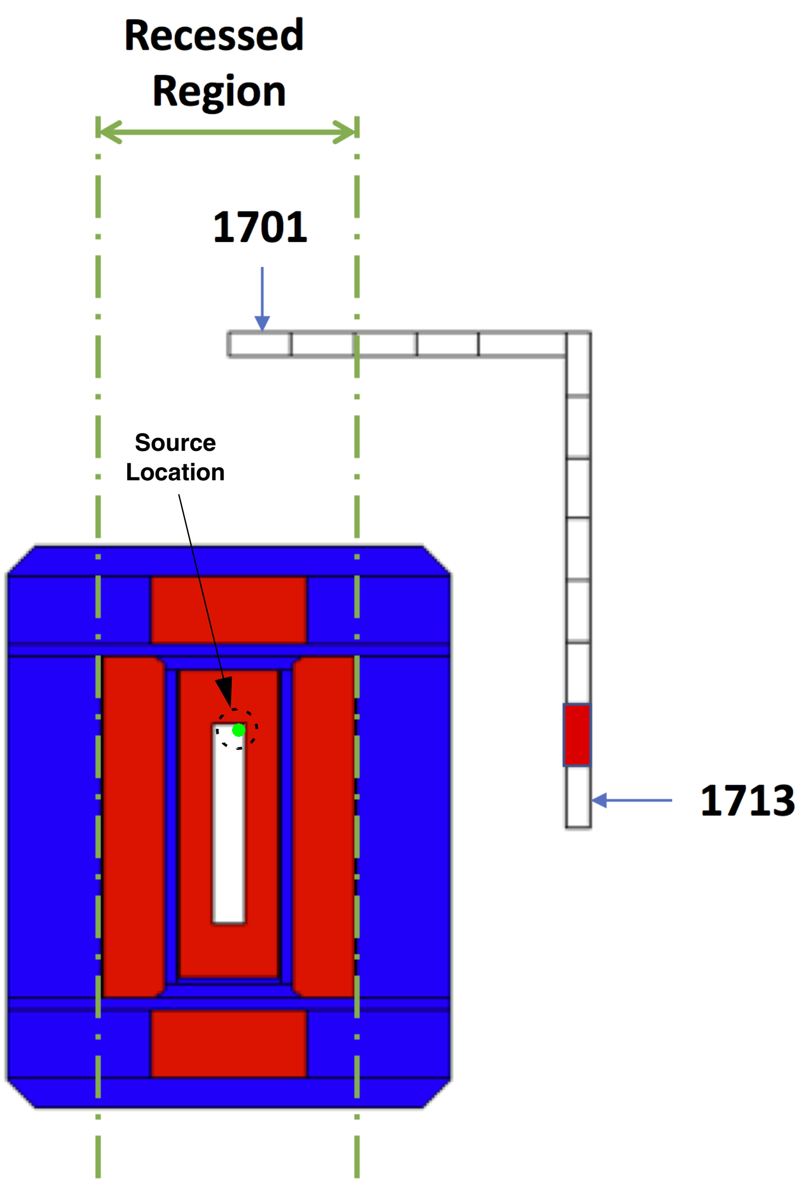

Figure 5-15. Transport Package Surface Tallies – Model AOS-025A

Table 5-49. Full Transport Package Surface Dose Rates/Ci – Model AOS-025A

Tally Cell	Isotope				
	Co-60	Cs-137	Ir-192	Ir-194	Yb-169
1701	8.42E+02	1.00E+01	1.42E+00	8.44E+00	6.75E-04
1702	8.13E+02	1.08E+01	1.56E+00	8.16E+00	7.15E-04
1703	7.36E+02	1.10E+01	1.60E+00	7.45E+00	7.43E-04
1704	7.36E+02	1.17E+01	1.70E+00	7.46E+00	7.84E-04
1705	6.78E+02	1.21E+01	1.81E+00	6.94E+00	8.41E-04
1706	4.96E+02	8.12E+00	1.19E+00	5.07E+00	5.60E-04
1707	4.96E+02	7.35E+00	1.05E+00	5.03E+00	4.87E-04
1708	5.31E+02	7.26E+00	1.02E+00	5.37E+00	4.79E-04
1709	6.98E+02	9.05E+00	1.24E+00	7.08E+00	5.75E-04
1710	1.01E+03	1.31E+01	1.78E+00	1.02E+01	8.23E-04
1711	1.28E+03	1.71E+01	2.30E+00	1.29E+01	1.07E-03
1712	1.35E+03	1.80E+01	2.42E+00	1.37E+01	1.13E-03
1713	1.16E+03	1.46E+01	1.95E+00	1.17E+01	9.05E-04

Table 5-50 lists each isotope's calculated maximum dose rate within the recessed region of the upper and lower impact limiters, based on the respective activity limit and maximum dose rate/curie within the region (tally cell 1701 or 1702). The Table 5-50 results show that there is an approximate 60% margin in the transport package surface dose rate within this region. Thus, moving the tally cells within this region 0.62 in. nearer to the shipping cask, based on the recessed region's dimensions, would not result in this location becoming the limiting location because the approximate increase in transport package surface dose rate for this deformation is only 25%.

Table 5-50. Maximum Transport Package Surface Dose Rate within Recessed Region of Upper and Lower Impact Limiters – Model AOS-025A

Maximum Dose Rate, by Isotope (mrem/hr)				
Co-60	Cs-137	Ir-192	Ir-194	Yb-169
112	108	116	111	114

5.5.8.2.2 Model AOS-050A

The Model AOS-050A's limiting dose rate is for a source that is located in the cask cavity's top corner, out the top of the transport package, on the deformed impact limiter. Figure 5-16 illustrates the Model AOS-050A transport package surface dose rate calculation's tally configuration. For the transport package surface, the tally cells wrap from the top to the side of the transport package, and are numbered 1701 to 1724. The maximum dose rate tally cell locations (1705 to 1707) for each isotope are highlighted in **red**. Table 5-51 lists the MCNP calculation transport package surface dose rate results for each isotope. The Table 5-51 results show that the top surface locations outside the recessed region are bounding; however, the limiting locations are near the recessed region within the upper and lower impact limiters (tally cells 1701 to 1704).

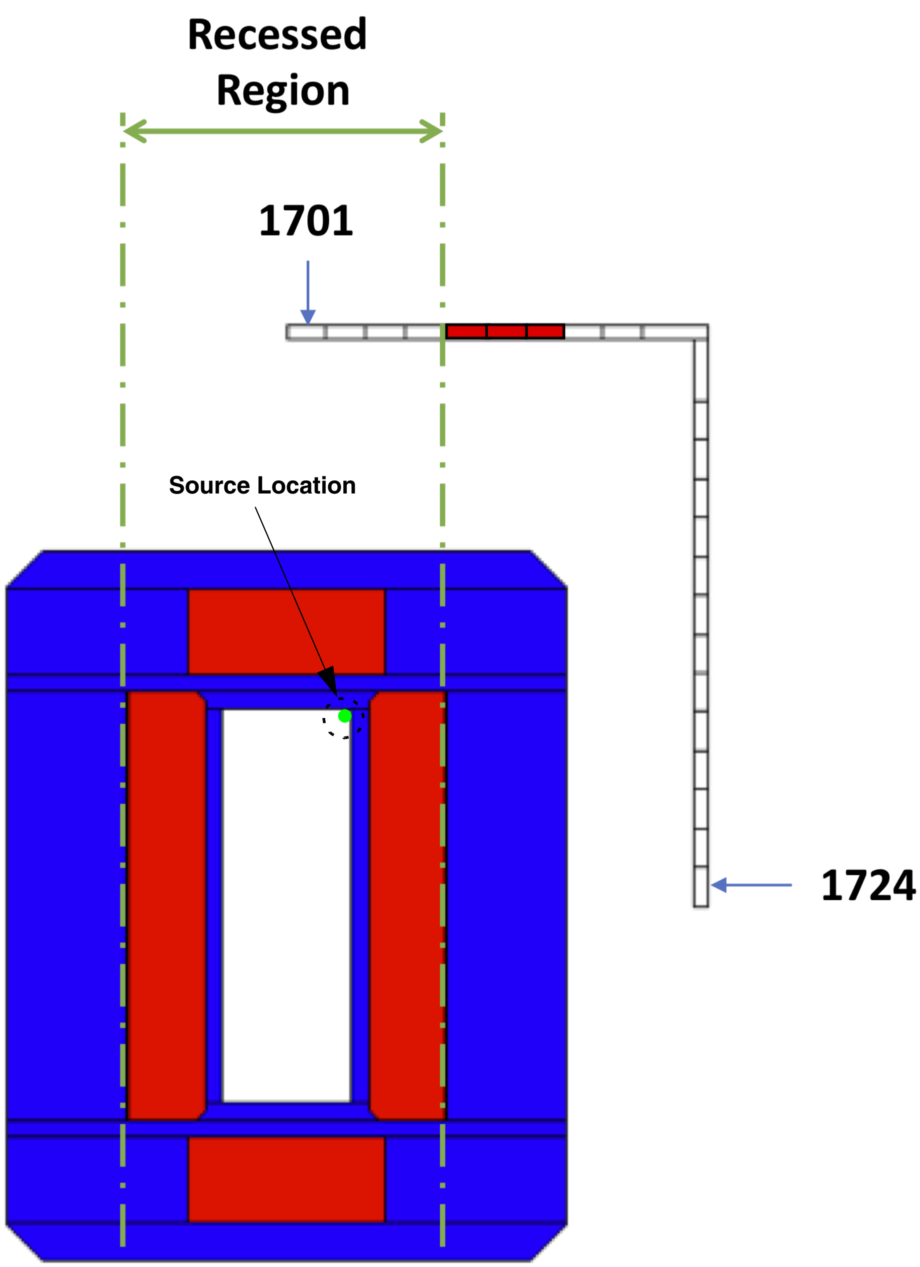

Figure 5-16. Transport Package Surface Tallies – Model AOS-050A

Table 5-51. Full Transport Package Surface Dose Rates/Ci – Model AOS-050A

Tally Cell	Isotope						
	Co-60	Cs-137	Hf-181	Ir-192	Ir-194	Yb-169	Zr/Nb-95
1701	1.29E+02	4.14E+00	8.99E-01	8.90E-02	3.67E-01	8.54E-03	2.75E+01
1702	1.49E+02	5.33E+00	1.19E+00	1.11E-01	4.70E-01	1.17E-02	3.51E+01
1703	1.72E+02	6.84E+00	1.53E+00	1.23E-01	5.28E-01	1.51E-02	4.42E+01
1704	1.90E+02	8.08E+00	1.80E+00	1.33E-01	5.03E-01	1.79E-02	5.24E+01
1705	2.08E+02	8.94E+00	1.95E+00	1.43E-01	5.73E-01	1.91E-02	5.82E+01
1706	2.34E+02	9.34E+00	1.95E+00	1.55E-01	6.21E-01	1.83E-02	6.20E+01
1707	2.40E+02	9.17E+00	1.82E+00	1.27E-01	5.08E-01	1.62E-02	6.18E+01
1708	2.27E+02	8.47E+00	1.61E+00	9.35E-02	3.65E-01	1.33E-02	5.76E+01
1709	1.98E+02	7.32E+00	1.36E+00	6.79E-02	2.62E-01	1.05E-02	5.03E+01
1710	1.53E+02	5.55E+00	1.03E+00	4.24E-02	1.66E-01	7.41E-03	3.79E+01
1711	1.31E+02	4.64E+00	8.71E-01	2.96E-02	1.24E-01	6.49E-03	3.17E+01
1712	1.26E+02	4.37E+00	8.07E-01	2.33E-02	1.11E-01	5.88E-03	3.00E+01
1713	1.29E+02	4.29E+00	7.86E-01	1.92E-02	1.07E-01	5.60E-03	2.99E+01
1714	1.21E+02	3.82E+00	6.79E-01	1.49E-02	1.09E-01	4.48E-03	2.69E+01
1715	1.18E+02	3.56E+00	6.16E-01	1.29E-02	1.31E-01	4.06E-03	2.54E+01
1716	1.23E+02	3.63E+00	6.30E-01	1.43E-02	1.78E-01	4.32E-03	2.59E+01
1717	1.16E+02	3.46E+00	6.28E-01	1.81E-02	2.43E-01	4.47E-03	2.46E+01
1718	1.01E+02	3.01E+00	5.62E-01	2.20E-02	3.20E-01	4.12E-03	2.14E+01
1719	8.80E+01	2.37E+00	4.42E-01	2.41E-02	3.94E-01	3.27E-03	1.70E+01
1720	7.28E+01	1.69E+00	3.03E-01	2.72E-02	4.49E-01	2.21E-03	1.24E+01
1721	5.74E+01	1.12E+00	1.93E-01	2.60E-02	4.70E-01	1.37E-03	8.54E+00
1722	4.30E+01	7.05E-01	1.20E-01	2.34E-02	4.41E-01	7.89E-04	5.67E+00
1723	3.12E+01	4.39E-01	7.19E-02	1.92E-02	3.80E-01	4.68E-04	3.64E+00
1724	2.08E+01	2.79E-01	4.29E-02	1.43E-02	2.97E-01	3.02E-04	2.30E+00

Table 5-52 lists each isotope's calculated maximum dose rate within the recessed region of the upper and lower impact limiters, based on the respective activity limit and maximum dose rate/curie within the region (tally cell 1704). The Table 5-52 results show that the margin to the regulatory limit is not large for this region. Thus, an approximate 25% dose rate increase could result in external dose rates that exceed the regulatory limit. Thus, additional cases are added to more-accurately calculate the dose rate within this region for all isotopes except Ir-194 because Ir-194 has significant margin to the regulatory limit due to the exposed side transport package surface between the impact limiters being the bounding location. (Refer to Appendix 5.5.8.1.)

Table 5-52. Maximum Transport Package Surface Dose Rate within Recessed Region of Upper and Lower Impact Limiters – Model AOS-050A

Maximum Dose Rate, by Isotope (mrem/hr)[a]						
Co-60	**Cs-137**	**Hf-181**	**Ir-192**	**Ir-194**	**Yb-169**	**Zr/Nb-95**
143	156	166	154	83	169	152

a. *Based on the Original Activity Limits. (Refer to Table 5-53.)*

For the other Model AOS-050A isotope cases, the maximum tally cell (1704) within the recessed region is shifted down to match the offset provided by the recessed region within the upper and lower impact limiters, rather than the deformed surface of the outer region. As a result, the top transport package surface tally is moved to axial location Z = 33.91. (Refer to Table 5-48.) All other tallies are removed for this specific case. Figure 5-17 illustrates this new model with the shifted tally cell location, with an 11.02-cm offset provided by the recessed region within the upper and lower impact limiters. (Refer to Table 5-47.)

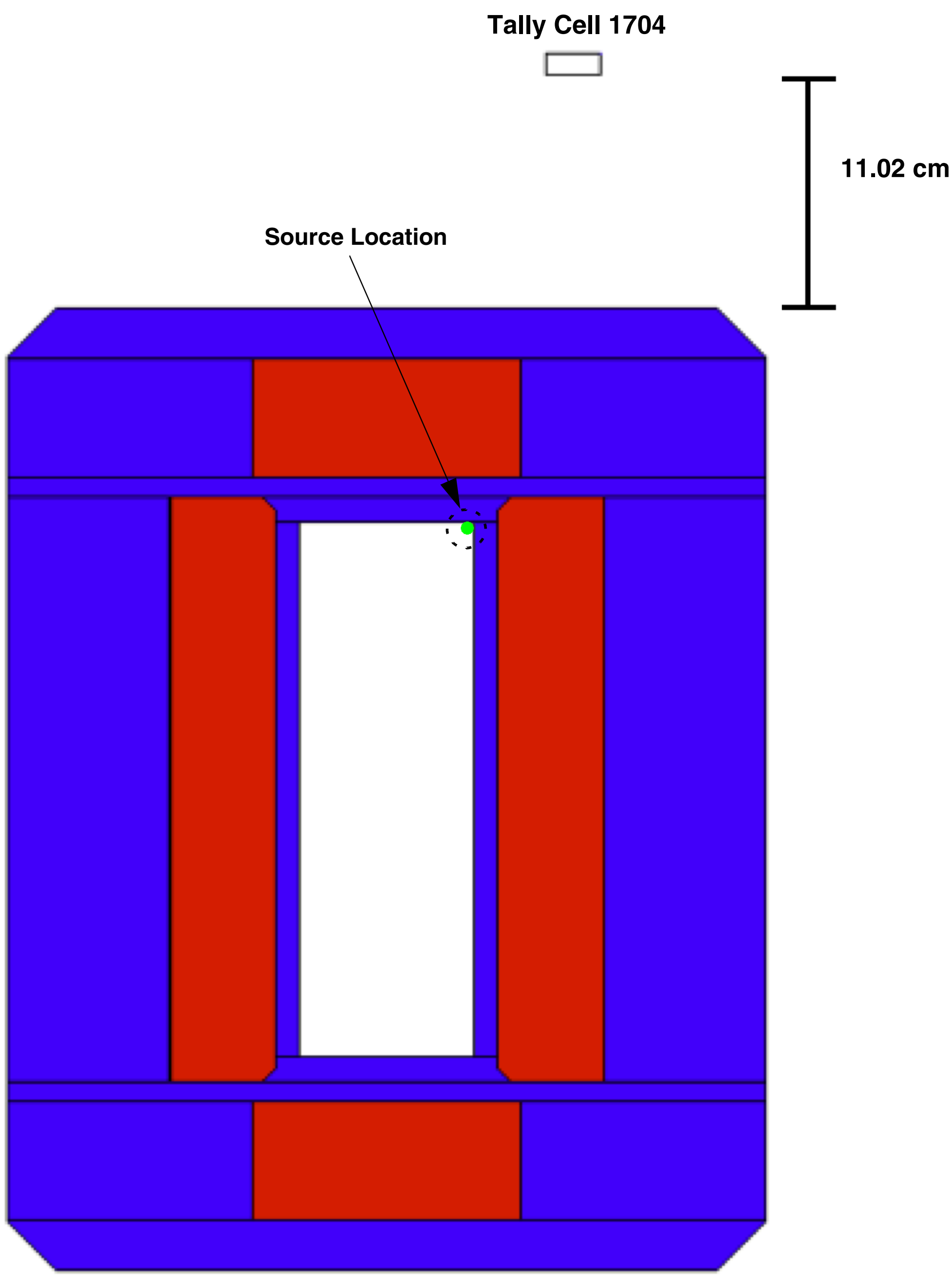

Figure 5-17. Recessed Region Model – Model AOS-050A

Table 5-53 provides the run results of this updated model illustrated in Figure 5-17, including comparisons to the maximum dose rates calculated from the base MCNP models with an offset based on the deformed impact limiter. The Table 5-53 results show that the activity limits of some isotopes are reduced to account for this transport package surface dose rate increase, considering the recessed region within the upper and lower impact limiters. The Co-60 and Ir-194 activity limits are not changed by this calculation.

Table 5-53. Dose Rates within Recessed Region of Upper and Lower Impact Limiters – Model AOS-050A

Isotope	Original A_{limit} (Ci)	New A_{limit} (Ci)	Deformed Impact Limiter		Recessed Region	
			Dose Rate/Ci (mrem/hr/Ci)	Maximum Dose Rate (mrem/hr)[a]	Dose Rate/Ci (mrem/hr/Ci)	Maximum Dose Rate (mrem/hr)[a]
Co-60	7.50E-01	7.47E-01[b]	2.400E+02	179.3	2.410E+02	180.0
Cs-137	1.93E+01	1.72E+01[b]	9.345E+00	160.7	1.044E+01	179.5
Hf-181	9.23E+01	7.66E+01[b]	1.951E+00	149.5	2.349E+00	180.0
Ir-192	1.16E+03	1.07E+03[b]	1.555E-01	166.4	1.669E-01	178.6
Yb-169	9.44E+03	7.77E+03[b]	1.907E-02	148.2	2.317E-02	180.0
Zr/Nb-95	2.90E+00	2.66E+00[b]	6.204E+01	165.0	6.768E+01	180.0

a. *Based on dose rate/Ci value times new activity limit.*

b. *New activity limit due to increased dose rate within recessed region of upper and lower impact limiters.*

5.5.8.2.3 Models AOS-100A and AOS-100A-S

The Model AOS-100A and AOS-100A-S's limiting dose rate is for a source that is located in the cask cavity's top corner, out the top corner of the transport package, 1-m from the deformed impact limiter. This is the case for all isotopes except Co-60-C, which is limited by the exposed side shipping cask surface between the upper and lower impact limiters. (Refer to Appendix 5.5.8.1.) Figure 5-18 illustrates the Model AOS-100A and AOS-100A-S 1-m TI dose rate calculation's tally configuration. For the 1-m TI, the tally cells wrap from the top to the side of the transport package, and are numbered 1901 to 1944. The maximum dose rate tally cell locations (1907 to 1915) for each isotope are highlighted in **red**. Table 5-54 lists the MCNP calculation 1-m TI dose rate results of tally cells 1901 to 1920 for each isotope. For all tally cells from 1920 to 1944, the dose rate continually decreases for each isotope. The Table 5-54 results show that the 1-m TI locations outside the recessed region are bounding; however, the limiting locations are relatively near the recessed region (tally cells 1901 to 1904), depending on the isotope.

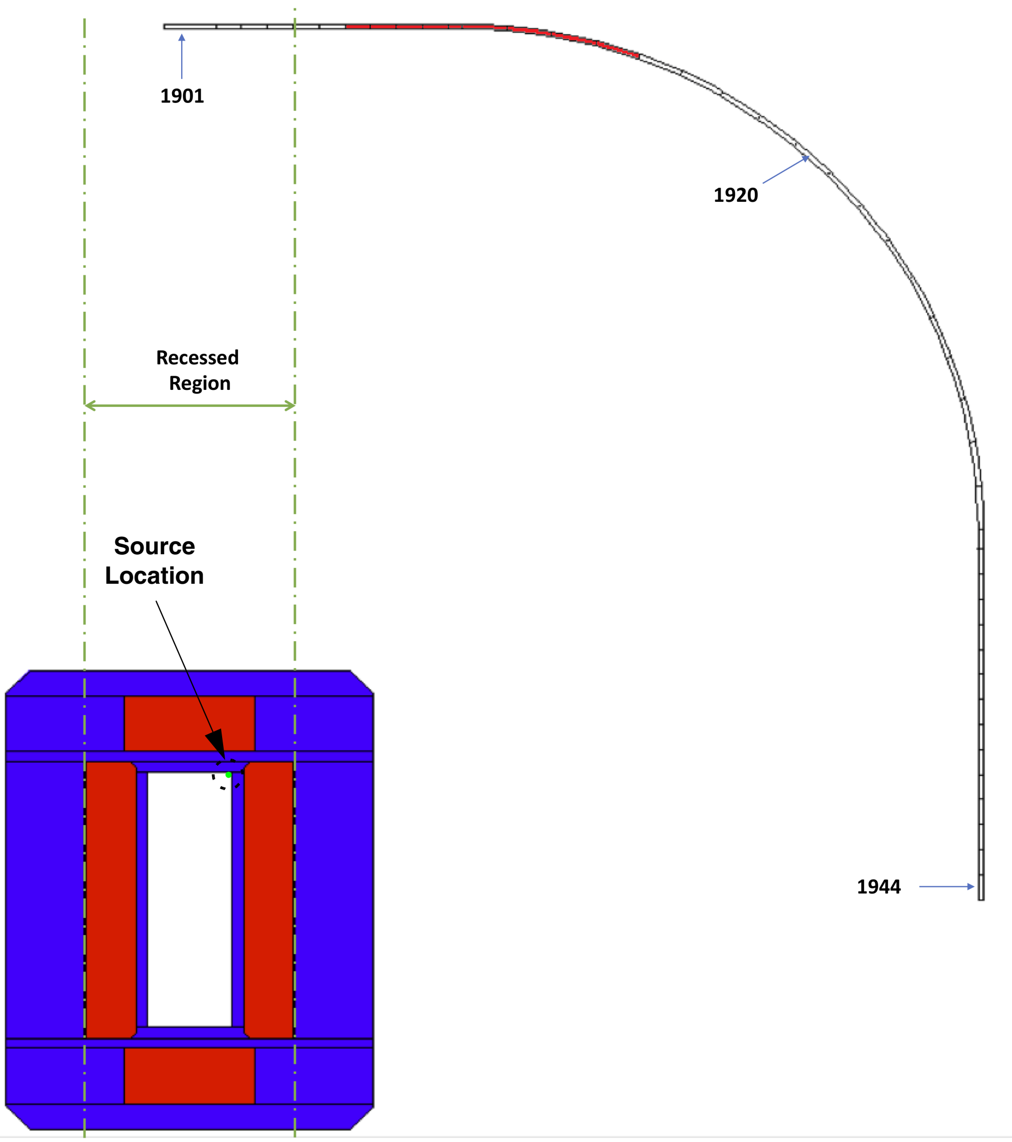

Figure 5-18. 1-m TI Tallies – Models AOS-100A and AOS-100A-S

Table 5-54. 1-m TI Dose Rates/Ci – Models AOS-100A and AOS-100A-S

Tally Cell	Isotope							
	Co-60	Co-60-B	Co-60-C[a]	Cs-137	Hf-181	Ir-192	Ir-194	Zr/Nb-95
1901	2.13E-02	5.62E-03	3.02E-04	1.95E-04	1.62E-05	3.55E-05	2.45E-04	1.88E-03
1902	2.42E-02	6.50E-03	3.80E-04	2.17E-04	1.83E-05	4.00E-05	2.84E-04	2.12E-03
1903	2.54E-02	7.27E-03	3.65E-04	2.29E-04	1.90E-05	4.25E-05	2.88E-04	2.19E-03
1904	2.69E-02	7.57E-03	3.34E-04	2.34E-04	1.98E-05	4.45E-05	3.04E-04	2.34E-03
1905	2.80E-02	7.85E-03	3.51E-04	2.44E-04	2.05E-05	4.60E-05	3.23E-04	2.41E-03
1906	2.88E-02	8.09E-03	3.53E-04	2.48E-04	2.07E-05	4.57E-05	3.36E-04	2.43E-03
1907	2.98E-02	8.30E-03	3.57E-04	2.53E-04	2.08E-05	4.54E-05	3.43E-04	2.47E-03
1908	3.07E-02	8.53E-03	3.56E-04	2.52E-04	2.03E-05	4.55E-05	3.53E-04	2.49E-03
1909	3.12E-02	8.63E-03	3.66E-04	2.53E-04	2.04E-05	4.62E-05	3.57E-04	2.49E-03
1910	3.16E-02	8.82E-03	3.95E-04	2.50E-04	1.96E-05	4.52E-05	3.66E-04	2.45E-03
1911	3.20E-02	9.01E-03	4.45E-04	2.46E-04	1.94E-05	4.46E-05	3.72E-04	2.49E-03
1912	3.22E-02	9.31E-03	4.28E-04	2.38E-04	1.82E-05	4.36E-05	3.73E-04	2.38E-03
1913	3.27E-02	9.95E-03	4.07E-04	2.24E-04	1.68E-05	3.99E-05	3.86E-04	2.27E-03
1914	3.29E-02	1.07E-02	3.34E-04	2.07E-04	1.50E-05	3.72E-05	3.87E-04	2.14E-03
1915	3.24E-02	1.09E-02	2.75E-04	1.88E-04	1.32E-05	3.37E-05	3.86E-04	1.98E-03
1916	3.13E-02	8.80E-03	2.21E-04	1.70E-04	1.15E-05	3.02E-05	3.76E-04	1.82E-03
1917	2.92E-02	6.54E-03	1.77E-04	1.50E-04	9.80E-06	2.69E-05	3.54E-04	1.62E-03
1918	2.63E-02	5.05E-03	1.47E-04	1.29E-04	8.22E-06	2.31E-05	3.22E-04	1.42E-03
1919	2.30E-02	3.91E-03	1.20E-04	1.10E-04	6.87E-06	1.97E-05	2.85E-04	1.22E-03
1920	1.94E-02	3.03E-03	1.02E-04	9.20E-05	5.68E-06	1.63E-05	2.40E-04	1.02E-03

a. Based on the bounding source geometry in Table 5-33 (Arc Segment with ID = 6 in. and q = 80°).

Table 5-55 lists each isotope's calculated maximum dose rate within the recessed region of the upper and lower impact limiters, based on the respective activity limit and maximum dose rate/curie within the region (tally cell 1904 for all but Co-60-C; tally cell 1903 for Ci-60-C). The Table 5-55 results show that the margin to the regulatory limit significantly varies, depending on the isotope of interest. For any of these isotopes, a 10% dose rate increase would not result in the 1-m TI regulatory limit of 10 mrem/hr being exceeded because of the 10% margin included in all activity limits. Based on the Table 5-55 results, if the dose rate were increased by 10%, the isotope nearest to the regulatory limit would be Ir-192, at 9.55 mrem/hr. However, to hold the 10% margin to the regulatory dose rate limits, the activity limit of any isotope that would exceed 9 mrem/hr within this region is reduced to a level that maintains the full 10% margin. Table 5-56 lists the original and new activity limits, as well as the maximum dose rate within the recessed region with a 10% increase in the calculated dose rate/curie value. The new activity limits listed in Table 5-56 are used as the updated activity limits for each isotope that is used by Models AOS-100A and AOS-100A-S.

Table 5-55. Maximum 1-m TI Dose Rate within Recessed Region of Upper and Lower Impact Limiters – Models AOS-100A and AOS-100A-S

Maximum Dose Rate, by Isotope (mrem/hr)							
Co-60	**Co-60-B**	**Co-60-C**	**Cs-137**	**Hf-181[a]**	**Ir-192**	**Ir-194**	**Zr/Nb-95**
7.35	6.23	3.66	8.30	1.83	8.68	7.07	8.44

a. *Activity limited based on shipping cask's thermal limit. (Refer to Table 1-2, "10 CFR 71.47(a) Activity Limits (All Isotopes Except Ir-192 and Ir-194) – All Models.")*

Table 5-56. Maximum Dose Rates within Recessed Region of Upper and Lower Impact Limiters – Models AOS-100A and AOS-100A-S

Isotope	Maximum Dose Rate/Ci (mrem/hr/Ci)[a]	Original		New	
		A_{limit} (Ci)	Maximum Dose Rate (mrem/hr)	A_{limit} (Ci)	Maximum Dose Rate (mrem/hr)
Co-60	2.961E-02	2.73E+02	8.08E+00	2.73E+02	8.08E+00
Co-60-B	8.325E-03	8.23E+02	6.85E+00	8.23E+02	6.85E+00
Co-60-C	4.181E-04	9.63E+03	4.03E+00	9.63E+03	4.03E+00
Cs-137	2.570E-04	3.55E+04	9.12E+00	3.50E+04	9.00E+00
Hf-181	2.182E-05	9.23E+04	2.01E+00	9.23E+04	2.01E+00
Ir-192	4.898E-05	1.95E+05	9.54E+00	1.84E+05	9.00E+00
Ir-194	3.347E-04	2.32E+04	7.78E+00	2.32E+04	7.78E+00
Zr/Nb-95	2.571E-03	3.61E+03	9.28E+00	3.50E+03	9.00E+00

a. *Based on maximum dose rate/curie within the recessed region increased by 10% times the activity limit.*

5.5.8.2.4 Model AOS-100B

The Model AOS-100B's limiting dose rate is for a source that is located in the cask cavity's top or top corner, out the top of the transport package, 1-m from the deformed impact limiter. Figure 5-19 illustrates the Model AOS-100B top corner source 1-m TI dose rate calculation's tally configuration. For the 1-m TI, the tally cells wrap from the top to the side of the transport package, and are numbered 1901 to 1944. The maximum dose rate tally cell locations (1902 and 1903) for each isotope are highlighted in **red**. Table 5-57 lists the MCNP calculation 1-m TI dose rate results of tally cells 1901 to 1920 for each isotope. For tally cells 1920 to 1944, the dose rate continually decreases for each isotope. The Table 5-57 results show that the 1-m TI locations within the recessed region are bounding due to the less-effective carbon steel axial shielding that is used in the Model AOS-100B.

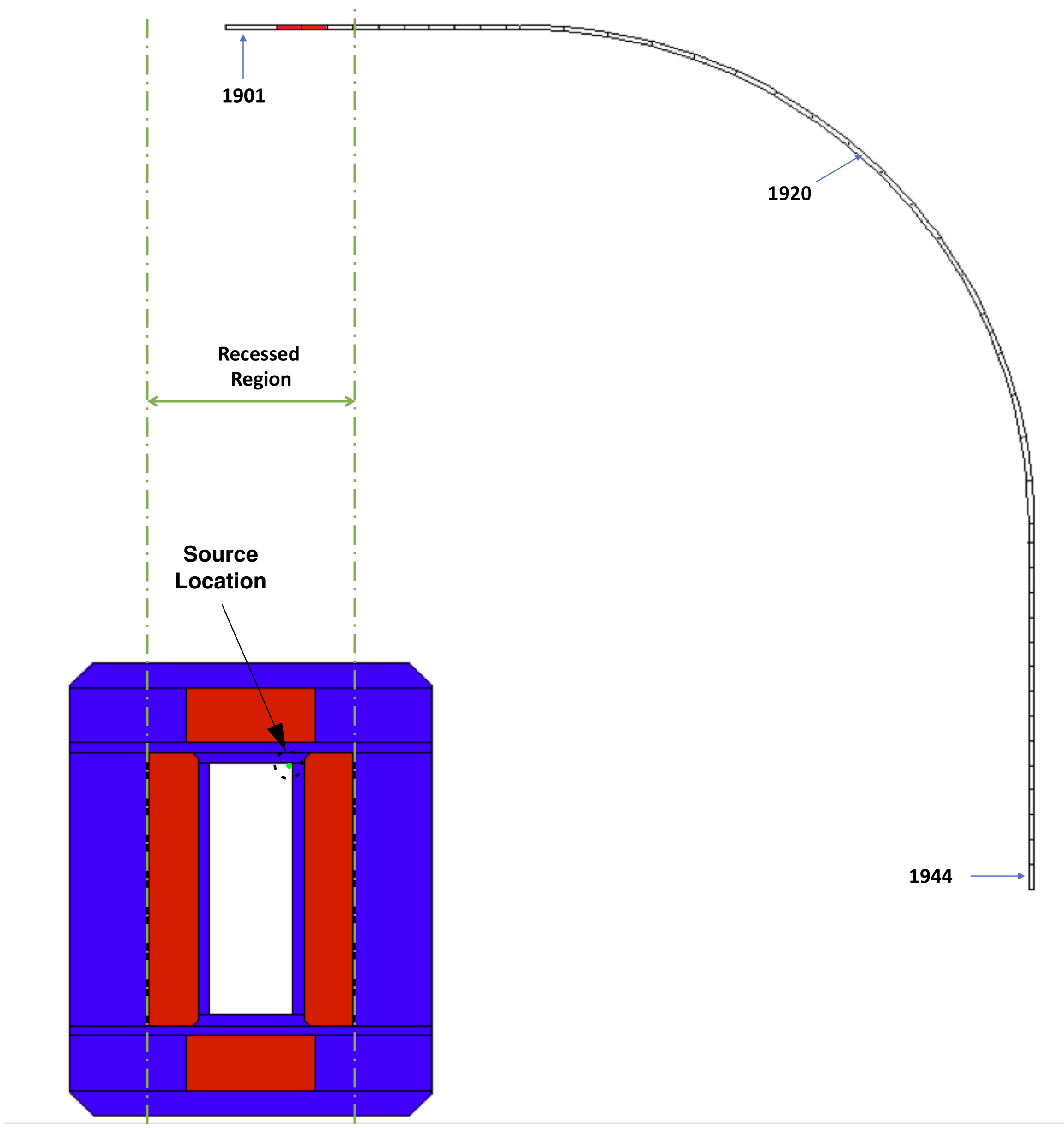

Figure 5-19. 1-m TI Tallies – Model AOS-100B

Table 5-57. 1-m TI Dose Rate/Ci – Model AOS-100B

1-m TI Dose Rate/Ci, by Isotope (mrem/hr)						
Tally Cell	**Co-60**	**Cs-137**	**Hf-181**	**Ir-192**	**Ir-194**	**Zr/Nb-95**
1901	8.10E-01	1.51E-02	2.00E-03	3.23E-03	8.84E-03	1.19E-01
1902	8.27E-01	1.54E-02	2.05E-03	3.34E-03	9.10E-03	1.23E-01
1903	8.24E-01	1.54E-02	2.05E-03	3.34E-03	9.12E-03	1.23E-01
1904	8.25E-01	1.52E-02	2.01E-03	3.23E-03	9.00E-03	1.20E-01
1905	7.91E-01	1.47E-02	1.94E-03	3.22E-03	8.74E-03	1.20E-01
1906	7.85E-01	1.43E-02	1.84E-03	3.03E-03	8.50E-03	1.15E-01
1907	7.38E-01	1.36E-02	1.78E-03	2.93E-03	8.12E-03	1.09E-01
1908	7.08E-01	1.29E-02	1.69E-03	2.74E-03	7.70E-03	1.03E-01
1909	6.63E-01	1.21E-02	1.57E-03	2.58E-03	7.26E-03	9.66E-02
1910	6.17E-01	1.12E-02	1.45E-03	2.42E-03	6.91E-03	9.03E-02
1911	6.01E-01	1.07E-02	1.39E-03	2.26E-03	6.44E-03	8.54E-02
1912	5.40E-01	9.68E-03	1.23E-03	2.03E-03	5.86E-03	7.70E-02
1913	4.62E-01	8.23E-03	1.04E-03	1.74E-03	5.19E-03	6.61E-02
1914	3.95E-01	6.95E-03	8.75E-04	1.46E-03	4.38E-03	5.61E-02
1915	3.34E-01	5.78E-03	7.28E-04	1.22E-03	3.69E-03	4.68E-02
1916	2.80E-01	4.80E-03	5.98E-04	1.00E-03	3.12E-03	3.88E-02
1917	2.30E-01	3.94E-03	4.93E-04	8.32E-04	2.57E-03	3.21E-02
1918	1.90E-01	3.25E-03	4.08E-04	6.78E-04	2.10E-03	2.63E-02
1919	1.56E-01	2.67E-03	3.31E-04	5.55E-04	1.73E-03	2.16E-02
1920	1.27E-01	2.19E-03	2.70E-04	4.57E-04	1.41E-03	1.78E-02

Table 5-58 lists each isotope's calculated maximum dose rate within the recessed region of the upper and lower impact limiters, based on the respective activity limit and maximum dose rate/curie within the region (tally cell 1902 or 1903). Because these tallies are the limiting locations for the 1-m TI, the maximum dose rate for each isotope is approximately 9 mrem/hr. The values vary slightly above or below 9 mrem/hr due to the rounding of activity limits. A 10% dose rate increase within this region would not result in the 1-m TI regulatory limit of 10 mrem/hr being exceeded because the resulting maximum dose rate would be approximately 9.9 mrem/hr. However, to maintain a safety margin between the maximum dose rates and regulatory limit, all final Model AOS-100B activity limits are reduced by 10% to account for the external dose rate increase. Table 5-59 lists the original and new activity limits, as well as the maximum dose rate within the recessed region with a 10% increase in the calculated dose rate/curie value. The new activity limits in Table 5-59 are used as the updated activity limits for each isotope that is used by Model AOS-100B.

Table 5-58. Maximum 1-m TI Dose Rate within Recessed Region of Upper and Lower Impact Limiters – Model AOS-100B

Maximum Dose Rate, by Isotope (mrem/hr)					
Co-60	**Cs-137**	**Hf-181**	**Ir-192**	**Ir-194**	**Zr/Nb-95**
9.02	8.96	9.00	8.98	9.00	9.00

Table 5-59. Maximum Dose Rates within Recessed Region of Upper and Lower Impact Limiters – Model AOS-100B

Isotope	Maximum Dose Rate/Ci (mrem/hr/Ci)[a]	Original		New	
		A_{limit} (Ci)	Maximum Dose Rate (mrem/hr)	A_{limit} (Ci)	Maximum Dose Rate (mrem/hr)
Co-60	9.098E-01	1.09E+01	9.92E+00	9.89E+00	9.00E+00
Cs-137	1.694E-02	5.82E+02	9.86E+00	5.29E+02	8.96E+00
Hf-181	2.256E-03	4.39E+03	9.90E+00	3.99E+03	9.00E+00
Ir-192	3.674E-03	2.69E+03	9.87E+00	2.44E+03	8.98E+00
Ir-194	1.003E-02	9.87E+02	9.90E+00	8.97E+02	9.00E+00
Zr/Nb-95	1.355E-01	7.31E+01	9.90E+00	6.65E+01	9.00E+00

a. *Based on maximum dose rate/curie within the recessed region increased by 10% times the activity limit.*

5.6 REFERENCES

[5.1] U.S. Nuclear Regulatory Commission (NRC), *Title 10 Code of Federal Regulations, Part 71 (10 CFR 71)*, "Packaging and Transportation of Radioactive Material."

[5.2] Oak Ridge National Laboratory, *ORNL/TM-2005/39 Version 6.1*. "SCALE: A Comprehensive Modeling and Simulation Suite for Nuclear Safety Analysis and Design," June, 2011.

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