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(Docket No. 71-9316)

Radioactive Material Transport Packaging System

Safety Analysis Report

for Model AOS-025, AOS-050, and AOS-100 Transport Packages

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Revision History

Revision	Date	Description of Changes
A	January 11, 2008	Preliminary release.
B	June 20, 2009	Preliminary release.
C	September 11, 2009	Preliminary release.
D	September 28, 2010	Preliminary release.
E	October 11, 2011	Preliminary release.
F	February 1, 2012	Initial Release.
G	July 27, 2012	• Update to include cask lid elastomeric seal, and included text so the cask lid metallic seal is differentiated from the new elastomeric seal. • Applied miscellaneous corrections (table of changes included with cover page of the submittal).
H	December 30, 2012	• Updated in response to NRC RAIs. • Applied miscellaneous corrections (table of changes included with cover page of the submittal).
H-1	March 11, 2016	• Updated to add new isotope, Ir-194. • General update to correct errors and incorporate changes communicated to NRC in letters dated April 4, May 14, and September 26, 2013, and May 6, June 5, and August 5, 2015. • Applied miscellaneous updates and corrections (table of changes included with cover page of the submittal).
H-2	June 27, 2016	Updated in response to NRC RAI.
H-3	May 3, 2017	Clarified *Special Form* material shipment requirements and applied miscellaneous corrections.
H-4	November 28, 2017	Updated Cask Thread Sealant-related information.
H-5	July 20, 2018	• **Chapter 1** – Revised Subsection 1.2.2 (added discussion relating to isotope mixtures); revised Table 1-2 (deleted footnote e and renumbered remaining footnotes); added Table 1-2b; updated Table 1-5 drawing revisions • **Chapter 2** – Replaced Paragraph 2.5.3.1.4; added Appendix 2.12.16 • **Chapter 5** – Added Appendix 5.5.5, Appendix 5.5.6, and Appendix 5.5.7 • **Chapter 7** – Added Appendix 7.5.1 • Applied miscellaneous corrections (table of changes included with cover page of the submittal)
H-6	December 10, 2018	• Update in response to NRC RAI (10-09-2018) addressing changes and clarifications in SAR Chapters 1, 5, 7, and 8 • Applied miscellaneous corrections (table of changes included with cover page of the submittal)
H-7	January 25, 2019	• Updated in response to NRC questions (email dated 01-15-2019) addressing changes and clarifications in SAR Chapters 1, 2, 5, and 7 • Table of changes included with the cover page of the submittal

1.2.1.2 Impact Limiter

The impact limiter is a major component consisting of a thin-walled cylindrical shell, with a dish head at one end and a flat disk at the other end. At the flat-disk end, there is a cylindrical recess, with an internal profile identical to that of the cask end profile. This cavity accommodates the cask in the transport configuration. Figure 2-5, "Isometric View – Typical Impact Limiter," presents an isometric view of the impact limiter.

Twelve (12) squared ribs are attached to the inside wall of the cylindrical recess section. Eight (8) of these ribs extend beyond the flat disk plate, which are used as turnbuckle attachment points. The turnbuckles are used to join the impact limiters and to partially enclose the cask component. For the Model AOS-025, the two (2) impact limiters entirely cover the cask, and the turnbuckles are replaced with "J" hooks.

The transport package exterior incorporates one (1) or more tamper-indicating devices, that are not readily breakable. While intact (that is, not broken), these devices provide evidence that the package has not been opened by unauthorized persons. (For further details regarding the tamper-indicating devices, refer to Chapter 7, "Package Operations.")

1.2.1.3 Cask Lid Seal

Two (2) types of cask lid seals are used. One consists of two (2) elastomeric O-Rings, a cross-section captured within one (1) or two (2) flat metal retainer rings to form a unit. The other is a metallic, double "C" cross-section arrangement.

The elastomeric seal is comprised of two (2) components:

- **O-Rings** – Silicone, Parker Compound S1224-70, ASTM D2000
- **Retainer Rings** – ASME SA-240/ ASTM A240, Type 304 or 316 Stainless Steel

The metallic seal is comprised of three (3) components:

- **Jacket** – Silver, ASTM B742
- **Spring** – Nickel-chromium alloy 90 UNS N07090
- **Lining** – SS304L UNS S30403 (may/may not be present)

The seal design provides a means for leak testing between the two (2) O-Rings (elastomeric seal) or double "C" cross-sections (metallic seal), by way of the cask lid's Test Port feature. (For further details regarding the cask lid seal, refer to Appendix 4.5.1, "Garlock Helicoflex Cask Lid Metallic Seal and AOS Cask Lid Elastomeric Seal Drawings.")

1.2.1.4 Other Components

In addition to the previously mentioned components, the AOS Transport Packaging System uses other components or structures, in support of its operations. A series of liners and shielding plates enhances the shielding characteristics for shipments of specific content. Refer to Table 1-2, Table 1-2a, and Table 1-2b for the requirements of when to use these shielding devices.

A transport pallet is used as a base for the transport packages, for tying down the package during transport.

The shipping cage is a five (5)-sided metal structure, with the pallet creating a sixth side, which completes a cube shape. Each side covered with an expandable metal mesh or screen material, that keeps unauthorized persons away from the transport package surfaces during transport, and provides a means to meet temperature regulation requirements.

The packages have no tie-down devices nor structural parts that can be used for unintended tie-down, thus satisfying the additional requirements of *10 CFR 71.45(b)* **[1.1]**.

1.2.2 Contents

Table 1-2 and Table 1-2a provide a list of the isotopes that are authorized for use with the AOS Transport Packaging System. Table 1-2a provides pre-determined mixtures of the Ir-192 and Ir-194 isotopes that are acceptable within each shipping cask model. Other isotope mixtures, including mixtures of Ir-192 and Ir-194 that do not fall directly under one the predetermined mixtures in Table 1-2a, are permitted within the shipping cask contents when external dose rate and decay heat limit compliance is demonstrated per the guidance specified in Appendix 7.5.1, "Dose Rate and Decay Heat Limit Compliance." Isotopes that emit only low-energy gammas and/or betas (that is, all emissions, including those from their progeny, are less than 0.3 MeV) are permitted for transport in the Model AOS-100A and AOS-100A-S shipping casks. To clarify, this requirement applies to the full beta spectrum, **not** the average beta energy (that is, $E_{max,\beta} \leq 0.3$). Isotopes that meet this criteria:

- Do not need to be considered for dose rate calculations
- Need to be accounted for only when calculating the shipping cask contents' total decay heat

Table 1-2 and Table 1-2a demonstrate the use of curie content to meet the radioactive and thermal maximum limits specified in Table 1-3, for individual isotopes within each transport package model. Furthermore, the shielding requirements specified in Table 1-2 and Table 1-2a apply, where applicable. The activity limits presented in Table 1-2a should be interpreted as follows: for a shipment with a total Ir-194 impurity up to the specified activity, the corresponding Ir-192 activity limit is listed (for example, for Model AOS-050A, any shipment with a total Ir-194 activity up to 10 Ci, the Ir-192 activity limit is 1,009 Ci). For Models AOS-100A and AOS-100A-S, if the isotope activities exceed the values listed in Table 1-2, the activity limits for each isotope specified in Table 1-2b may be used, provided that the shipping cask is shipped as exclusive use.

The AOS Transport Packaging System can be used for transporting solid radioactive materials in *Normal* and *Special Form*. Any materials with a melting point less than 538°C (1,000°F) are required to be in *Special Form*. *Special Form* materials require a current Special Form Competent Authority Certificate. Dispersible *Normal Form* materials are required to be enclosed within an inner container. An inner container is considered to be a "shoring device."

Fissile materials and irradiated fissile materials containing fission products are not authorized for this packaging. In addition, no free-standing liquid is permitted.

The package can be shipped by surface or air transport, and meets the requirements for non-exclusive transport. (Refer to Table 1-2 and Table 1-2a.) For air transport, quantities are limited to the lesser of Table 1-2, Table 1-2a, or 3,000 A_2.

All shoring materials used within the cask cavity must have a melting point greater than (i) 600°F for Co-60 in metallic form and Cs-137 in the form of cesium chloride and (ii) 900°F for all other contents.

Radioactive contents can be in any location within the cask cavity, and unconstrained within the inner containers. Holders, fixtures, and packaging materials (shoring devices) must be used to secure the inner containers, so that the inner containers are immobilized. The containers must be comprised of materials that are compatible with the radioactive contents and cask cavity.

Radioactive contents are limited by the external radiation levels specified in *10 CFR 71.47* and *71.51* **[1.1]**, and *49 CFR 173.441* **[1.3]**. Exclusive-Use mode of shipment is required whenever the radiation dose rates of the package exceed the external radiation standards in *10 CFR 71.47(a)* **[1.1]** for non-exclusive use shipment. For Models AOS-100A and AOS-100A-S, when shipped as exclusive use, the activity limits for each isotope are specified in Table 1-2b.

There are no materials added to the package for the purpose of neutron absorption nor moderation. Radiation shields (that is, liners, axial shielding plates, and/or cavity spacer plates) are required in certain cases, as stipulated in Table 1-2, Table 1-2a, and Table 1-2b.

The construction materials of the AOS Transport Packaging System and their proposed contents are compatible with one another; no chemical nor galvanic reactions are expected to occur, including the generation of combustible gas.

The transport packages shall be loaded under ambient atmospheric pressure and temperature conditions. The containment boundary will not normally be pressurized; however, internal heating of the enclosed gases can increase the pressure.

The maximum gross weight of the AOS Transport Packaging System, including contents, is listed in Table 1-1.

The maximum decay heats, listed in Table 1-2, Table 1-2a, and Table 1-2b, are calculated using the constants presented in Chapter 5, "Shielding Evaluation."

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Table 1-2. *10 CFR 71.47(a)*[a] Activity Limits (All Isotopes Except Ir-192 and Ir-194)[b] – All Models

Isotope[c]	Decay Heat (W/Ci)[d]	Model							
		AOS-025		AOS-050		AOS-100			
		A (10W)		A (100W)		A, A-S (400W)		B (400W)	
		TBq	Ci	TBq	Ci	TBq	Ci	TBq	Ci
Co-60	1.55E-02	4.92E-03	1.33E-01	2.76E-02	7.47E-01	1.01E+01	2.73E+02	3.66E-01	9.89E+00
Co-60-B	1.55E-02	–		–		3.05E+01	8.23E+02	–	
Co-60-C	1.55E-02	–		–		3.56E+02	9.63E+03	–	
Cs-137	4.99E-03	3.70E-01	1.00E+01	6.36E-01	1.72E+01	1.30E+03	3.50E+04	1.96E+01	5.29E+02
Hf-181	4.33E-03	–		2.83E+00	7.66E+01	3.41E+03[e]	9.23E+04[e]	1.46E+02	3.99E+03
Zr/Nb-95[f]	1.62E-02	–		9.84E-02	2.66E+00	1.30E+02	3.50E+03	2.43E+00	6.65E+01
Yb-169	2.55E-03	1.45E+02[e]	3.92E+03[e]	2.87E+02	7.77E+03	–		–	
Shipping Configuration		Use of Tungsten Alloy Shielding Liner 183C8485 is required		No additional shielding is required		**Co-60-B** quantities require use of Tungsten Alloy Axial Shielding Plates 183C8491 **Co-60-C** quantities require use of Tungsten Alloy Axial Shielding Plates 183C8491 and Stainless Steel –or– Aluminum Cavity Spacer Plates 183C8518		No additional shielding is required	

a. *Reference* **[1.1]**.

b. *Refer to Table 1-2a for Ir-192 and Ir-194 activity limits.*

c. *Solid material, including metals, that meets Normal or Special Form criteria. Special Form materials require a current Special Form Competent Authority Certificate.*

d. *For detailed calculations of these values, refer to Appendix 5.5.1, "AOS Cask Isotopic Heat Load Calculations."*

e. *Activity limit based on cask decay heat limit (rounded down to listed significant figures).*

f. *Activity limits for parent/daughter mixed isotope systems apply to the parent isotope. An equilibrium concentration of the daughter is assumed in the evaluations provided in Chapter 5, "Shielding Evaluation," to provide limiting dose and heat responses for the AOS Transport Packaging System.*

Table 1-2a. *10 CFR 71.47(a)*[a] Ir-192 and Ir-194 Activity Limits – All Models

Model	Ir-192 Limit		Ir-194 Impurity		Decay Heat (W)[b]	Shipping Configuration
	TBq	Ci	TBq	Ci		
AOS-025A (10W)	2.62	71	0.0185	0.5	0.44	Use of Tungsten Alloy Shielding Liner 183C8485 is required
	2.33	63	0.0740	2.0	0.40	
	2.10	57	0.1110	3.0	0.37	
AOS-050A (100W)	37.33	1,009	0.37	10	6.24	Use of Stainless Steel Axial Shielding Plates 183C8519 is required
	34.78	940	0.74	20	5.87	
	29.67	802	1.48	40	5.13	
	24.60	665	2.22	60	4.39	
	19.49	527	2.96	80	3.66	
	14.39	389	3.70	100	2.92	
AOS-100A, AOS-100A-S (400W)	2,286.37	61,794	148.00	4,000	400.00	No additional shielding is required
	2,094.42	56,606	370.00	10,000	400.00	
AOS-100B (400W)	80.51	2,176	3.70	100	13.87	No additional shielding is required
	67.37	1,821	8.51	230	12.39	

a. *Reference* **[1.1]**.

b. *Ir-192 and Ir-194 generate 6.13E-03 W/Ci and 5.30E-03 W/Ci, respectively. (Refer to Table 5-22, "AOS Cask Isotopic Heat Load Results.")*

Table 1-2b. *10 CFR 71.47(b)*[a] Activity Limits – Model AOS-100A and AOS-100A-S[b]

Isotope	Decay Heat (W/Ci)[c]	Models AOS-100A and AOS-100A-S (400W)	
		TBq	Ci
Co-60	1.55E-02	1.70E+01	4.60E+02
Co-60-B	1.55E-02	5.85E+01	1.58E+03
Co-60-C[d e]	1.55E-02	9.54E+02	2.58E+04
Cs-137	4.99E-03	2.09E+03	5.65E+04
Hf-181[e]	4.33E-03	3.41E+03	9.23E+04
Ir-192[e]	6.13E-03	2.41E+03	6.52E+04
Ir-194	5.30E-03	1.48E+03	4.00E+04
Zr/Nb-95[f]	1.62E-02	2.15E+02	5.81E+03
Shipping Configuration		**Co-60-B** quantities require use of Tungsten Alloy Axial Shielding Plates 183C8491 **Co-60-C** quantities require use of Tungsten Alloy Axial Shielding Plates 183C8491 and Stainless Steel –or– Aluminum Cavity Spacer Plates 183C8518	

a. *Reference* **[1.1]**.

b. *Activity limits based on Table 5-39, "Exclusive Use Activity Limit Maximum Dose Rates and Decay Heat – Models AOS-100A and AOS-100A-S."*

c. *For detailed calculations of these values, refer to Appendix 5.5.1, "AOS Cask Isotopic Heat Load Calculations."*

d. *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).*

e. *Activity limit based on the shipping cask's decay heat limit (rounded down to listed significant figures).*

f. *Activity limits for parent/daughter mixed isotope systems apply to the parent isotope. An equilibrium concentration of the daughter is assumed in the evaluations provided in Chapter 5, "Shielding Evaluation," to provide limiting dose and heat responses for the AOS Transport Packaging System.*

Table 1-3. Content Limitations – All Models

Model	Type	Content[a]	Decay Heat		Weight[b]	
			Watt	Btu/hr.	kg	lbs.
AOS-025A	Solid Material	*Normal Form* or *Special Form*	10	34.15	4.5	10
AOS-050A			100	341.5	27	60
AOS-100A			400	1,366	227	500
AOS-100B						
AOS-100A-S						

a. *Special Form materials require a current Special Form Competent Authority Certificate.*

b. *Maximum weight of contents including any additional shielding and shoring devices. Weight of contents can be adjusted so as not to exceed the maximum authorized gross weight of the package.*

1.3 APPENDIX

1.3.1 AOS Transport Packaging System, Certification Drawings

Table 1-5 lists the certification drawings for the AOS Transport Packaging System's assembly, impact limiter, cask, liner, axial shielding plates, and cavity spacer plates, by model.

Table 1-5. AOS Transport Packaging System Certification Drawing List – All Models

Component	Drawing Part Number and Revision, by Model									
	AOS-025A	Rev.	AOS-050A	Rev.	AOS-100A	Rev.	AOS-100B	Rev.	AOS-100A-S	Rev.
Assembly	166D8142	J	105E9718	J	105E9711	K	105E9711	K	105E9711	K
Impact Limiter	105E9722	I	166D8138	I	105E9713	J	105E9713	J	105E9713	J
Cask[a]	166D8143	I	166D8137	I	105E9712G001	L	105E9712G002	L	105E9719	L
Liner	183C8485	H	–	–	–	–	–	–	–	–
Axial Shielding Plates	–	–	183C8519	A	183C8491	I	–	–	183C8491	I
Cavity Spacer Plates	–	–	–	–	183C8518	B	–	–	183C8518	B

a. The G00x number appended to select drawing numbers represents a group within the drawing.

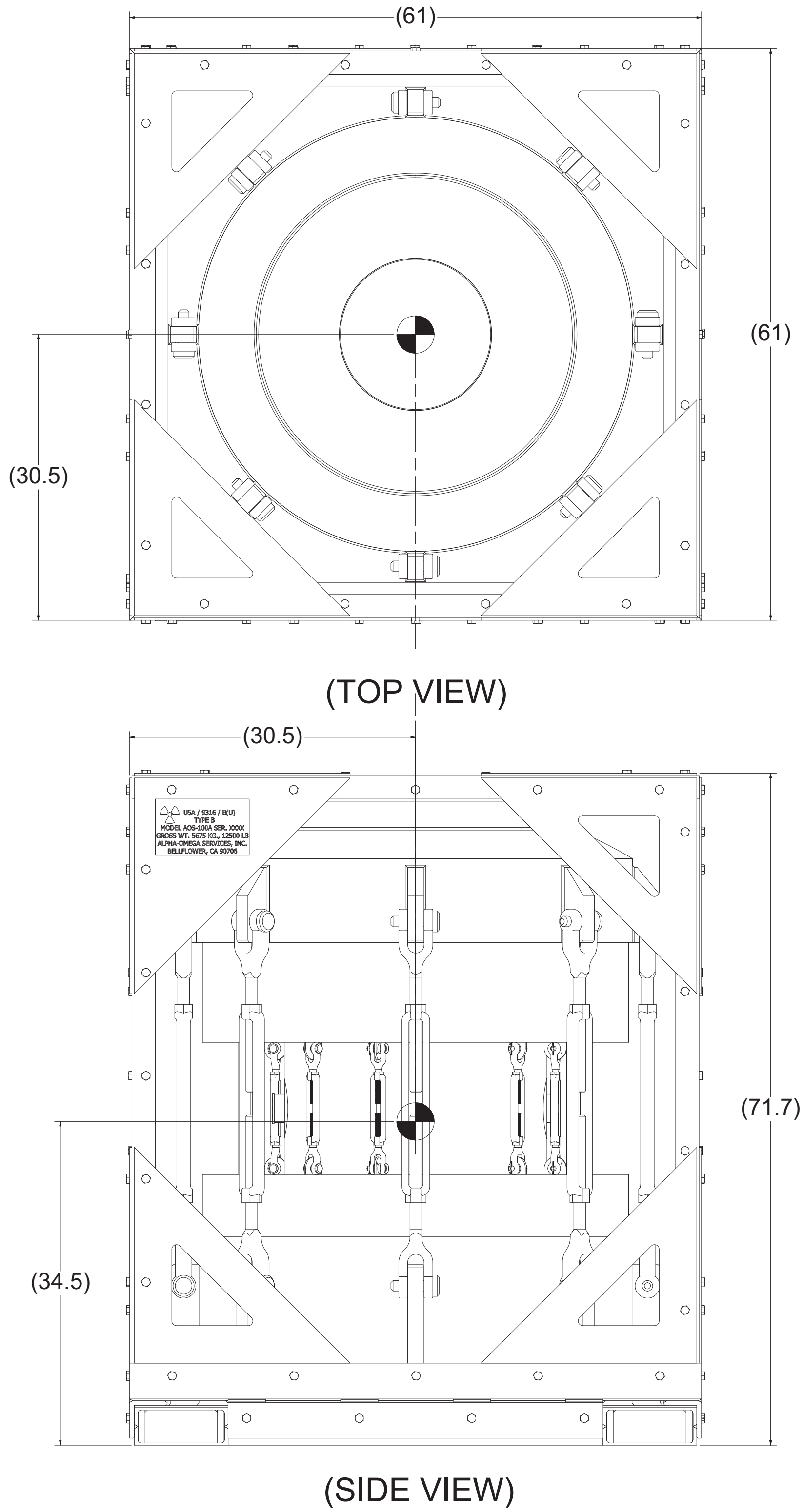


Figure 2-12. Center of Gravity – Model AOS-100

Note: *Dimensions are in inches.*

2.5 LIFTING AND TIE-DOWN STANDARDS FOR ALL PACKAGES

The following information is presented:

- Lifting Devices
- Tie-Down Devices
- Other Devices

2.5.1 Lifting Devices

10 CFR 71.45(a) **[2.1]** requires that lifting devices that are a structural part of the transport package must be capable of supporting three times the weight (3 W) of the loaded package, without generating stress in any material of the package in excess of its yield stress.

Figure 2-13 presents a cross-section of the trunnion area, as well as the force diagram associated with the lifting loads. The dimensions for the figure are listed in Table 2-20.

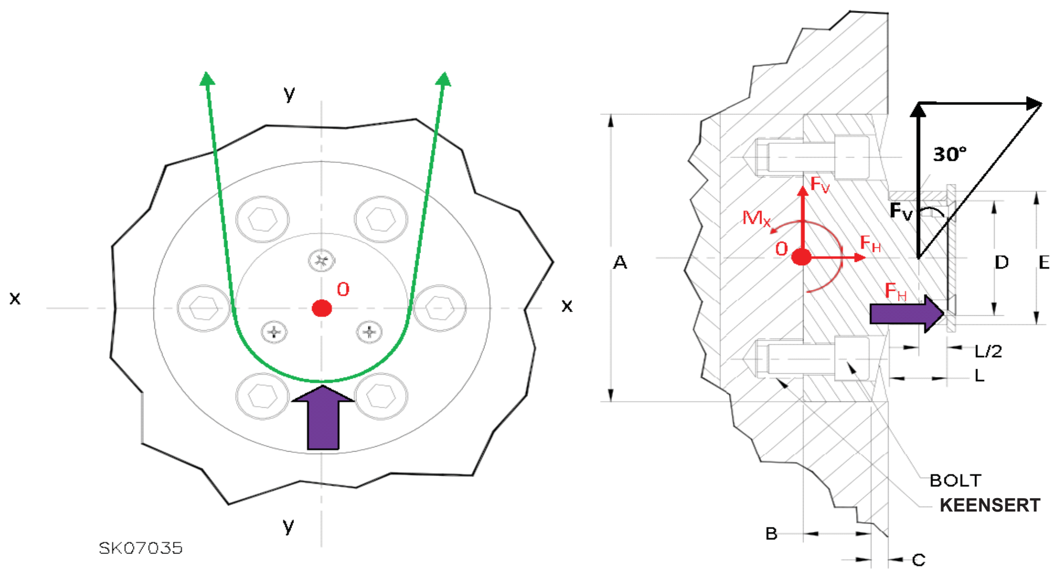


Figure 2-13. Trunnion Area Cross-Section and Force Diagram Associated with Lifting Loads

2.5.3.1.4 Analysis of Shipping Cage Fasteners – Model AOS-100

Shipping Cage Properties

Center of Gravity = H = 46.6 in.

Length = L = 61.0 in.

Mass = W = 450 lbs.

Fastener Properties

16-1/2 in. bolts

$A = 0.141\ in^2$

Yield Stress =

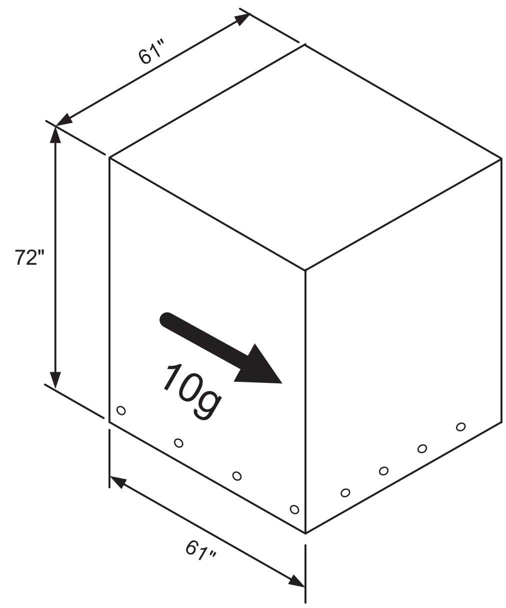
F_y = 105 ksi (SST Type 410)

-or-

F_y = 50 ksi (Nitronic 60 per ASTM A193 Grade B8S)

Yield Stress in shear =

$S_y = 0.58 \times F_y = 29$ ksi



Maximum Inertia Force

G = 10.0g

The acceleration of 10g tends to tip the Shipping Cage about one edge. The tipping moment, M is:

$$M = W \times G \times H = 450 \times 10 \times 46.6 = 209{,}700 \text{ in-lb.}$$

The tipping of the Shipping Cage is conservatively assumed to be resisted by only four screws in shear. The total force on the screws is:

$$F = \frac{M}{L} = \frac{209{,}700 \text{ in-lb.}}{61 \text{ in.}} = 3{,}438 \text{ lbs.}$$

The shear stress within each screw is:

$$\tau = \frac{F}{4A} = \frac{3{,}438 \text{ lbs.}}{4 \times 0.141 \text{ in}^2} = 6{,}095 \text{ psi}$$

Therefore, the Margin of Safety is:

$$MS = \frac{S_y}{\tau} - 1 = \frac{29{,}000 \text{ psi}}{6{,}095 \text{ psi}} - 1 = 3.8$$

2.6.6 Water Spray

The containment capabilities of the AOS Transport Packaging System are not compromised by water spray, because all external surfaces are comprised of stainless steel, and the closure seal is impervious to water. Furthermore, it is shown that the containment boundary of the AOS Transport Packaging System cask component is leak-tight, thus preventing water from entering the cask cavity. Refer to Chapter 4, "Containment," for a description of the containment boundary and its capability to prevent leakage.

2.6.7 Free Drop

Note: *The following analysis does not consider the energy that the shipping cage absorbs during a free drop. For the Free Drop Shipping Cage analysis, refer to Appendix 2.12.16.*

Each AOS Transport Packaging System model was analyzed to the effect of a free drop, using the LIBRA code. The transport package models were evaluated for a drop distance, based upon the model's weight, as listed in Table 2-34. The Drop condition evaluation is based upon the energy displacement curves developed by the 30-ft. drop analysis. The maximum displacements are determined from the energy displacement curves, and are listed in Table 2-35.

The analyses conducted consider three (3) orientations, as illustrated in Figure 2-27. The orientation that produced the most stress upon the cask component of the AOS Transport Packaging System was used as the load condition to be included in the Load Combination procedure.

Table 2-34. Free-Drop Distance – All Models

Model	Maximum Authorized Package Weight[a]		Free-Drop Distance	
	kg	lbs.	m	ft.
AOS-025A	100	220	1.2	4
AOS-050A	681	1,500	1.2	4
AOS-100A	5,675	12,500	0.9	3
AOS-100B	4,994	11,000		
AOS-100A-S	5,675	12,500		

a. The weights that comprise the maximum authorized package weight are defined in Table 2-7.

Table 2-35. Maximum Displacements in Free Drops, Normal Conditions of Transport – All Models

Model	Drop		Head-On		Side		Cg/Corner	
	cm	in.	cm	in.	cm	in.	cm	in.
AOS-025	121.9	48.0	1.52	0.60	0.96	0.38	2.54	1.00
AOS-050	121.9	48.0	3.81	1.50	3.05	1.20	6.73	2.65
AOS-100	91.4	36.0	6.60	2.60	5.08	2.00	12.19	4.80

2.12 APPENDIX

This appendix presents the following information:

- Data CDs
- Structural Evaluation Results – Models AOS-025, AOS-050, and AOS-100
  - Structural Evaluation Results – Model AOS-025A
  - Structural Evaluation Results – Model AOS-050A
  - Structural Evaluation Results – Models AOS-100A and AOS-100A-S
  - Structural Evaluation Results – Model AOS-100B
- LIBRA Finite Element Analysis Program and Verification Problems
- Description of LIBRA Files and Post-Processors: AOS Safety Analysis Report
- Selected Material Properties References
- Impact (Free-Drop) Test Report
  - Test Report: Drop Tests of the Alpha Omega Services Shipping Cask for Radioactive Material
  - Free-Drop Test Activity Record – Pre- and Post-Leak Test
- Dimensional Inspection Report
- Analysis of Content-Cask Lid Impact
- Comparison of Libra Static and Dynamic Impact Analysis
- Effect of Ribs on Stress at Foam-Cask Interface
- Analysis of 30-Ft. Drops with Shipping Cages
- Analysis of Tie-Down Devices
- Certificate of Conformance, General Plastics FR-3700 Series Foam – AOS-165A Prototype
- Analysis of Shipping Cage Lifting Bars – Models AOS-050A and AOS-100
- Shielding/Spacer Component Evaluation – Models AOS-050A, AOS-100A, and AOS-100A-S

2.12.15 Shielding/Spacer Component Evaluation – Models AOS-050A, AOS-100A, and AOS-100A-S

The axial shielding plates and cavity spacer plates generically refer to shoring components that are added within the Model AOS-050A, AOS-100A, and AOS-100A-S cask cavity for specific isotope shipping configurations, as listed in Table 2-357.

Table 2-357. Additional Required Shoring Components – Models AOS-050A, AOS-100A, and AOS-100A-S

Model	Component	Certification Drawing[a]	Material of Construction	Required for Isotope Shipments of[b]	Description
AOS-050A	Axial Shielding Plates	183C8519	Stainless Steel	Ir-192 Ir-194	Used to offset the cask contents from the cask plug and cask bottom. This dual-purpose shoring component provides both spacing (that is, distance) and supplemental shielding of the cask contents.
AOS-100A AOS-100A-S	Axial Shielding Plates	183C8491	Tungsten Alloy	Co-60-B Co-60-C	Used to offset the cask contents from the cask plug and cask bottom. This dual-purpose shoring component provides both spacing (that is, distance) and supplemental shielding of the cask contents.
	Cavity Spacer Plates	183C8518	Stainless Steel –or– Aluminum[c]	Co-60-C	Used to offset the supplemental axial shielding plates and cask contents from the cask plug and cask bottom, which provides spacing necessary to meet regulatory dose rate limits.

a. *Refer to Table 1-5, "AOS Transport Packaging System Certification Drawing List – All Models," for drawing revision levels.*

b. *As per 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 – Models AOS-100A and AOS-100A-S."*

c. *Refer to Paragraph 2.12.15.6 for details.*

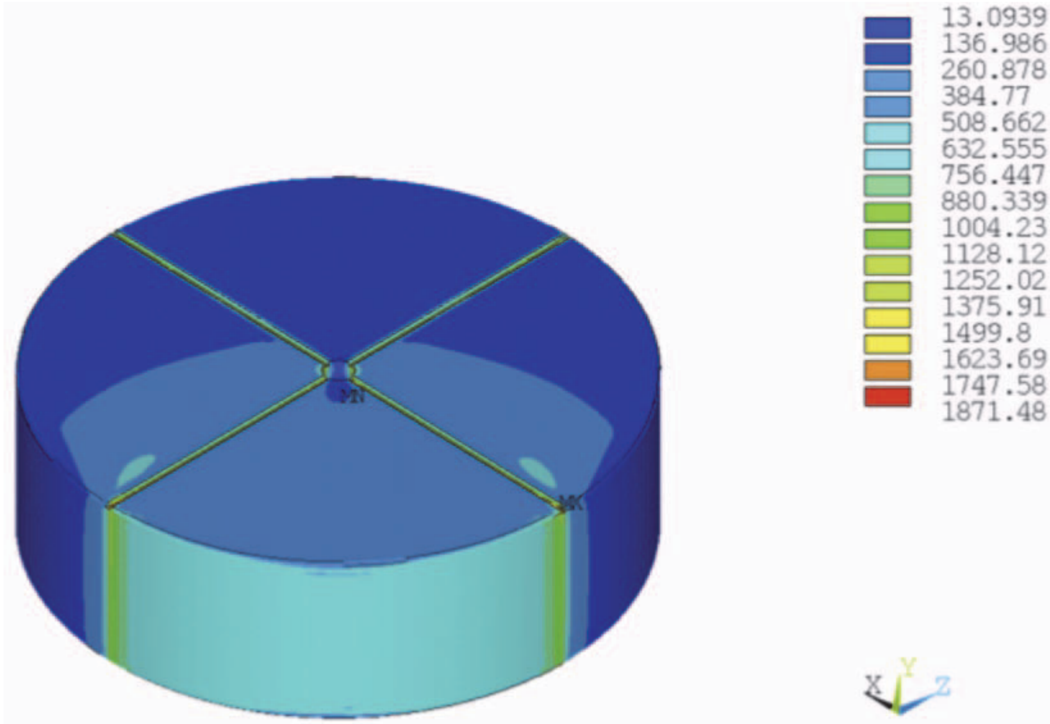


Figure 2-128. Cavity Spacer Plate Side Drop ANSYS Stress Results – Models AOS-100A and AOS-100A-S

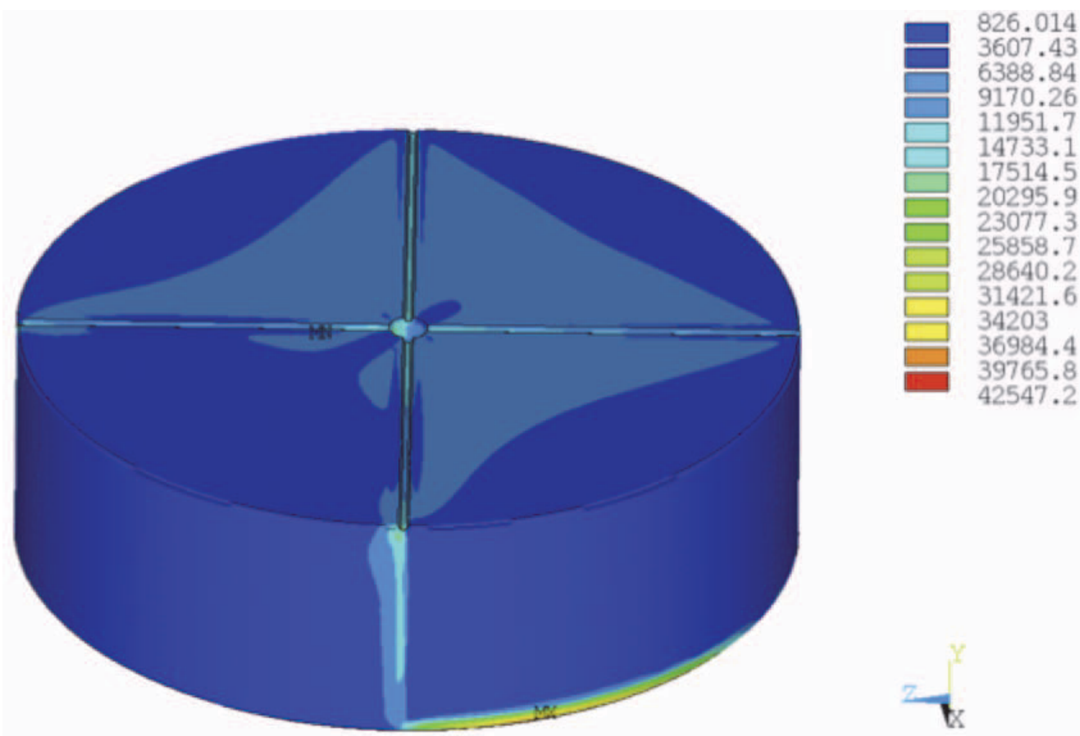


Figure 2-129. Cavity Spacer Plate Corner Drop ANSYS Stress Results – Models AOS-100A and AOS-100A-S

[2.20] Communication from ATI Firth Sterling to Alpha-Omega Services, Inc., and GE Energy.

[2.21] Parker O-Ring Division, *Evaluation of Parker Compound S1224-70 to ASTM D2000 7GE705 A19 B37 EA14 EO16 E036 F19 G11 Compound Data Sheet*, Kentucky, June 19, 1996.

[2.22] Fitzroy, Nancy D., Ed., *Heat Transfer Data Book*, General Electric Company, New York, November, 1970 Edition, Section G502.5, p. 7.

[2.23] Touloukian, Y. S., *Thermophysical Properties of Matter, Metallic Elements and Alloys*, 1971.

[2.24] Fischer, L. E. and W. Lai, *NUREG/CR-3854, Fabrication Criteria for Shipping Containers*, Lawrence Livermore Laboratory, Prepared for U.S. Nuclear Regulatory Commission (NRC), Livermore, California, March, 1985.

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[2.27] ASTM International, *ASTM F1145 - 05(2011)*, *Standard Specification for Turnbuckles, Swaged, Welded, Forged*, Table 3, West Conshohocken, PA, 2011.

[2.28] Shigley, Joseph E., *Mechanical Engineering Design*, Chapter 6, “The Design of Screws, Fasteners, and Connections,” McGraw Hill, Inc., 3rd Edition, 1977.

[2.29] American Society of Mechanical Engineers, *ASME Boiler and Pressure Vessel Code*, *Section VIII, Division 1*, 2004 Ed., No Addendum.

[2.30] U.S. Nuclear Regulatory Commission (NRC), *Regulatory Guide 7.11*, “Fracture Toughness Criteria of Base Material for Ferritic Steel Shipping Cask Containment Vessels with a Maximum Wall Thickness of 4 Inches (0.1 m),” 1991.

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[2.32] McConnell, J. W. Jr., A. L. Ayers, Jr., and M. J. Tyacke, *NUREG/CR-6407*, *Classification of Transportation Packaging and Dry Spent Fuel Storage System Components According to Importance to Safety,* Idaho National Engineering Laboratory, Prepared for U.S. Nuclear Regulatory Commission (NRC), Idaho Falls, Idaho, February, 1996.

[2.33] American Society of Mechanical Engineers, *ASME Boiler and Pressure Vessel Code*, *Section III, Division 1,* 2004 Ed., No Addendum.

[2.34] ANSYS, Inc. ANSYS documentation release 15.0, November, 2013.

The maximum decay heat for each AOS Transport Packaging System model is distributed across the cask cavity surface. Condition 3 (fire transient) analysis is initiated at the steady-state Condition 1, in which the maximum solar load is applied.

Table 3-1. Transport Package Thermal Environment Conditions – All Models

Condition	Conditions of Transport	Thermal Environment
1	Normal	38°C (100°F) ambient with maximum decay heat and maximum solar load.
2	Normal	38°C (100°F) ambient with maximum decay heat.
3	Hypothetical Accident (Fire)	Fire transient, t = 0 to 8.0 hours.
4	Normal	-40°C (-40°F) ambient with maximum decay heat.
5	Normal	-40°C (-40°F) ambient.
6	Normal	-29°C (-20°F) ambient with maximum decay heat.
7	Normal	-29°C (-20°F) ambient.

3.1.2 Contents' Decay Heat

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," provide the maximum decay heat and radioactivity for the AOS Transport Packaging System contents. This includes Decay Heat (W/Ci) values for each radioisotope listed, showing that the decay heat is consistent with the maximum quantity of radioactivity contents. A summary of the Decay Heat values is shown in Table 3-2. The method that is used for calculating the decay heat for isotope mixtures in Models AOS-100A and AOS-100A-S is presented in Appendix 5.5.5, "Shipments of Multiple Isotopes under 10 CFR 71.47(a)."

Table 3-2. Contents' Decay Heat – All Models

Model	Contents' Decay Heat (W)
AOS-025A	10
AOS-050A	100
AOS-100A	400
AOS-100B	400
AOS-100A-S	400

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 – Models 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.

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

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.

5.3.1.4 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.

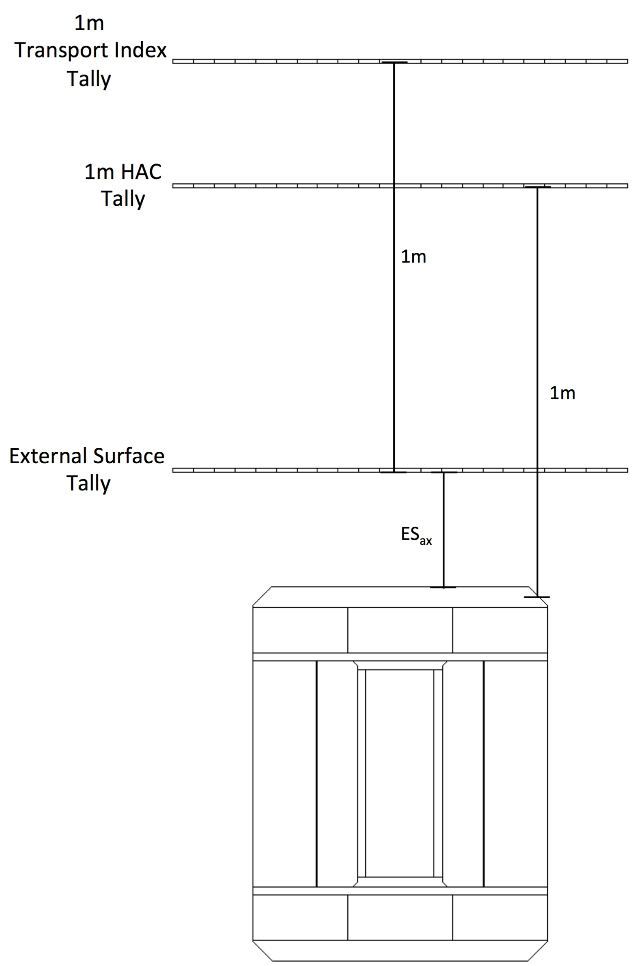

Figure 5-5. Shielding Model Tallies for Top Source Location

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

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.

$$0.9 * \mathrm{Dose}_{\mathrm{Total}}\left[\frac{\mathrm{mrem}}{\mathrm{hr}}\right] = \mathrm{Dose}_{+2\mathrm{sig}}^{192}\left[\frac{\frac{\mathrm{mrem}}{\mathrm{hr}}}{\mathrm{Ci}}\right] * A^{192}[\mathrm{Ci}] + \mathrm{Dose}_{+2\mathrm{sig}}^{194}\left[\frac{\frac{\mathrm{mrem}}{\mathrm{hr}}}{\mathrm{Ci}}\right] * A^{194}[\mathrm{Ci}] \tag{5-6}$$

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.

$$A^{192}[\mathrm{Ci}] = \frac{0.9 * \mathrm{Dose}_{\mathrm{Total}}\left[\frac{\mathrm{mrem}}{\mathrm{hr}}\right] - \mathrm{Dose}_{+2\mathrm{sig}}^{194}\left[\frac{\frac{\mathrm{mrem}}{\mathrm{hr}}}{\mathrm{Ci}}\right] * A^{194}[\mathrm{Ci}]}{\mathrm{Dose}_{+2\mathrm{sig}}^{192}\left[\frac{\frac{\mathrm{mrem}}{\mathrm{hr}}}{\mathrm{Ci}}\right]} \tag{5-7}$$

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 5-18. 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 5-29. 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		✔	✔

Table 5-30. THIS TABLE INTENTIONALLY LEFT BLANK

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.

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** – $400\,\frac{J}{s} \times \frac{1\text{ eV}}{1.602167\text{E-19J}} \times \frac{1\gamma}{0.2\text{E6 eV}} \times \frac{1\text{ Ci}}{3.7\text{E10}\frac{\gamma}{s}} = 3.374\text{E5 Ci}$
- **0.3-MeV gammas** – $400\,\frac{J}{s} \times \frac{1\text{ eV}}{1.602167\text{E-19}} \times \frac{1\gamma}{0.3\text{E6 eV}} \times \frac{1\text{ Ci}}{3.7\text{E10}\frac{\gamma}{s}} = 2.249\text{E5 Ci}$

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. $E_{max,\beta} \leq 0.3$). 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	$\sum_{i}^{n} A_i \times Q_i \leq Q_{Limit}$

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)

Q_{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).*

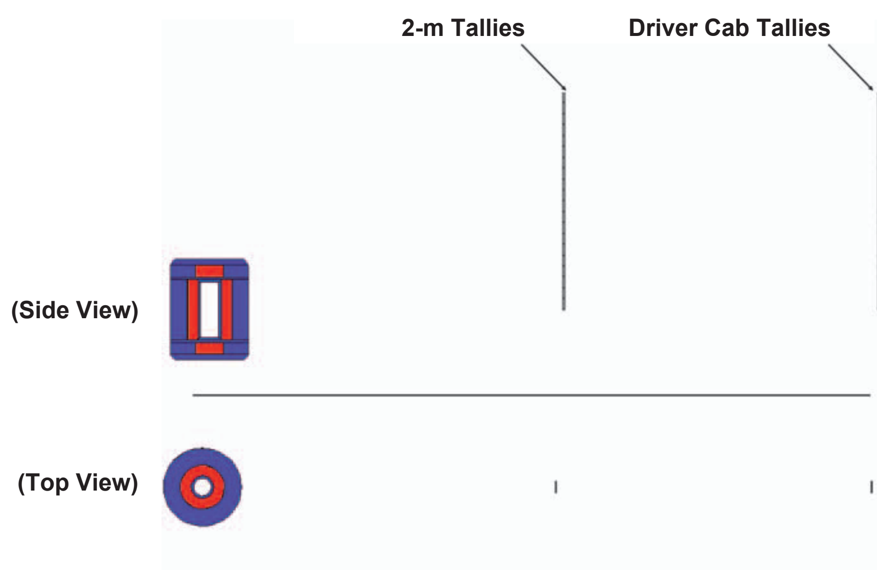

Figure 5-9. Exclusive Use MCNP Tally Locations

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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:

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

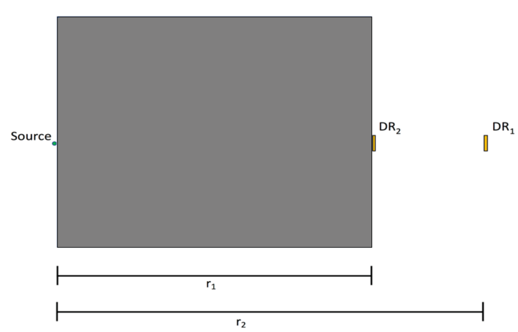


Figure 5-10. Simplified 1D Dose Rate Calculations

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.

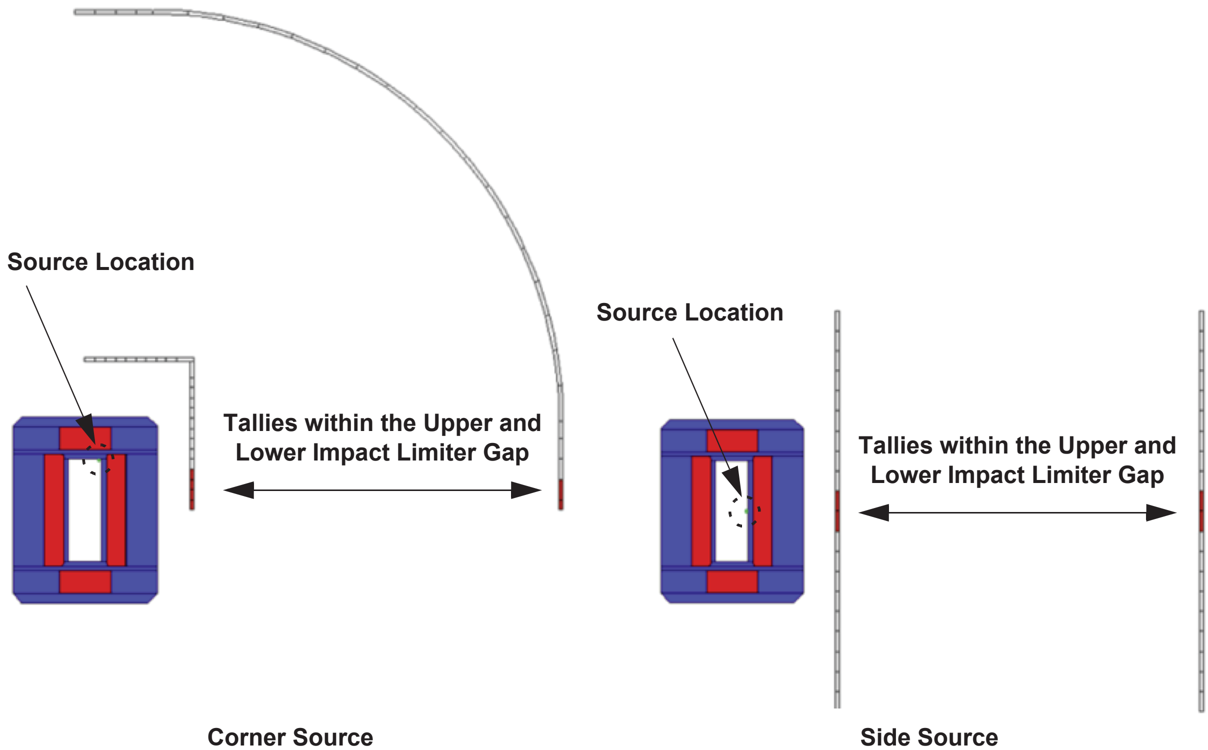


Figure 5-11. Impact Limiter Gap Dose Rate Locations – Model AOS-050A

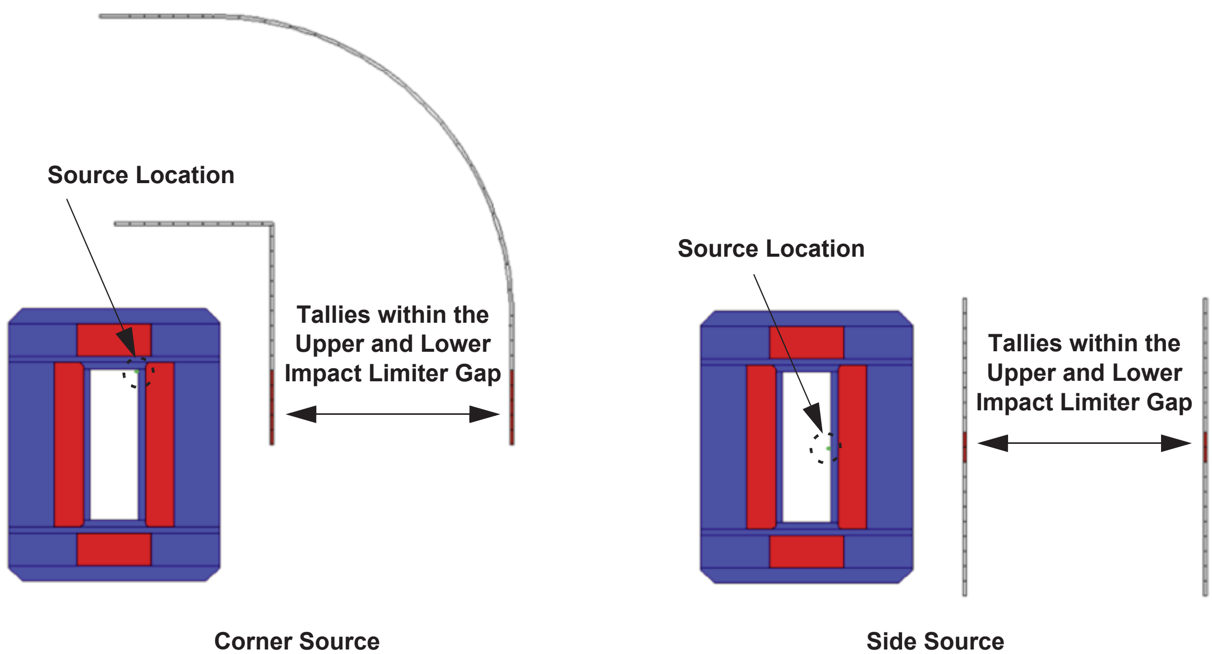


Figure 5-12. Impact Limiter Gap Dose Rate Locations – Models AOS-100A, AOS-100A-S, and AOS-100B

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

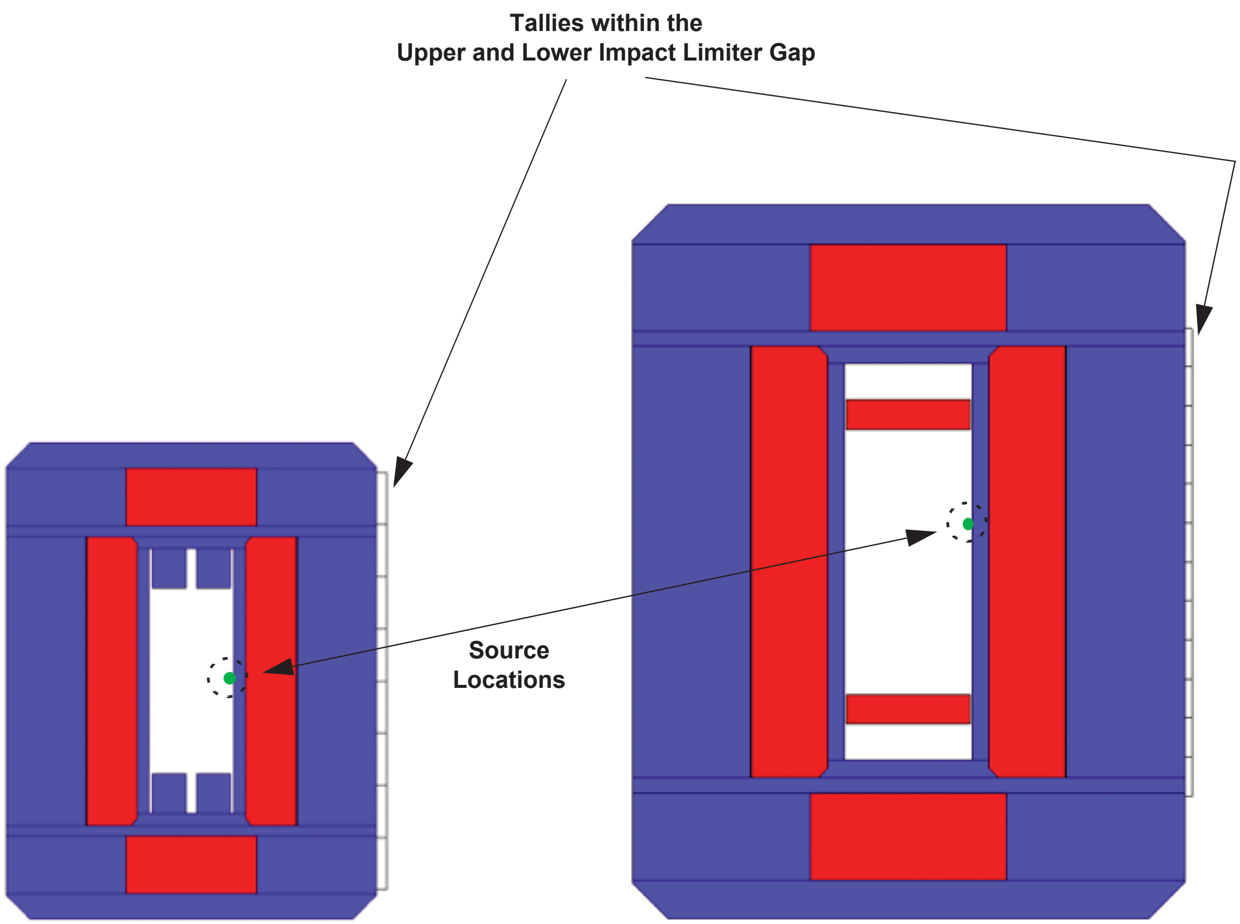
a. *Calculated as the dose rate/Ci value listed times the isotope activity limit based on the corner location, as calculated in Subsection 5.4.4.*

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.*



Ir-194 (Model AOS-050A)

Co-60-C (Models AOS-100A and AOS-100A-S)

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.

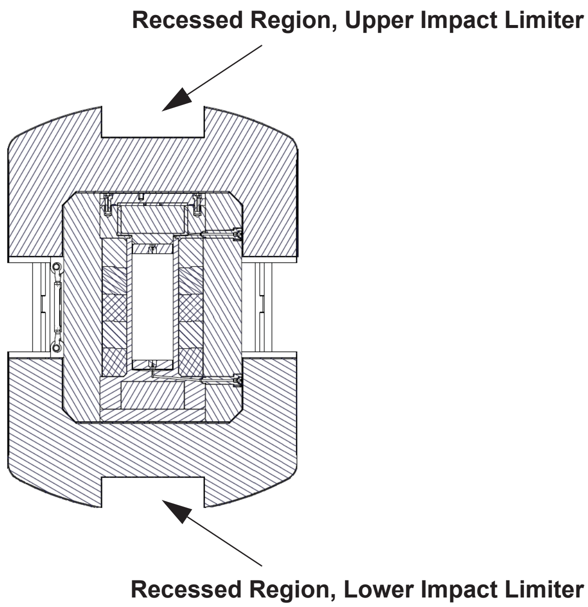


Figure 5-14. Example Cross-Sectional View Showing Impact Limiter Recessed Regions – Models AOS-100A and AOS-100B Shown

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.

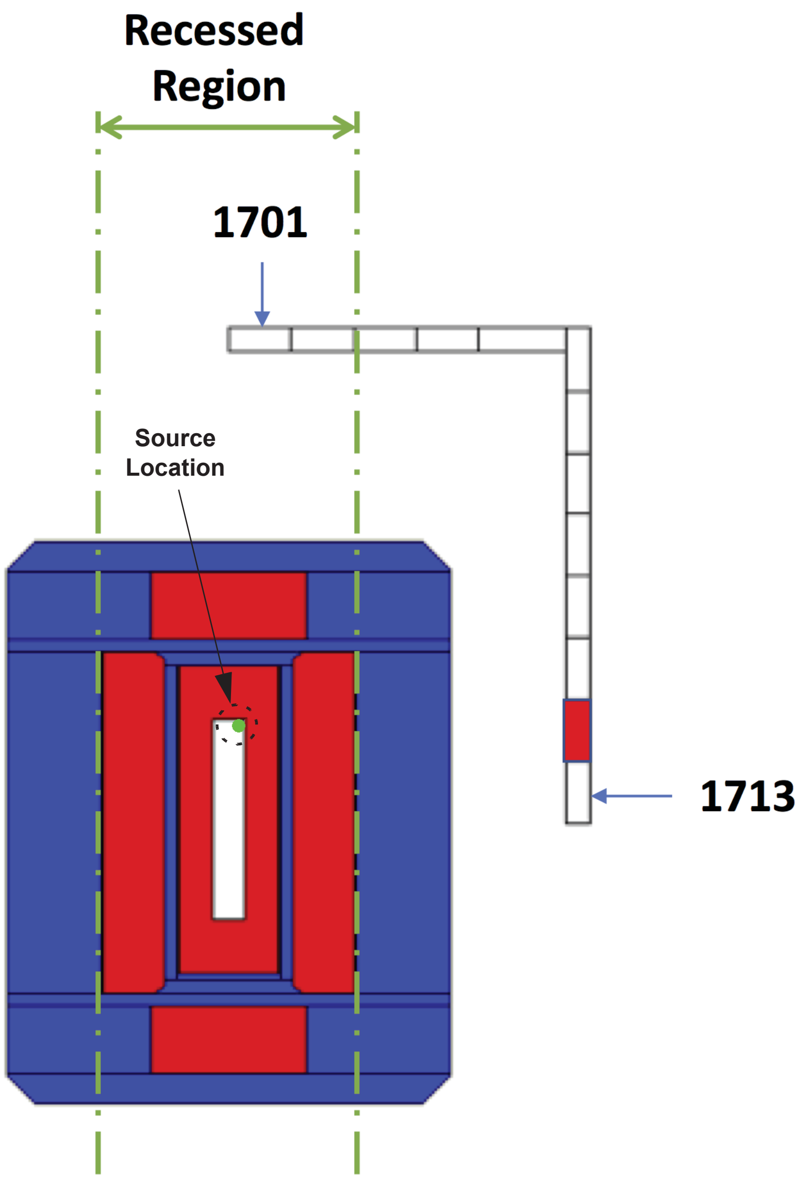


Figure 5-15. Transport Package Surface Tallies – Model AOS-025A

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).

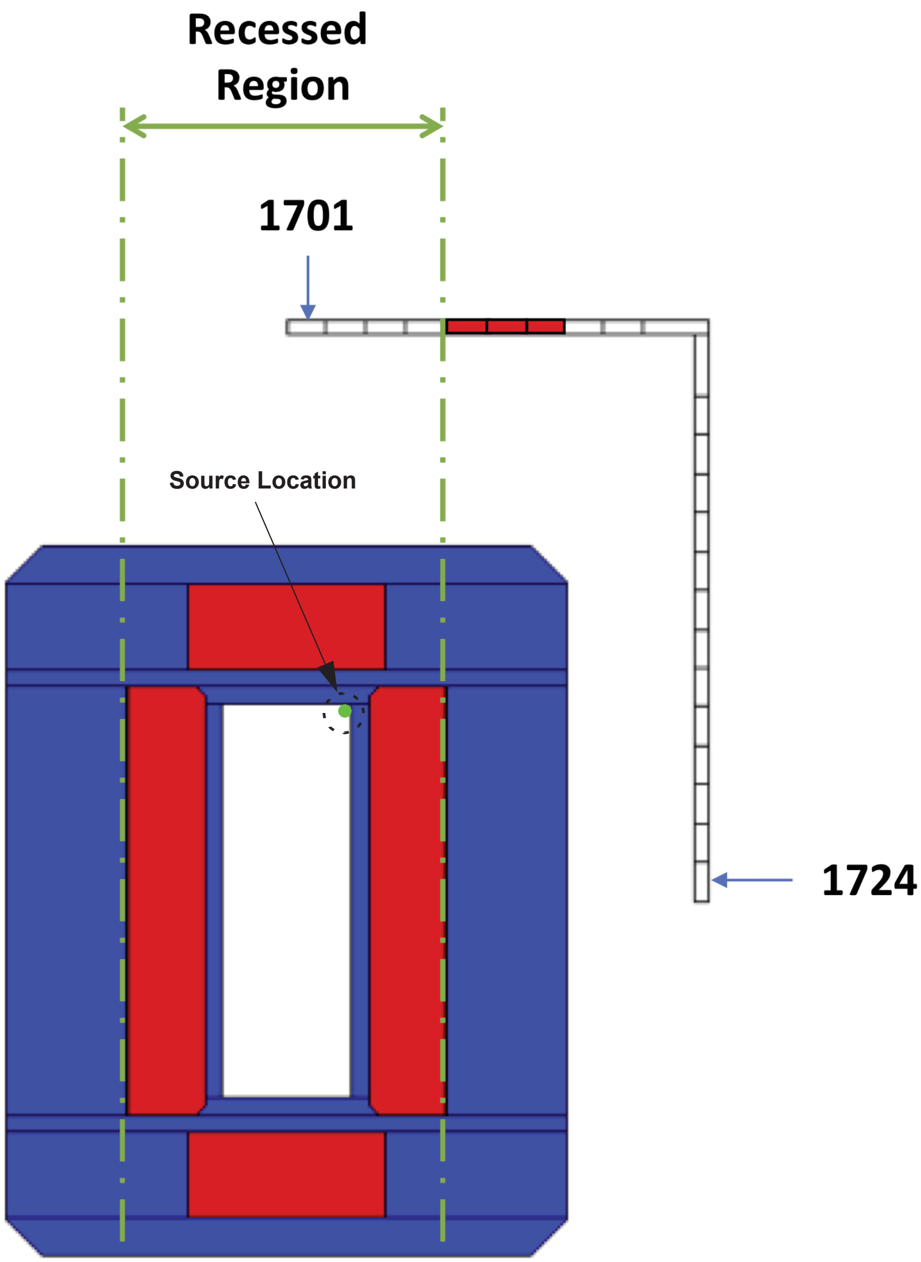


Figure 5-16. Transport Package Surface Tallies – Model AOS-050A

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.)

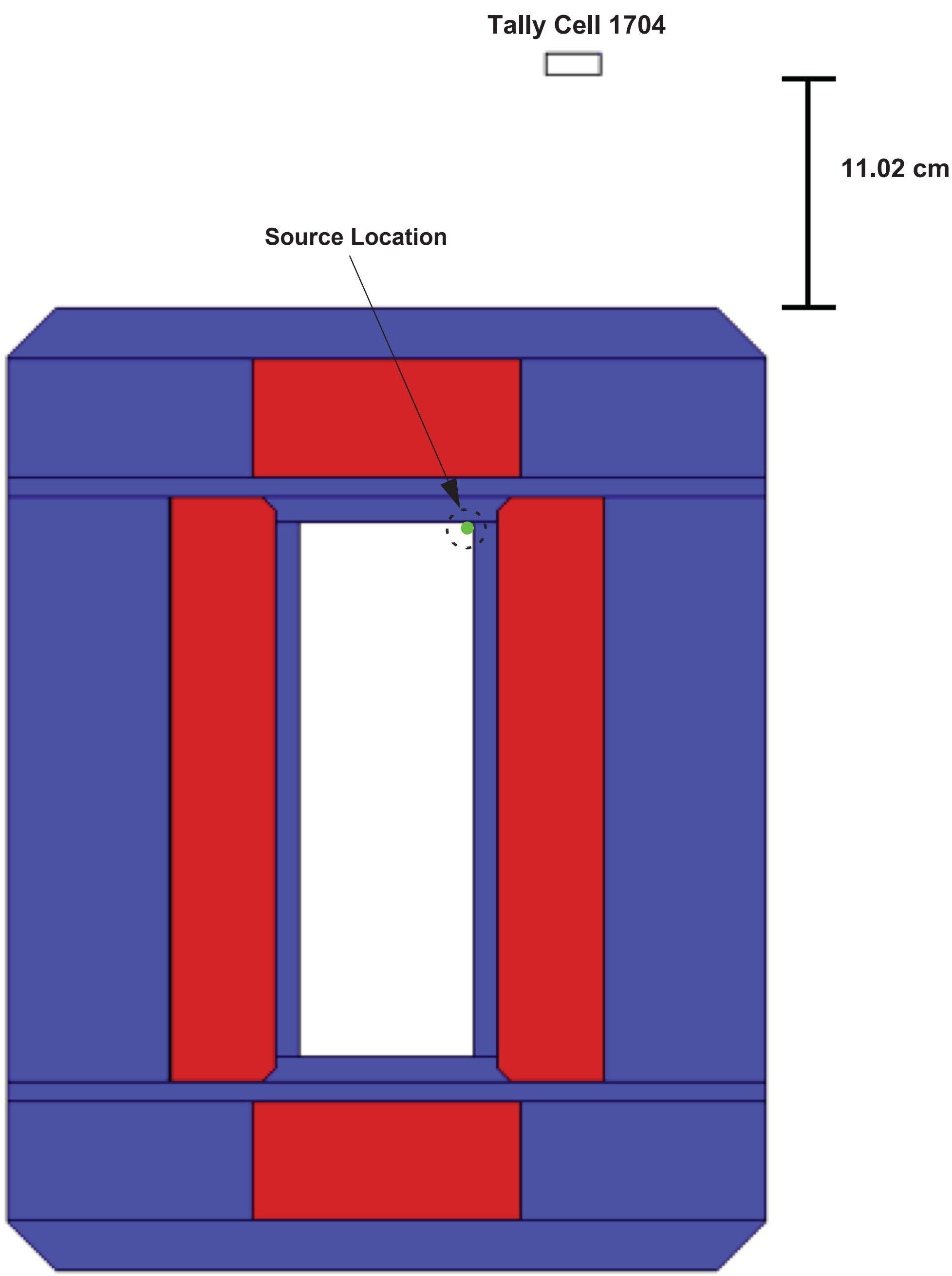


Figure 5-17. Recessed Region Model – Model AOS-050A

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.

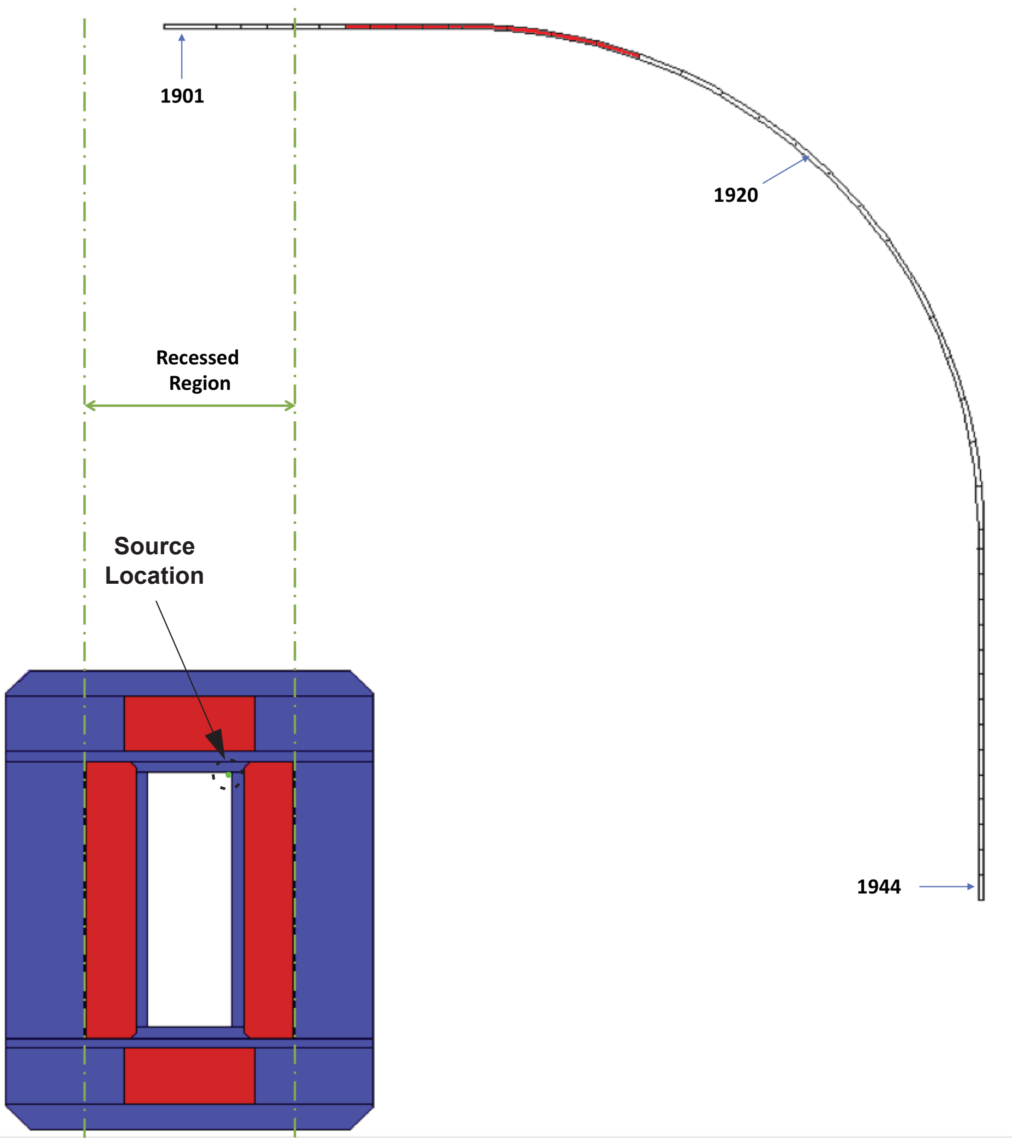


Figure 5-18. 1-m TI Tallies – Models AOS-100A and AOS-100A-S

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

		Original		**New**	
Isotope	**Maximum Dose Rate/Ci (mrem/hr/Ci)[a]**	**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.

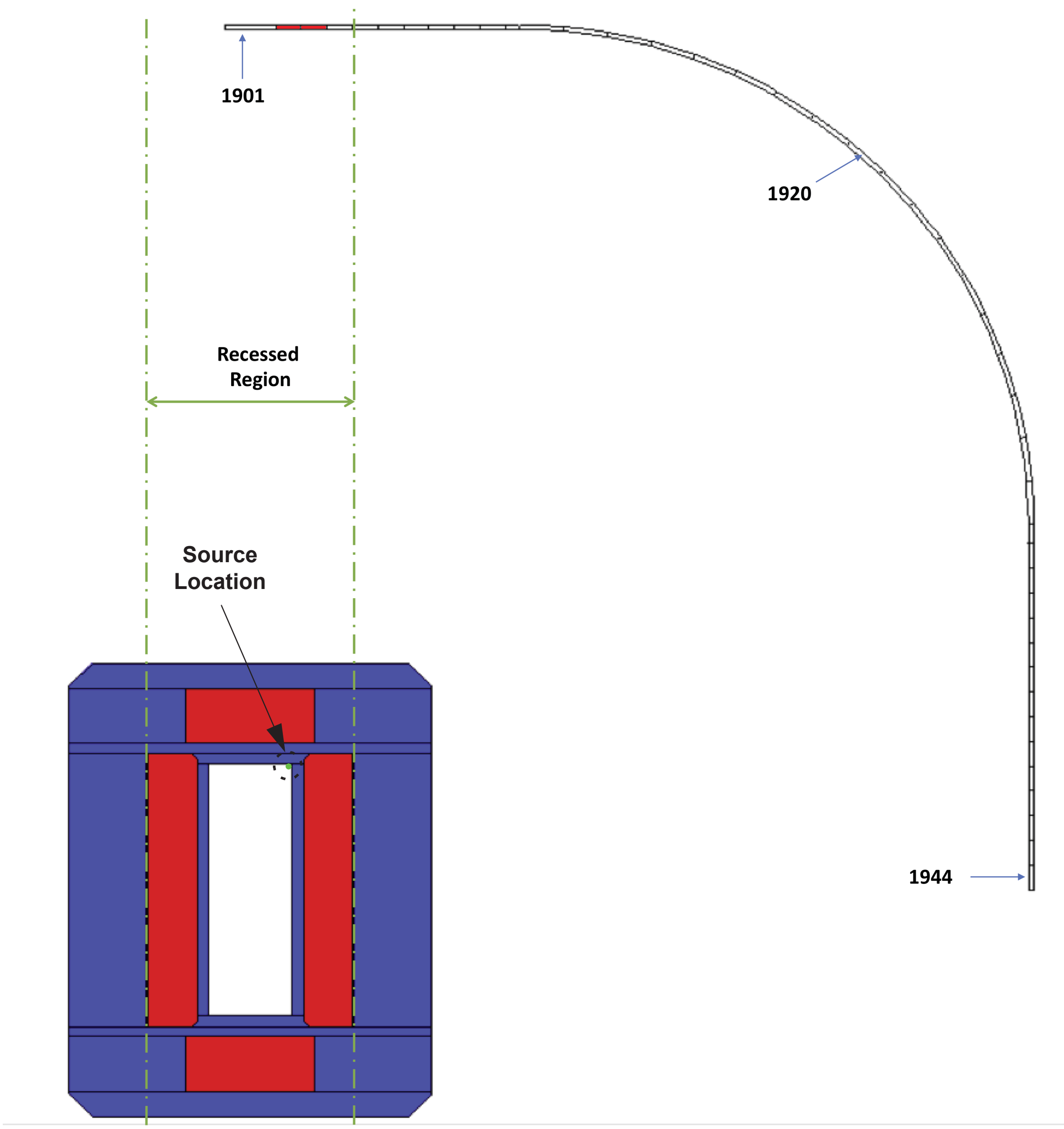


Figure 5-19. 1-m TI Tallies – Model AOS-100B

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.

[5.3] Goorley T., et al., *Initial MCNP 6 Release Overview – MCNP6 Version 1.0*, Los Alamos National Laboratory, LA-UR-13-22934, April, 2013.

[5.4] Conlin J., et al., *Listing of Available ACE Data Tables*, Los Alamos National Laboratory, LA-UR-13-21822, Rev. 4, June, 2014.

[5.5] American Nuclear Society, *ANSI/ANS-6.1.1-1977*, “Neutron and Gamma-Ray Fluence-to-Dose Factor,” 1977.

[5.6] SAE International, *AMST 21014*, “Tungsten Base Metal, High Density,” September 1, 1998.

[5.7] International Commission on Radiological Protection, “Nuclear Decay Data for Dosimetric Calculations,” ICRP Publication 107, 2008.

7.1 PACKAGE LOADING

Note: *The operational steps provided in this section apply to all AOS Radioactive Material Transport Packaging System models (Models AOS-025A, AOS-050A, AOS-100A, AOS-100B, and AOS-100A-S). Any step specific to a given Model is identified within the step.*

Part of the transport package loading preparation is to perform a Pre-Shipment Engineering Evaluation following *IAEA TS-R-1, Paragraph 502*, *10 CFR 71.87*, and *49 CFR 173.475* (References **[7.1]**, **[7.2]**, and **[7.3]**, respectively). The evaluation is used to ensure that the packaging, with its proposed contents, satisfies the applicable requirements of the transport package's license or certificate. This evaluation includes, but is not limited to, the review of the following:

- Proposed contents' isotopic composition, quantities, and decay heat;
- Proposed contents' form, weight, and geometry. If the content is defined as *Special form*, verify its certification from the competent authorities;
- Identify shoring device to be used. All shoring materials used within the cask cavity must have a melting point greater than (i) 600°F for Co-60 in metallic form and Cs-137 in the form of cesium chloride and (ii) 900°F for all other contents;
- Shielding requirements (use of additional shielding devices may be required for shipment);
- Structural requirements;
- Thermal requirements;
- Pressure requirements;
- Shipping hardware (such as liners, racks, dividers, baskets, and shoring devices);
- Maintenance records.
- Personnel qualification.

In addition, operations at the loading facility must safely support a range of activities, from receiving and inspecting the package, to preparing the loaded transport package for shipment. Each loading facility must provide fully trained personnel and detailed operating procedures to cover these activities.

7.1.1 Preparation for Loading

7.1.1.1 Receiving and Inspecting the Empty Transport Package

To receive and inspect the empty transport package:

a. Position the transport vehicle in the Receiving Inspection area.

b. Visually inspect the transport package for damage and proper labeling and marking. Refer to the shipping paper for shipment category and compare the marking and labels on the package to the requirement of Reference **[7.3]**.

7.1.1.2 Removing the Transport Package from the Transport Vehicle

To remove the transport package from the transport vehicle:

a. Position the transport vehicle, in the job staging area, for transport package removal. This operation can be aided by the use of a overhead crane or forklift truck.

b. Position the spreader bar or forks, then connect the appropriate slings and shackles to remove the shipping cage.

c. Remove the shipping cage and tie-down hardware.

d. Verify that the radiation and external contamination levels are in compliance with regulatory requirements *IAEA TS-R-1, Paragraph 508*, *10 CFR 71.87(i)*, *49 CFR 173.428*, and *10 CFR 20.1906* (References **[7.1]**, **[7.2]**, **[7.3]**, and **[7.4]**, respectively).

Note: *The transport package's bottom surface is not accessible until the transport package is removed from the pallet. As a result, when measurements are required, the radiation and external contamination levels on the transport package's bottom surface are assessed after the shipping cask is removed in step g.*

e. Record any finding(s), and notify the Job Supervisor for disposition of the finding(s). Findings must be evaluated against *10 CFR 71.95* **[7.2]**, to determine whether they require regulatory notification, so that proper action can be taken. The Job Supervisor is responsible for direct oversight of the personnel that are performing the work.

f. Depending upon site-specific constraints, do one of the following:

   - Remove the upper impact limiter from the cask, then place the impact limiter into temporary storage.
   - Install trunnions. Prior to the installation, apply an anti-vibration compound on the trunnion bolt threads.
   - Lift and remove the entire package from the transport vehicle, then set down the package in an appropriate location. Next, remove the impact limiters from the shipping cask, then place the impact limiters in temporary storage.

g. Remove the cask, using the appropriate rigging equipment.

h. Transfer the cask to the loading area.

7.1.2 Loading of Contents

7.1.2.1 Preparing for Loading

To prepare the transport package for loading:

a. Verify that the content to be loaded is authorized by the current transport package's Certificate of Compliance. (Refer to the Pre-Shipment Engineering Evaluation in Section 7.1 and guidance in Appendix 7.5.1.)

b. Perform a visual inspection. Note any damage or unusual conditions. If part functionality is impaired, repair or replace the part, as required, and document the repair or replacement, then re-inspect the part. Notification and approval of AOS is required. Replacement or repair of any component requires that all original examinations and tests initially prescribed be performed.

c. Depending upon the particular transport package model, remove the cask trunnions and install a lifting device specific to the facility. If using a forklift to transport the cask, protect the cask surface and secure the cask to the forks with straps. If lifting by crane, with or without a spreader bar, the lifting slings must not make an angle greater than 30°, measured from the vertical.

d. With proper radiological protection and monitoring, remove the cask lid and cask lid plug for visual inspection of the cavity.

e. Record any finding(s), and notify the Job Supervisor for disposition of the finding(s). Findings must be evaluated against *10 CFR 71.95* **[7.2]**, to determine whether they require regulatory notification, so that proper action can be taken.

f. Visually inspect the cask and cask lid sealing surfaces for damage or foreign material. The presence of foreign material or deep radial scratches that may result in a failed Pre-Shipment Leakage Rate test should be repaired or replaced, as required, and AOS is to be notified for written disposition.

g. Remove the cask drain port, test port, and cask vent port covers, and pipe plugs. Completely remove all thread sealant from the pipe plugs.

h. **Optional** – Install the lid guide pins, 90° apart. Use of the lid guide pins is mainly needed for proper alignment of the cask lid with the cask lid attachment bolt holes. The lid guide pins also protect the cask lid elastomeric or metallic seal.

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7.1.2.2 Loading Irradiated Hardware or Other Contents

To load contents:

a. Place the radioactive contents to be shipped into a shoring device (such as a rack, basket, or other such device).

   The liner, axial shielding plates, and/or cavity spacer plates are used as necessary, per the requirements listed in Table 7-1.

b. Shore the load within the cavity, if needed.

c. Place the cask lid plug into the cask.

Table 7-1. Additional Required Shielding – Models AOS-025A, AOS-050A, AOS-100A, and AOS-100A-S

Model	Component	Certification Drawing[a]	Comments
AOS-025A	Liner	183C8485	Shielding liner is mandatory for all contents. (Refer to the current revision of the current revision of the NRC Certificate of Compliance 9316.)
AOS-050A	Axial Shielding Plates[b]	183C8519	Used when shipping Ir-192 and Ir-194 isotopes. (Refer to the current revision of the NRC Certificate of Compliance 9316.)
AOS-100A AOS-100A-S	Axial Shielding Plates	183C8491	Used when additional shielding is required for Co-60. (Refer to the current revision of the current revision of the NRC Certificate of Compliance 9316.)
	Cavity Spacer Plates	183C8518	

a. Refer to Table 1-5, "AOS Transport Packaging System Certification Drawing List – All Models," for drawing revision levels.

b. If the Model AOS-050A axial shielding plates include threaded screw holes, each hole must be filled with a setscrew during shipment.

7.1.2.3 Installing the Cask Lid

Note: *Visually inspect the cask and lid sealing surfaces, as well as the cask lid seal to be used, for damage that can prevent proper sealing of the sealing joint. Refer to Subsection 8.2.2, "Leakage Tests [8.4]," for detailed inspection of these items. If the metallic cask lid seal is replaced, prior to the shipment of Normal Form material, a Maintenance Test must be performed, in accordance with ANSI N14.5 (Reference* **[7.8]***). The elastomeric seal option is acceptable for use only with Special Form contents, in which the cask contents provide containment for the radioactive contents.*

To install the cask lid, after verifying that the cask lid seal is properly installed, use proper rigging to slowly lower the cask lid onto the cask. Carefully monitor this operation to ensure that the cask lid is properly aligned. During the placement of the cask lid, two lid guide pins may be installed in the cask lid threaded holes perpendicular to each other to maintain alignment of the cask lid attachment bolt holes with the cask lid threaded holes.

7.1.3.2 Removing the Cask from the Loading Area

To remove the cask from the loading area, in preparation for transport:

a. Carefully measure the cask radiation levels, while removing the cask from the storage basin or cell area.

b. Decontaminate the cask to a level consistent with *IAEA TS-R-1, Paragraph 508*, *10 CFR 71.87(i)*, and *49 CFR 173.443* (References **[7.1]**, **[7.2]**, and **[7.3]**, respectively).

7.1.3.3 Pre-Shipment Leak Testing

To verify that the containment system of the transport package is properly assembled for shipment, perform one of the following Pre-Shipment Leak tests – Test A1, A2 or B – depending on the cask lid seal type.

Note: *When the Model AOS-100A-S is used, both cask lid seals must be leak tested.*

Test A1 – Gas Pressure Rise: When Using Elastomeric Cask Lid Seals for *Special Form* Contents (Tests: Cask Lid(s), Vent and Drain Ports)

To perform a pre-shipment verification of the elastomeric lid seal:

a. Perform the test by evacuating the space between the cask lid seal's elastomeric O-Ring seals, –or– the cavities outside the cask vent and drain ports, and then measuring the pressure rise.

Note: *The cask vent port and cask drain port need to be leak tested only if the ports have been opened since they were last tested.*

Note: *The gas pressure rise leak test is performed using a test manifold, isolation valve, vacuum gauge, and vacuum pump. Use only the test apparatus described in the test procedure.*

b. Connect the test manifold to the test port. Evacuate the test volume to the required level. and then close the isolation valve.

c. Disconnect the vacuum pump and then wait for the prescribed hold time. After the hold time, the acceptance criterion is a pressure rise that is less than or equal to 0.1 psig.

Test A2 – Gas Pressure Drop: When Using Elastomeric Cask Lid Seals for *Special Form* Contents (Tests: Cask Lid(s), Vent and Drain Ports)

To perform a pre-shipment verification of the elastomeric lid seal:

a. Perform the test by pressurizing the space between the cask lid seal's elastomeric O-Ring seals, –or– the cavities outside the cask vent and drain ports, and then measuring the pressure drop.

Note: *The cask vent port and cask drain port need to be leak tested only if the ports have been opened since they were last tested.*

Note: *The gas pressure drop leak test is performed using a test manifold, isolation valve, pressure gauge, and pump. Use only the test apparatus described in the test procedure.*

b. Connect the test manifold to the test port. Evacuate the test volume to the required level. and then close the isolation valve.

c. Disconnect the pump and then wait for the prescribed hold time. After the hold time, the acceptance criterion is a pressure drop that is less than or equal to 0.1 psig.

Test B – Tracer Gas When Using Metallic Cask Lid Seal for *Normal* or *Special Form* Contents (Tests: Lid (Cask Lid Seal), Vent and Drain Ports)

To leak test the containment system:

a. Perform a leak test of the cask lid seal, drain threaded pipe plugs, and vent threaded pipe plugs, with a thermal conductivity sensing instrument or mass spectrometer device with a sensitivity of at least 1.0×10^{-8} ref-cm^3/sec.

b. Set up the test instrument in accordance with written procedures and the instrument manufacturer's guidance.

Note: *Leak Test criteria for leak rates must meet the requirement of Reference [7.8].*

c. Evacuate the cask cavity and then backfill the cask cavity with helium to a pressure of at least one (1) atmosphere.

d. With the instrument selected in step a calibrated with a calibration standard within the range of 1.0×10^{-8} to 5.0×10^{-7} ref-cm^3/sec, check the following for indications of leakage:
   - Package containment with the test instrument, through the test port
   - Volume between the double "C" cross-sections
   - Around the threaded joint area of the drain and vent threaded pipe plugs

e. If leakage greater than 1×10^{-7}ref-cm^3/sec, corrected for the nature of the tracer gas and temperature condition at the time of the test, is detected, repair or replace the damaged component(s), and then re-test for indications of leakage.

7.1.3.4 Preparing the Cask for Transport of Radioactive Material

To prepare the cask for transporting radioactive material:

a. Transport the cask to the staging area.

b. Perform radiological surveys to demonstrate compliance with transport package surface dose rate requirements (refer to Table 7-3), consistent with *IAEA TS-R-1, Paragraph 531*, *10 CFR 71.47* and *71.87(j)*, and *49 CFR 173.441* (References **[7.1]**, **[7.2]**, and **[7.3]**, respectively).

Table 7-3. Maximum Distance from Loaded Cask Surface to Take Transport Package Surface Dose Rate Measurements – All Models

	Axial Dose Point Maximum Distance from Cask Surface[a]	Radial Dose Point Maximum Distance from Cask Surface
Model	in.	in.
AOS-025	2	2
AOS-050	4	–
AOS-100	8	–

a. *Equivalent to the minimum distance provided by the impact limiters to the transport package surface.*

c. Remove any site-specific lifting devices from the cask.

Note: *The transport packages require that the lower impact limiter must first be installed on the pallet, before placing the cask in the impact limiter.*

d. Verify that the contamination levels on the outer shipping cask surfaces and impact limiters (both inner and outer surfaces) are in compliance with regulatory requirements *IAEA TS-R-1, Paragraph 508*, *10 CFR 71.87(i)*, and *49 CFR 173.443* (References **[7.1]**, **[7.2]**, and **[7.3]**, respectively).

e. Verify that the lower impact limiter is installed on the pallet:

   1. **If the lower impact limiter was left on the pallet** – Place the cask into the impact limiter/ pallet assembly.

   2. **If the complete transport package was removed** – Place the lower impact limiter on the pallet, then place the cask into the lower impact limiter.

f. Install and secure the upper impact limiter.

g. Verify that the lettering on the identification nameplate is distinguishable and conforms to the Packaging Certification drawing requirement. Re-stamp the lettering or replace the nameplate, if necessary.

h. Remove old shipping labels and apply new ones, based upon the proposed payload, meeting the requirements of *IAEA TS-R-1, Paragraphs 526* and *541* through *543* and/or *49 CFR 172.403* (References **[7.1]** and/or **[7.7]**, respectively).

i. Apply security seals to two (2) opposite latch pins or turnbuckles, as illustrated in Figure 7-5 and Figure 7-6, respectively. (Alternatively, refer to step k.)

j. Complete the radiological survey of the transport package and transport vehicle, consistent with *IAEA TS-R-1, Paragraphs 530* through *532*, *10 CFR 71.47* and *71.87(j)*, and *49 CFR 173.441* (References **[7.1]**, **[7.2]**, and **[7.3]**, respectively).

Note: *For the 1-m TI dose rate, the 1-m distance is from the transport package surface (that is, the shipping cask or impact limiter surface),* ***not*** *the shipping cage surface.*

k. Install the shipping cage. If the shipping cage includes the optional lifting bar, install the lifting bar guards so that the lifting bar cannot be used for lifting of the entire package or for tie down. If the security seals were not applied in step i, apply two (2) security seals between the shipping cage and pallet, on opposing sides.

l. Apply any additional shipping label or marking that might be required to properly represent the transport package and its content, in accordance with Reference **[7.3]**.

m. Apply the security seal, if used, to the shipping cage, as illustrated in Figure 7-7.

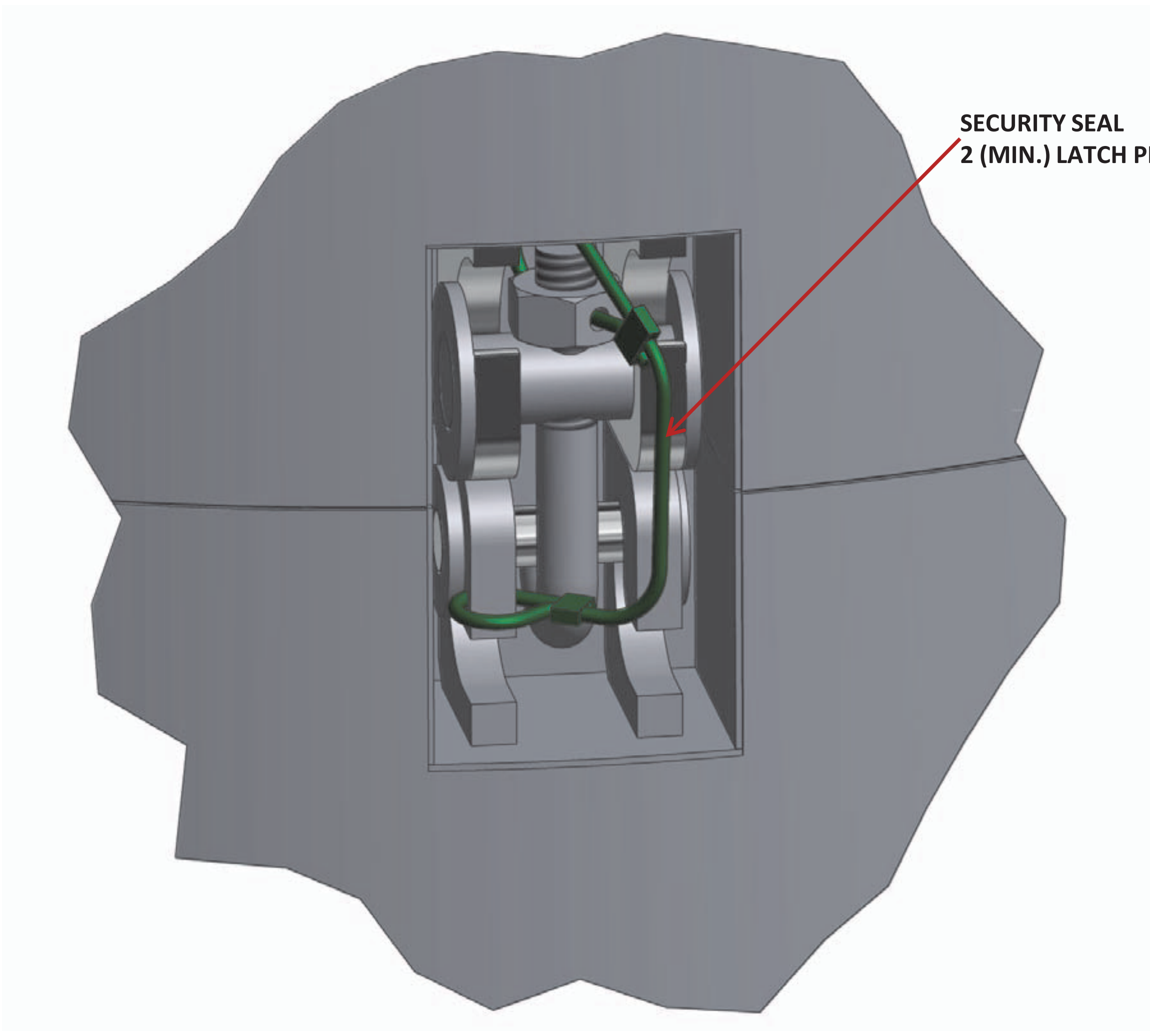

Figure 7-5. Latch Pin Security Seal

7.2 PACKAGE UNLOADING

Note: *The operational steps provided in this section apply to all AOS Radioactive Material Transport Packaging System models (Models AOS-025A, AOS-050A, AOS-100A, AOS-100B, and AOS-100A-S). Any step specific to a given Model is identified within the step.*

Operations at the unloading facility are largely the reverse of the loading operations. Each unloading facility must provide fully trained personnel, and supply detailed operating procedures to cover all activities. As required by *10 CFR 71.89* **[7.2]**, the consignor shall send to the consignee, in advance of the shipment, instructions for safely opening the transport package.

Before handling the packages, consider the following items:

a. Review all shipping manifests against what is expected.

b. Ensure that personnel involved in operations of the AOS Transport Packaging System are familiar with all documents pertinent to the operation and maintenance of the transport packages, and that they have received HAZMAT training, per *49 CFR 172.704* **[7.7]**.

c. Review Table 2-7, "AOS Transport Packaging System Maximum Authorized Package Weight and Cg Locations – All Models" (which lists the packages and their components weights), for the purpose of selecting the proper handling devices.

d. Review Table 3-3, "Maximum Temperature Summary, Normal Conditions of Transport – All Models," Table 3-4, "Maximum Temperature Summary, Hypothetical Accident Conditions of Transport (Condition 3) – All Models," Table 4-6, "Maximum Cask Cavity Pressure Due to Normal Conditions of Transport – All Models," and Table 4-7, "Maximum Cask Cavity Pressure Due to Fire Condition – All Models," to be apprised of the packaging surface temperature and cavity pressures. These values represent maximum conditions.

e. Review the Activity Limits listed in the current revision of the NRC Certificate of Compliance 9316. These values represent maximum conditions. For shipping multiple isotopes, or isotopes that emit only low-energy gamma/beta emitters (that is, all emissions, including those from their progeny, are ≤ 0.3 MeV), refer to the guidance provided in Appendix 7.5.1.

f. Review the AOS Transport Packaging System certification drawings listed in the current revision of the NRC Certificate of Compliance 9316 and Table 1-5, "AOS Transport Packaging System Certification Drawing List – All Models," in preparation for Receiving Inspection.

g. All repairs require AOS approval prior to performing the repairs. Any replacement of components requires notification to AOS.

7.2.1 Receipt of Package from Carrier

To receive the transport package from the carrier:

a. Verify the integrity of the transport package's security seals. If seals are broken, indicating package tampering, isolate the transport package and immediately notify the site's Safeguards organization, then wait for their instructions. Otherwise, if the security seals are on the shipping cage, remove the security seals by cutting the wires, then properly dispose of the security seals. If the security seals are connected to the impact limiters, remove the seals after the shipping cage is detached.

Note: *"Safeguards organization" refers to the organization or person at the facility responsible for radioactive material control and accounting.*

b. Position the transport vehicle in the Receiving Inspection area.

c. Visually inspect the transport package for damage and proper labeling and marking. Refer to the shipping paper for shipment category and compare the marking and labels on the package to the requirement of Reference **[7.3]**.

d. Position the transport vehicle in the job staging area, for transport package removal. This operation can be aided by the use of an overhead crane or forklift truck.

e. Position the spreader bar or forks, then connect the appropriate slings and shackles to remove the shipping cage.

f. Remove the shipping cage and tie-down hardware.

g. Verify that the radiation and external contamination levels are in compliance with regulatory requirements *IAEA TS-R-1, Paragraphs 508* and *530 through 532*, *10 CFR 71.47* and *71.87(i)*, *49 CFR 173.441* and *173.443*, and *10 CFR 20.1906* (References **[7.1]**, **[7.2]**, **[7.3]**, and **[7.4]**, respectively).

Note: *The transport package's bottom surface is not accessible until the transport package is removed from the pallet. As a result, when measurements are required, the radiation and external contamination levels on the transport package's bottom surface are assessed after the shipping cask is removed in step j.*

h. Record any finding(s), and notify the Job Supervisor for disposition of the finding(s). Findings must be evaluated against *10 CFR 71.95* **[7.2]**, to determine whether they require regulatory notification, so that proper action can be taken. The Job Supervisor is responsible for direct oversight of the personnel that are performing the work.

i. Depending upon site-specific constraints, do one of the following:

- Remove the upper impact limiter from the cask, then place the impact limiter into temporary storage.
- Install trunnions. Prior to the installation, apply an anti-vibration compound on the trunnion bolt threads.
- Lift and remove the entire transport package from the transport vehicle, then set down the package in an appropriate location. Next, remove the impact limiters from the shipping cask, then place the impact limiters in temporary storage.

j. Remove the cask, using the appropriate rigging equipment.

k. Perform radiological and smear surveys of the cask surfaces, as described in step a in Paragraph 7.2.2.

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7.3 PREPARATION OF EMPTY PACKAGE FOR TRANSPORT

Note: *The operational steps provided in this section apply to all AOS Radioactive Material Transport Packaging System models (Models AOS-025A, AOS-050A, AOS-100A, AOS-100B, and AOS-100A-S). Any step specific to a given Model is identified within the step.*

This section describes operations that are typically performed after transporting radioactive material.

7.3.1 Inspecting the Cask Cavity

To inspect the cask cavity:

a. Remove the cask lid and cask lid plug from the empty cask and verify that the cask is empty.
b. Gather the necessary information, per site procedure, so that personnel can certify the transport package is "empty."
c. Perform a radiological survey of the cavity, to determine the extent of any contamination, in accordance with user (site) procedures.
d. If the cask is shipped as "empty," decontaminate the cavity to the limits defined in *IAEA TS-R-1, Paragraph 520*, and *49 CFR 173.428* (References **[7.1]** and **[7.3]**, respectively).
e. Visually inspect the cask cavity and ensure that there is no free-standing water. If free-standing water is present, dry the cask cavity. (The drying instructions are provided in Paragraph 7.1.3.1.)

7.3.2 Installing and Securing the Cask Lid

Note: *Re-use of the lid seal is allowed for empty packaging.*

To install and secure the cask lid:

a. Using proper rigging, slowly lower the cask lid plug and lid onto the cask, over the lid guide pins (if used). Carefully monitor this operation, to ensure that the cask lid is properly aligned.

Note: *The torque sequence is stamped on the top surface of the cask lid, about the bolt location.*

b. Torque the cask lid attachment bolts (refer to Table 7-2) in a crisscross pattern, with a final pass all the way around, to ensure even seal compression.
c. Inspect the cask, to ensure that the cask drain port plugs, cask vent port plugs, and covers are properly installed.

7.3.3 Leak Testing to Verify the Assembly

Not applicable. Leak testing is not performed on empty packaging.

7.3.4 Preparing the Empty Cask for Transport

Decontaminate the external surfaces of the empty cask, to a level consistent with *IAEA TS-R-1, Paragraph 508*, and *49 CFR 173.443* (References **[7.1]** and **[7.3]**, respectively). Perform a dose rate survey to demonstrate compliance with regulatory requirements *IAEA TS-R-1, Paragraph 516*, and *49 CFR 173.428* (References **[7.1]** and **[7.3]**, respectively).

7.5 APPENDIX

7.5.1 Dose Rate and Decay Heat Limit Compliance

Dose rate and decay heat limit compliance should be demonstrated through one of the following methods:

- **Shipping cask contents that contain a single radioisotope (or mixture of only Ir-192 and Ir-194)** – Ensure that the isotope's activity does not exceed its limit for the appropriate shipping cask variant listed in the current revision of the NRC Certificate of Compliance 9316. If the limits determined based on *10 CFR 71.47(b)* **[7.2]** are used, the transport package must be shipped as exclusive use. If the isotope is not listed for the shipping cask variant, –or– the isotope's activity within the shipping cask contents is greater than the listed activity limit, the shipping cask contents are not acceptable for shipment.
- **Shipping cask contents that contain multiple radioisotopes, including low-energy gamma and/or beta emitters** (as defined in Appendix 5.5.6, "Isotopes Insignificant to External Dose Rates") – Calculate the external dose rates and shipping cask contents' total decay heat, using the method defined in Appendix 5.5.5, "Shipments of Multiple Isotopes under 10 CFR 71.47(a)," and Appendix 5.5.7, "10 CFR 71.47(b) Exclusive Use Activity Limits for Models AOS-100A and AOS-100A-S." All dose rate and decay heat calculations should be documented on an AOS QA program-approved form, similar to the example provided in Figure 7-8 for the external dose rate calculation methodology. The following items outline dose rate limits and shipping cask decay heat limit *10 CFR 71.47(a, b)* (Reference **[7.1]**) compliance:

  A Dose Rate Limit and Shipping Cask Decay Heat Limit *10 CFR 71.47(a)* Compliance

  For each shipping cask model, demonstrate compliance with shipping cask decay heat limits and *10 CFR 71.47(a)* dose rate limits, using the decay heat limit of the respective shipping cask from Table 1-3, "Content Limitations – All Models," the equations in Table 5-34, "10 CFR 71.47(a) Dose Rate Acceptance Criteria for Multiple Isotopes," and the values from the respective Appendix 5.5.5 Multiple Isotope Calculation Reference Value Summary tables (Table 5-35, Table 5-35a, Table 5-35b, and Table 5-35c for Models AOS-100A and AOS-100A-S, AOS-025A, AOS-050A, and AOS-100B, respectively).

  B Dose Rate Limit and Shipping Cask Decay Heat Limit *10 CFR 71.47(b)* Compliance

  For Models AOS-100A and AOS-100A-S, if it is determined that the contents' radionuclide inventory results in external dose rates that exceed *10 CFR 71.47(a)* limits, *10 CFR 71.47(b)* regulatory dose rate limits may be used, provided that:

  - Transport package is shipped as exclusive use, and
  - Compliance with external dose rate limits are calculated using the equations listed in Table 5-40a, "10 CFR 71.47(b) Dose Rate Acceptance Criteria for Multiple Isotopes," and isotope values listed in Table 5-41, "Multiple Isotope Exclusive Use Calculation Reference Values – Models AOS-100A and AOS-100A-S."

  Low energy gamma and beta emitters (that is, all emissions, including those from their progeny, are ≤ 0.3 MeV) are permitted in Models AOS-100A and AOS-100A-S, without accounting for any contribution to external dose rates. To clarify, this requirement applies to the full beta spectrum, **not** the average beta energy (that is, $E_{max,\beta} \leq 0.3$ MeV). For each isotope within this category, the decay heat Q-value (in W/Ci) shall be determined using the SCALE 6.1 ORIGEN (Reference **[7.9]**) decay library *origen.rev03.decay.data*, and the contribution to the total decay heat from these isotopes and their progeny shall be included. This applies to contents under both A and B above. Based on these requirements, transporting a single low energy gamma and/or beta emitter is acceptable, given that the procedures provided above are followed, and the contents do **not** exceed the Model AOS-100A and AOS-100A-S shipping cask 400-W decay heat limit.

Low energy gamma and beta emitters are **not** permissible contents in the Model AOS-025A, AOS-050A, and AOS-100B shipping cask models. These shipping cask models are restricted to isotopes that are specifically listed in the respective tables of the current revision of the current revision of the NRC Certificate of Compliance 9316 and Appendix 5.5.5.

AOS
Alpha-Omega Services, Inc.

Calculation Sheet - Procedure for Mixing Isotopes in AOS-100A

PR9110.5 Table 1 Column No. 1	Enter proposed shipment activity in this column (Ci)	PR9110.5 (6.3) Table 1 Column No. 2	PR9110.5 (6.5) Table 1 Column No. 3	PR9110.5 (6.4) Table 1 Column No. 4	PR9110.5 (6.6) Table 1 Column No. 5
A_i Isotope		R_{Si} Dose Rate/ Curie on External Surface (mrem/hr/Ci)	R_{1mCi} Dose Rate/ Curie at 1m from Shipping Cask Surface (mrem/hr/Ci)	R_{1mPi} Dose Rate/ Curie at 1m from Transport Package Surface (mrem/hr/Ci)	Q_i Heat Generation Rate (W/Ci)
Co-60		3.912E-01	5.545E-02	3.292E-02	1.550E-02
Co-60-B		1.139E-01	1.833E-02	1.093E-02	1.550E-02
Co-60-C		1.868E-02	1.833E-02	5.314E-04	1.550E-02
Cs-137		3.188E-03	4.152E-04	2.570E-04	4.990E-03
Hf-181		2.595E-04	3.413E-05	2.182E-05	4.330E-03
Ir-192		5.802E-04	7.547E-05	4.898E-05	6.130E-03
Ir-194		4.502E-03	6.536E-04	3.871E-04	5.300E-03
Zr-95/Nb-95		3.098E-02	4.106E-03	2.571E-03	1.620E-02
H-3		0	0	0	3.380E-05
C-14		0	0	0	2.940E-04
V-49		0	0	0	2.640E-05
Fe-55		0	0	0	3.470E-05
Ni-63		0	0	0	1.040E-04
I-125		0	0	0	3.590E-04

	Calculated Total Radiation Levels:			**Maximum Value:**
Dose Rate on External Surface =	0.00E+00	mrem/hr	TRUE	180 mrem/hr maximum
Dose Rate at 1m from Shipping Cask Surface =	0.00E+00	mrem/hr	TRUE	900 mrem/hr maximum
Dose Rate at 1m from Transport Package Surface =	0.00E+00	mrem/hr	TRUE	9.0 mrem/hr maximum
	Calculated Total Heat:			
Total Heat Generation =	0.00E+00	W	TRUE	400 W maximum

NOTE: Only those isotopes identified in the SAR, AOS Document No. FM9054 and low energy gamma/beta emitters are to be evaluated and shipped (See PR9110.5 Table 1)

Document Approval:			
Completed By:		**Engineering Approval:**	
Name/Signature:	**Date:**	**Name/Signature:**	**Date:**
QA:		**President:**	
Name/Signature:	**Date:**	**Name/Signature:**	**Date:**

Figure 7-8. Example Dose Rate/Decay Heat Calculation Sheet (Model AOS-100A Non-Exclusive Shipment Version Shown)

7.6 REFERENCES

[7.1] *International Atomic Energy Agency (IAEA) Safety Standards Series No. TS-R-1* (*IAEA TS-R-1*), "Regulations for the Safe Transport of Radioactive Material," 1996 Ed. (as amended 2003).

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

[7.3] U.S. Department of Transportation (DOT), *Title 49, Code of Federal Regulations, Part 173 (49 CFR 173)*, "Shippers – General Requirements for Shipments and Packagings."

[7.4] U.S. Nuclear Regulatory Commission (NRC), *Title 10, Code of Federal Regulations, Part 20 (10 CFR 20)*, "Standards for Protection Against Radiation."

[7.5] U.S. Nuclear Regulatory Commission (NRC), *Title 10, Code of Federal Regulations, Part 21 (10 CFR 21)*, "Reporting of Defects and Noncompliance."

[7.6] U.S. Department of Transportation (DOT), *Title 49, Code of Federal Regulations, Part 171 (49 CFR 171)*, "General Information, Regulations, and Definitions."

[7.7] U.S. Department of Transportation (DOT), *Title 49, Code of Federal Regulations, Part 172 (49 CFR 172)*, "Hazardous Materials Table, Special Provisions, Hazardous Materials Communications, Emergency Response Information, and Training Requirements."

[7.8] American National Standards Institute, *ANSI N14.5-1997*, "Radioactive Materials – Leakage Tests on Packages for Shipment," February 5, 1998.

[7.9] 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.

8.1.5.3 Seal Testing

The testing conducted upon the seal during its fabrication is based upon the manufacturer's QA system requirements to produce a "Safety Classification A Component" **[8.7]**.

8.1.5.4 Fabrication

Table 8-8 summarizes the AOS Transport Packaging System Fabrication examination program.

Table 8-8. Fabrication Examination Program Summary

Test Category	Test Type	Reference	Test Description
Component	Adherence to Drawing	Certification Drawings. Refer to Table 1-5, "AOS Transport Packaging System Certification Drawing List – All Models."	Visual and Dimensional inspections.
Sub-assembly			
Assembly	Pressure and Containment	ASME Code, Section V, and applicable requirements of *NB-6112*, Section III, and *ANSI N14.5*, Section 7.3.	Pneumatic and Leakage test, per Reference **[8.4]**.
Weldment	NDE	ASME Code, Section V, and applicable requirements of *NX-5000*, Section III.	Visual, Penetrant, and Ultrasonic tests (VT, PT, and UT, respectively).

8.1.6 Shielding Tests

The AOS Transport Packaging System models use either tungsten alloy or carbon steel as their shielding material. Conducting a 100% UT examination, as well as dimensional and density checks of the shielding material, provide the necessary inspection processes for verifying the shielding attribute of these materials. As an **optional** additional test, prior to the first use of the transport package, a Co-60 source can also be used. The source is placed inside the cask cavity, and its outside surface is surveyed with a gamma detection instrument. The source strength must be high enough to generate an external reading consistent with the capability of the survey instrument. Equally spaced meridian and circumferential lines, along the vertical axis, divide the cask outside surface into approximately 10 x 10 cm (4 x 4 in.) squares. Dose rate readings are taken over each corner and center of the square area created by these lines. To verify the cask shielding material integrity, the measured dose rates should closely match the anticipated values from shielding/dose rate calculations, and large, unanticipated deviations should not exist between measurements.