

4. CONTAINMENT

Chapter 4 describes the RT-100 containment under the RT Quality Assurance Program [Ref. 1] and summarizes the results to demonstrate compliance with the structural requirements of 10 CFR 71 [Ref. 2]. This Chapter demonstrates the RT-100 containment boundary compliance with the permitted activity release limits specified in 10 CFR 71.51(a)(1) [Ref. 2] and 10 CFR 71.51(a)(2) [Ref. 2] for both normal conditions of transport (NCT) and hypothetical accident conditions (HAC) of transport. The reference leakage rates for various cask conditions are normally calculated, and the most bounding value is chosen as the maximum allowable leakage rate for the cask in order to ensure compliance with regulatory limits.

Due to the variety of inventories, diversity in both isotopic composition and in total activity concentration, the RT-100 has been established as a leaktight container. Leaktight is a degree of package containment that in a practical sense precludes any significant release of radioactive materials. This degree of containment is achieved by demonstration of a leakage rate less than or equal to 1×10^{-7} ref·cm³/s, of air at an upstream pressure of 1 atmosphere absolute and a downstream pressure of 0.01 atmosphere absolute or less (ANSI N14.5-1997 [Ref. 3]).

The containment review is based in part on the descriptions and evaluations presented in the General Information, Structural Evaluation and Thermal Evaluation sections of the application. Similarly, results of the containment review are considered in the review of Operating Procedures and Acceptance Tests and Maintenance Program. An example of the information flow for the containment review is shown in Figure 4-1 on the following page.

4.1 Description of Containment System

Section 4.1 provides a detailed description of the containment system. This description includes the containment vessel, welds, seals, lids, cover plates, and other closure devices relevant to the containment boundary of the cask. Materials of construction and applicable codes and standards are presented in the RT100 NM 1000-F - Bill of Material (Chapter 1, Appendix 1.4, Attachment 1.4-1).

4.1.1 Containment Vessel

The package containment system is defined as the inner shell of the shielded transport cask, together with the associated lid, O-ring seals, and lid closure bolts. The inner shell of the RT-100, or containment vessel, consists of a right circular cylinder of 1730 mm inner diameter and 1956 mm inside height. The shell is fabricated of stainless steel. At the base, the cylindrical shell is attached to a circular forged bottom with full penetration weld. At the top, the inner shell is attached to a circular forged flange with a full penetration weld. The primary lid is attached to the cask body with thirty-two (32) equally spaced M48 hex head bolts. A secondary lid covers an opening in the primary lid and is attached to the primary lid using eighteen (18) equally spaced M36 hex head bolts. Refer to Chapter 4, Section 4.1.4 for closure details. The inner shell is shown

to maintain stresses within allowable limits in Chapter 2, Section 2.6.7 for NCT and in Chapter 2, Section 2.7 for HAC. These evaluations demonstrate that the inner shell maintains its integrity and provides containment along with the closure system as described in Section 4.1.4.

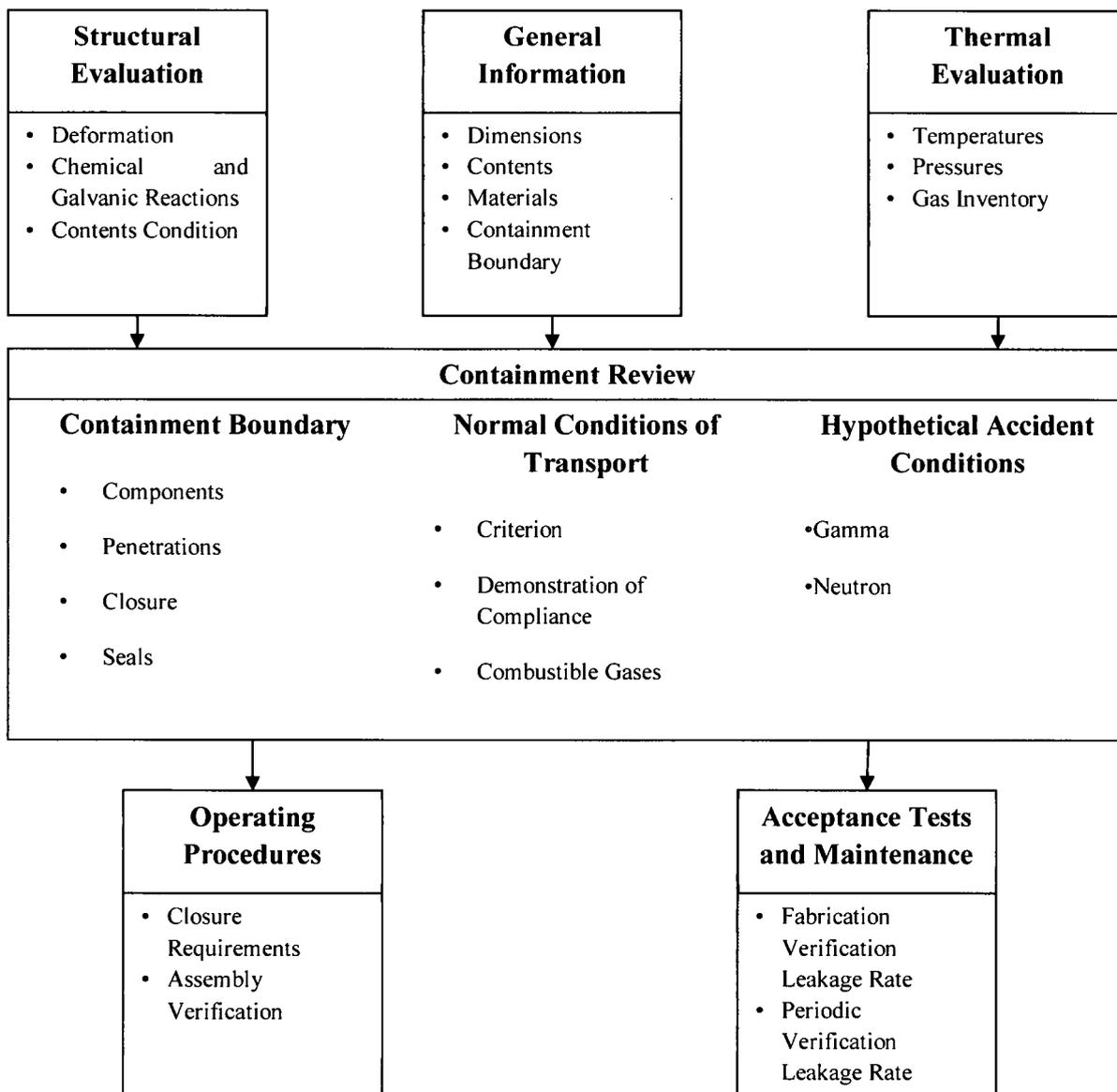


Figure 4-1 Information Flow for the Containment Review

4.1.2 Containment Penetration

There are three locations where the containment vessel may be penetrated. For each location, an inner O-ring seals the containment boundary.

- Primary lid
- Secondary lid
- Cask vent port cover plate

A vent port penetrates the primary lid into the main cask cavity. The vent penetration contains a quick disconnect valve and is sealed with the vent port cover plate. The primary lid, secondary lid and the cover plate are sealed with EPDM O-rings. Figure 4.1.2-1 illustrates the containment boundaries of the RT-100 (in red). The RT-100 does not rely on any valve or pressure relief device to meet the containment requirements. The quick disconnect valve is protected by the vent port cover plate which protects the valve from unauthorized operation and provides a sealed enclosure to retain any leakage from the device.

**WITHHELD PER
10 CFR 2.390**

4.1.3 Welds and Seals

The containment vessel is fabricated using full penetration welds. Lid seals are EPDM O-rings and are further addressed in Section 4.1.4. O-rings may be supplied by manufacturers such as those in Parker O-Ring Handbook ORD 5700 [Ref. 10] and Trelleborg Sealing Solutions O-Ring and Backup Rings Catalog, August 2011 [Ref. 11]. Additional information on the O-rings taken from these references is provided in Attachment 4.5-1 through Attachment 4.5-5.

Parker O-Ring Handbook ORD 5700 [Ref. 10] and Trelleborg Sealing Solutions O-Ring and Backup Rings Catalog, August 2011 [Ref. 11] contain information regarding the operating temperature range, gap permeability, and compression set for the material. The temperature performance of the EPDM O-rings is presented in Chapter 3, Section 3.2.1 and the application of the O-rings in the primary and secondary lid seals is addressed in Chapter 2, Appendix 2.13. EPDM radiation resistance is addressed in Radiation Resistance of Elastomers, IEEE Transactions on Nuclear Science, Vol. NS-32, No.5, October 1985 [Ref. 12], indicating that the material is radiation resistant up to 5×10^8 rads while retaining reasonable flexibility and strength, hardness, and very good compression set resistance. A copy of Reference 12 is provided in Attachment 4.5-5.

4.1.4 Closure

The primary lid closure consists of a partially recessed, 210 mm-thick stainless steel plate. The lid is supported at the perimeter of the cylindrical body by a thick flange (upper forging) which is welded to the top of the inner and outer cylindrical shells. The Primary Lid is attached to the cask body by thirty-two (32) equally spaced M48 hex head bolts. Two (2) EPDM O-rings are retained in machined grooves at the lid perimeter. Groove dimensions prevent over-compression of the O-rings by the closure bolt pre-load forces and hypothetical accident impact forces.

The cask is fitted with a recessed secondary lid which consists of 100 mm thick plate, a 60 mm thick lead gamma shield, and 10 mm thick closure plate. The Secondary Lid is attached to the Primary Lid with eighteen (18) equally spaced M36 hex head bolts. Two (2) EPDM O-rings are retained in machined grooves at the lid perimeter.

The quick-disconnect valve is housed under a 10mm thick stainless steel cover plate. The Quick-Disconnect Valve Cover Plate is attached to the primary lid with six (6) equally spaced M10 hex head bolts. Two (2) EPDM O-rings are retained in machined grooves at the lid perimeter.

The torque requirements for these bolts may be seen below in Table 4.1.4-1. Due to this closure setup, continuous venting from the RT-100 is precluded.

As stated above, the containment system is sealed by multiple bolted closures. These closures contain numerous bolts that are required to be tightened to specified torques using approved

procedures during the cask loading process. Secure closure is assured by the torque values specified and the assembly verification leak test performed prior to transport. The torques are specified in order to ensure that sufficient pre-load is applied to the bolts so that they will withstand loads from the maximum normal and accident condition pressures within the cavity.

The closure system is evaluated for NCT and HAC in Chapter 2, Appendix 2.13. Closure bolts are shown to maintain adequate design margin and allow the O-rings to maintain a positive seal at all times.

Table 4.1.4-1 Bolt Torque Requirements

Location	Size	Torque Values (N-m) ± 10% Lubricated
Primary Lid	M48	850
Secondary Lid	M36	350
Quick-Disconnect Valve Cover Plate	M10	27

4.1.5 Cavity Volume, Conditions, and Contents

The cavity dimensions are displayed in Table 4.1.5-1.

Table 4.1.5-1 Cask Cavity Dimensions

	Inches	Centimeters
L_{cavity}	77.2	196
D_{cavity}	68.1	173

Thus, the volume of the cylindrical cavity is

$$V_{cavity} = (\pi \cdot D_{cavity}^2 \cdot L_{cavity}) / 4$$

Table 4.1.5-2 Cask Cavity Volume

Total Cavity Volume [cm³]	4.60E+06
---	----------

The temperature under normal and accident conditions are determined based on the maximum internal cavity temperatures for normal and accident situations. Pressures and temperatures are provided by Calculation Package RTL-001-CALC-TH-0102, Rev. 6 [Ref. 8] and Calculation Package RTL-001-CALC-TH-0202, Rev. 6 [Ref. 9] for normal and accident situations, respectively. The standard leakage rate is the leakage rate of dry air when it is leaking from 1 atm (upstream pressure) to 0.01 atm (downstream pressure) at 298 K (ANSI N14.5-1997 [Ref. 3]). Dynamic viscosity values were generated based on the Sutherland equation

(“Fundamentals of Fluid Mechanics”, 5th edition [Ref. 14]), Introduction to Nuclear Engineering, 3rd edition [Ref.13] Table IV.4, ANSI N14.5-1997 [Ref. 3] Table B-1, Fundamentals of Fluid Mechanics Table B.4 [Ref. 14] Table B.4, and viscosity of gaseous helium table in Brookhaven National Laboratory, “Selected Cryogenic Data Notebook”, Aug. 1980 [Ref. 15].

Table 4.1.5-3 Parameters for Normal Transport and Accident Conditions

Parameter	Normal Conditions ⁸	Accident Conditions ⁹	Standard Conditions
P _u [atm]	3.38	6.8	1
P _d [atm]	1	1	0.01
P _a [atm]	2.19	3.9	0.505
T [°F]	176 (353 K, 80 °C)	302 (423 K, 150 °C)	76.7 (298 K, 25 °C)
M [g/mol]	29 (air), 4 (He)	29 (air), 4 (He)	29 (air), 4 (He)
μ [cP]	0.0207 (air), 0.0224 (He)	0.0236 (air), 0.0254 (He)	0.0185 (air), 0.0198 (He)
a [cm]	0.49	0.49	0.49

4.2 Allowable Leakage Rates at Test Conditions

Un-choked flow correlations are used as they better approximate the true measured flow rate for the leakage rates associated with transportation packages. Using the equations for molecular and continuum flow provided in NUREG/CR-6487 [Ref. 7], the corresponding leak hole diameter is calculated for the RT-100 for standard test conditions by solving Equation 4.1 for D, the leak hole diameter. The capillary length required for Equation 4.1 for the containment system is conservatively chosen as the O-ring groove width in the vent port cover plate lid, which is 0.49 cm.

Equation 4.1

$$L_{@P_a} = \left[\frac{2.49 \times 10^6 D^4}{a \cdot \mu} + \frac{3.81 \times 10^3 D^3 \sqrt{\frac{T}{M}}}{a \cdot P_a} \right] \times [P_u - P_d]$$

where:

- L_{@P_a} is the allowable leakage rate at the average pressure for standard conditions [cm³/s],
- a is the capillary length [0.49 cm],
- T is the temperature for standard conditions [K],
- M is the gas molecular weight [g/mol] = 29.0 for air, 4.0 for He from ANSI N14.5, Table B1,

μ is the dynamic viscosity for helium or air [cP],
 P_u is the upstream pressure [atm],
 P_d is the downstream pressure [atm],
 P_a is the average pressure; $P_a = (P_u + P_d)/2$ for standard conditions [atm], and
 D is the capillary diameter [cm].

The leak hole diameter is determined using the parameters for standard conditions presented in Table 4.1.5-3.

The allowable leakage rate for leaktight conditions is at the upstream pressure, the ratio presented in Equation 4.2 is used to convert Equation 4.1 to upstream leakage rate so that the capillary diameter can be determined.

Equation 4.2

$$L_{@P_a} = L_{@P_u} \frac{P_u}{P_a}$$

where:

$L_{@P_a}$ is the allowable leakage rate at the average pressure [cm^3/s] for standard conditions,
 $L_{@P_u}$ is the allowable leakage rate at the upstream pressure [cm^3/s] for standard conditions,
 P_u is the upstream pressure [atm],
 P_d is the downstream pressure [atm], and
 P_a is the average pressure; $P_a = (P_u + P_d)/2$ [atm].

The sensitivity for the leakage test procedures is established by ANSI N14.5-1997 [Ref. 3] as shown in Equation 4.3.

Equation 4.3

$$S = \frac{1}{2} \cdot \text{Leakage Rate}^1$$

4.3 Leakage Rate Test for Type B Packages

This section describes the leakage tests used to show that the RT-100 meets the containment requirements of 10 CFR 71.51 [Ref. 2]. Leak test requirements are further specified in Chapter 8, Section 8.1.4.

The following leakage tests are conducted on the RT-100 as required by ANSI N14.5 [Ref. 3]:

¹ Leakage rate in this case is the upstream pressure leakage rate at standard conditions.

Table 4.3-1 Leakage Tests of the RT-100 Package

Test	Frequency	Test Gas	Acceptance Criteria
Maintenance	After maintenance, repair (such as weld repair), or replacement of components of the containment system	Helium	$\leq L_{He}$
Fabrication	Prior to the first use of the RT-100		
Periodic	Within 12 months prior to next shipment		
Pre-Shipments	Before each shipment, after the contents are loaded and the package is closed	Nitrogen or air (optional)	No Leakage at a Sensitivity $\leq 10^{-3}$ ref-cm ³ /sec

*Adjusted for the individual properties of the test gas (calculated below); sensitivity is $\leq L_{He}/2$. As shown in Table 4.3-1, the Maintenance, Fabrication, and Periodic leakage tests may be performed using helium as the test gas. The acceptance criterion for these tests is the equivalent reference leakage rate for helium gas, L_{He} , which is calculated below.

4.3.1 Determination of Equivalent Reference Leakage Rate for Helium Gas

Section 4.3.1 determines the allowable leakage rate using the Helium gas which may be used to perform the annual verification leakage tests summarized in Table 4.3-1 above. This calculation uses formulas presented in ANSI N14.5 [Ref. 3].

It is known that the reference air leakage rate, L_R , is 1.00×10^{-7} ref-cm³/s based on leaktight criteria.

Using Equation 4.1 and Equation 4.2, the maximum capillary diameter, D_{max} , was determined:

$$L_{@P_u} = \left(\frac{2.49 \times 10^6 D_{max}^4}{(0.49 \text{ cm})(0.0185 \text{ cP})} + \frac{3.81 \times 10^3 D_{max}^3 \sqrt{\frac{298 \text{ K}}{29 \text{ g/mole}}}}{(0.49 \text{ cm})(0.505 \text{ atm})} \right) (1 \text{ atm} - 0.01 \text{ atm}) \left(\frac{0.505 \text{ atm}}{1 \text{ atm}} \right)$$

$$= 1 \times 10^{-7} \text{ cm}^3/\text{s}$$

Diameter values are inputted until the result of the above calculation is roughly equivalent to 1×10^{-7} ref-cm³/s. Solving for D_{max} iteratively yields:

$$D_{\max} = 1.3261\text{E-}04 \text{ [cm]}$$

The equivalent air/helium mixture that would leak from D_{\max} during a leak test, as described in Table 4.1.5-3, is determined. The leakage tests are performed with an air/helium mixture. The helium partial pressures can vary from 0.25 atm to 1.0 atm. An example with a helium partial pressure of 0.7 atm has been provided to illustrate the process used to determine the value of the variables used to determine the acceptable test leakage rates.

Assume the cask void is evacuated to 0.3 atm and then pressurized to 1.0 atm with an air/helium mixture.

$$P_{\text{void}} = P_{\text{air}} = 0.3 \text{ atm}$$

$$P_{\text{mix}} = 1.0 \text{ atm}$$

$$P_{\text{He}} = P_{\text{mix}} - P_{\text{air}} = 0.7 \text{ atm}$$

The downstream pressure, P_d , under standard conditions is 0.01 atm.

$$P_a = 0.5 \times (P_{\text{mix}} + P_d) \rightarrow P_a = 0.505 \text{ atm}$$

From ANSI N14.5 – 1997 [Ref. 3]:

$$M_{\text{He}} = 4.0 \text{ g/mol} \qquad M_{\text{air}} = 29.0 \text{ g/mol}$$

$$\mu_{\text{He}} = 0.0198 \text{ cP} \qquad \mu_{\text{air}} = 0.0185 \text{ cP}$$

The mass of the mixture of air/helium gases is then determined:

$$M_{\text{mix}} = \frac{M_{\text{He}}P_{\text{He}} + M_{\text{air}}P_{\text{air}}}{P_{\text{mix}}} \rightarrow M_{\text{mix}} = 11.5 \text{ g/mol} \quad \text{Eqn. B.7 from ANSI N14.5 [Ref. 3]}$$

$$\mu_{\text{mix}} = \frac{\mu_{\text{He}}P_{\text{He}} + \mu_{\text{air}}P_{\text{air}}}{P_{\text{mix}}} \rightarrow \mu_{\text{mix}} = 0.0194 \text{ cP} \quad \text{Eqn B.8 from ANSI N14.5 [Ref. 3]}$$

Change in viscosity as a function of temperature was taken into consideration by using the values listed in Table 4.3.1-1, and performing linear interpolation. Mixture viscosity was determined for each temperature using the same methodology described above.

Table 4.3.1-1 Helium and Air Viscosity

Temperature (Kelvin)	Helium Viscosity (cP)
250	0.0178 ²
275	0.0191 ²
300	0.0201 ³
350	0.0223 ³

Temperature (Kelvin)	Air Viscosity (cP)
273.15	0.0171 ⁴
278.15	0.0173 ⁴
283.15	0.0176 ⁴
288.15	0.0180 ⁴
293.15	0.0182 ⁴
298.15	0.0185 ⁴
303.15	0.0186 ⁴
313.15	0.0187 ⁴
323.15	0.0195 ⁴
333.15	0.0197 ⁴

Determine L_{mix} as a function of temperature

Temperature range for test = $T = 273$ to 328 K, or equivalently 31.73 °F to 130.73 °F

$$F_c(D_{max}) = \frac{2.49 \cdot 10^6 \cdot (D_{max})^4}{a \cdot \mu_{mix}} \quad \text{Equation B.3 from ANSI N14.5 – 1997 [Ref. 3]}$$

$$F_m(T) = \frac{3.81 \cdot 10^3 \cdot (D_{max})^3 \sqrt{\frac{T}{M_{mix}}}}{a \cdot P_a} \quad \text{Equation B.4 from ANSI N14.5 – 1997 [Ref. 3]}$$

$$L_{mix}(T) = (F_c + F_m(T)) (P_{mix} - P_d) \frac{P_a}{P_{mix}} \quad \text{Equation B.5 from ANSI N14.5 – 1997 [Ref. 3]}$$

Convert the test temperature to Fahrenheit: $T_F(T) = [(9/5)T_K - 459.67]$ °F

Figure 4.3.1-1 illustrates the air and helium mixture test leakage rates, L_{mix} , as a function of temperature in degrees Fahrenheit for helium partial pressures of 0.25, 0.35, 0.45, 0.55, 0.65, 0.75, 0.85, and 0.95 atm.

² Viscosity based on Reference 15

³ Viscosity based on Reference 13.

⁴ Viscosity based on Reference 14.

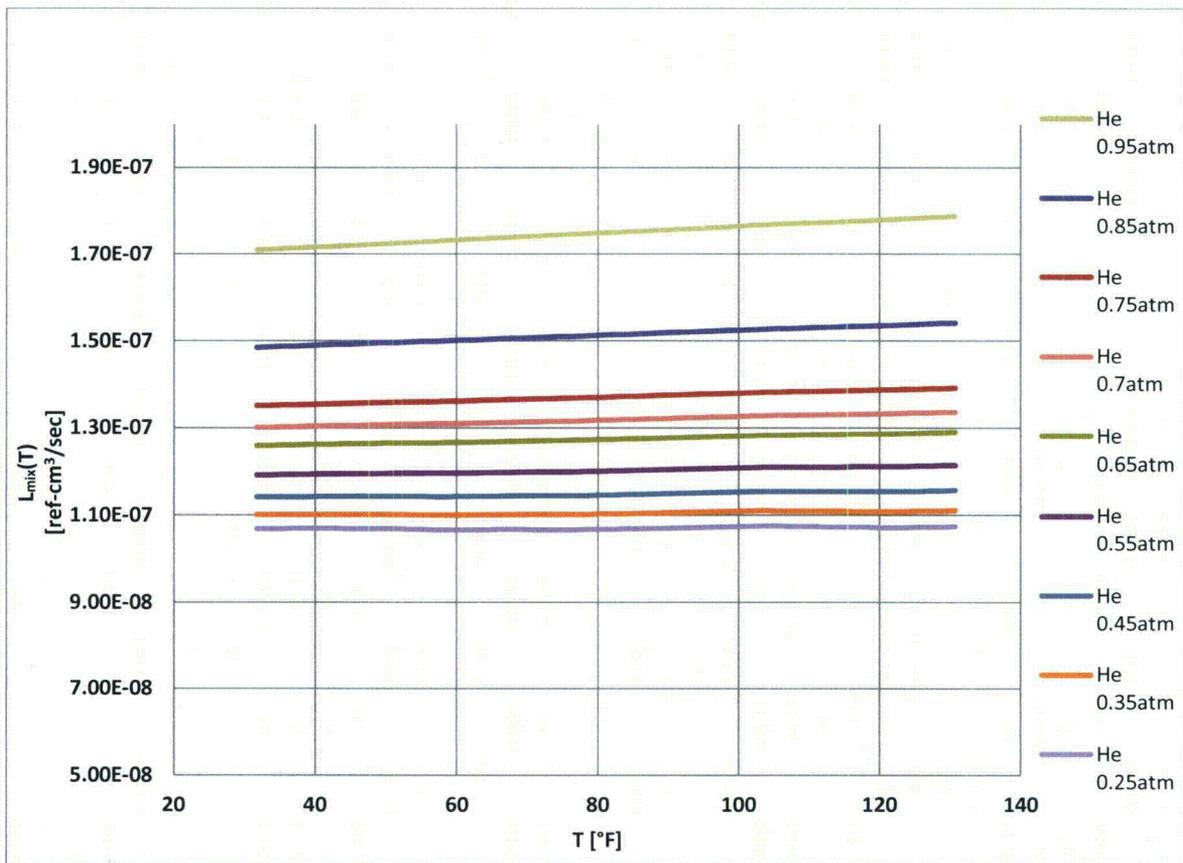


Figure 4.3.1-1 Allowable Air/Helium Mixture Test Leakage Rates

The helium component of this leak rate is determined by multiplying the leak rate of the mixture by the ratio of the helium partial pressure to the total mix pressure.

$$L_{\text{He}}(T) = L_{\text{mix}}(T) \cdot \frac{P_{\text{He}}}{P_{\text{mix}}}$$

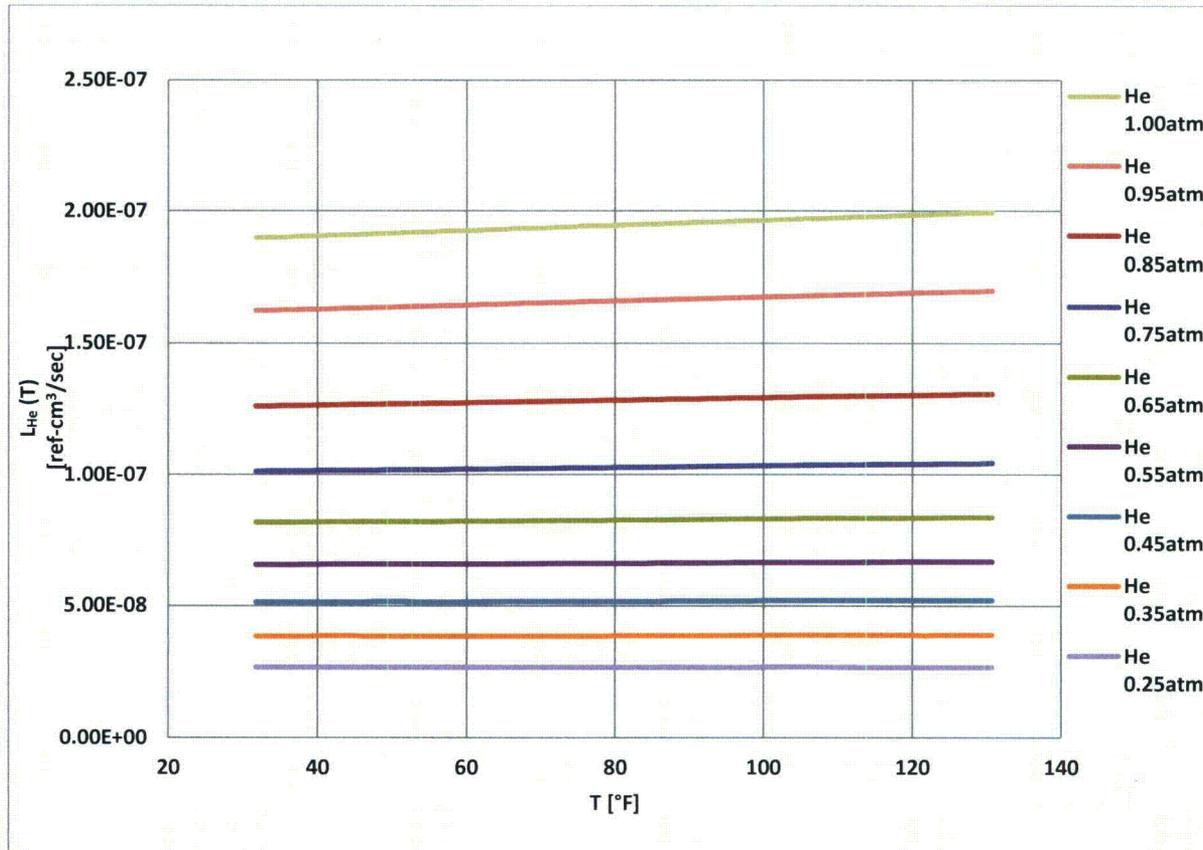


Figure 4.3.1-2 Allowable Helium Test Leakage Rates

Table 4.3.1-2 Allowable Helium Test Leakage Rates, cm³/sec

Temperature (°F)	Temperature (Kelvin)	Helium Leakage Rate P _{He} -1.0atm	Helium Leakage Rate P _{He} -0.85atm	Helium Leakage Rate P _{He} -0.65atm	Helium Leakage Rate P _{He} -0.45atm	Helium Leakage Rate P _{He} -0.25atm
31.73	273	1.897E-07	1.263E-07	8.185E-08	5.137E-08	2.672E-08
33.53	274	1.898E-07	1.263E-07	8.188E-08	5.138E-08	2.673E-08
35.33	275	1.900E-07	1.264E-07	8.191E-08	5.139E-08	2.673E-08
37.13	276	1.902E-07	1.265E-07	8.194E-08	5.141E-08	2.673E-08
38.93	277	1.903E-07	1.266E-07	8.198E-08	5.142E-08	2.673E-08
40.73	278	1.905E-07	1.267E-07	8.202E-08	5.144E-08	2.674E-08
42.53	279	1.907E-07	1.267E-07	8.205E-08	5.144E-08	2.673E-08
44.33	280	1.909E-07	1.268E-07	8.208E-08	5.144E-08	2.673E-08
46.13	281	1.911E-07	1.269E-07	8.211E-08	5.145E-08	2.672E-08
47.93	282	1.913E-07	1.270E-07	8.214E-08	5.145E-08	2.672E-08
49.73	283	1.914E-07	1.271E-07	8.217E-08	5.146E-08	2.671E-08
51.53	284	1.916E-07	1.272E-07	8.219E-08	5.145E-08	2.670E-08
53.33	285	1.918E-07	1.272E-07	8.221E-08	5.144E-08	2.668E-08
55.13	286	1.920E-07	1.273E-07	8.222E-08	5.144E-08	2.667E-08
56.93	287	1.922E-07	1.274E-07	8.224E-08	5.143E-08	2.666E-08
58.73	288	1.924E-07	1.275E-07	8.226E-08	5.142E-08	2.664E-08
60.53	289	1.925E-07	1.276E-07	8.230E-08	5.144E-08	2.665E-08
62.33	290	1.927E-07	1.277E-07	8.234E-08	5.145E-08	2.665E-08
64.13	291	1.929E-07	1.278E-07	8.238E-08	5.147E-08	2.666E-08
65.93	292	1.931E-07	1.278E-07	8.242E-08	5.148E-08	2.666E-08
67.73	293	1.933E-07	1.279E-07	8.246E-08	5.150E-08	2.667E-08
69.53	294	1.935E-07	1.280E-07	8.249E-08	5.151E-08	2.666E-08
71.33	295	1.936E-07	1.281E-07	8.253E-08	5.151E-08	2.666E-08
73.13	296	1.938E-07	1.282E-07	8.256E-08	5.152E-08	2.666E-08
74.93	297	1.940E-07	1.283E-07	8.259E-08	5.153E-08	2.665E-08
76.73	298	1.942E-07	1.284E-07	8.262E-08	5.153E-08	2.665E-08
78.53	299	1.944E-07	1.285E-07	8.267E-08	5.156E-08	2.666E-08
80.33	300	1.945E-07	1.286E-07	8.272E-08	5.159E-08	2.667E-08
82.13	301	1.947E-07	1.286E-07	8.276E-08	5.161E-08	2.669E-08
83.93	302	1.949E-07	1.287E-07	8.281E-08	5.164E-08	2.670E-08
85.73	303	1.951E-07	1.288E-07	8.286E-08	5.166E-08	2.671E-08
87.53	304	1.952E-07	1.289E-07	8.291E-08	5.169E-08	2.673E-08
89.33	305	1.954E-07	1.290E-07	8.296E-08	5.172E-08	2.675E-08
91.13	306	1.956E-07	1.291E-07	8.301E-08	5.176E-08	2.676E-08
92.93	307	1.958E-07	1.292E-07	8.306E-08	5.179E-08	2.678E-08
94.73	308	1.959E-07	1.293E-07	8.311E-08	5.182E-08	2.680E-08
96.53	309	1.961E-07	1.294E-07	8.317E-08	5.185E-08	2.681E-08

Table 4.3.1-2 Allowable Helium Test Leakage Rates, cm³/sec (Continued)

Temperature (°F)	Temperature (Kelvin)	Helium Leakage Rate P _{He} -1.0atm	Helium Leakage Rate P _{He} -0.85atm	Helium Leakage Rate P _{He} -0.65atm	Helium Leakage Rate P _{He} -0.45atm	Helium Leakage Rate P _{He} -0.25atm
98.33	310	1.963E-07	1.295E-07	8.322E-08	5.188E-08	2.683E-08
100.13	311	1.965E-07	1.296E-07	8.327E-08	5.191E-08	2.685E-08
101.93	312	1.966E-07	1.297E-07	8.332E-08	5.194E-08	2.686E-08
103.73	313	1.968E-07	1.297E-07	8.337E-08	5.197E-08	2.688E-08
105.53	314	1.970E-07	1.298E-07	8.340E-08	5.197E-08	2.687E-08
107.33	315	1.971E-07	1.299E-07	8.342E-08	5.197E-08	2.686E-08
109.13	316	1.973E-07	1.300E-07	8.344E-08	5.196E-08	2.685E-08
110.93	317	1.975E-07	1.300E-07	8.346E-08	5.196E-08	2.684E-08
112.73	318	1.977E-07	1.301E-07	8.348E-08	5.196E-08	2.683E-08
114.53	319	1.978E-07	1.302E-07	8.350E-08	5.195E-08	2.682E-08
116.33	320	1.980E-07	1.303E-07	8.352E-08	5.195E-08	2.681E-08
118.13	321	1.982E-07	1.304E-07	8.354E-08	5.195E-08	2.680E-08
119.93	322	1.984E-07	1.304E-07	8.356E-08	5.195E-08	2.679E-08
121.73	323	1.985E-07	1.305E-07	8.359E-08	5.195E-08	2.678E-08
123.53	324	1.987E-07	1.306E-07	8.363E-08	5.197E-08	2.679E-08
125.33	325	1.989E-07	1.307E-07	8.368E-08	5.199E-08	2.681E-08
127.13	326	1.990E-07	1.308E-07	8.373E-08	5.202E-08	2.682E-08
128.93	327	1.992E-07	1.309E-07	8.377E-08	5.205E-08	2.683E-08
130.73	328	1.994E-07	1.310E-07	8.382E-08	5.207E-08	2.685E-08

Figure 4.3.1-2 provides acceptable helium leakage rates at partial helium pressures of 0.25, 0.35, 0.45, 0.55, 0.65, 0.75, 0.85, 0.95, and 1.00 atm. Table 4.3.1-2 provides acceptable helium leakage rates for several helium partial pressures at temperatures ranging from 31.73 °F (273 K) to 130.73 °F (328 K). Figure 4.3.1-2 and Table 4.3.1-2 are to be used to determine the allowable leak rate L_{He} for the maintenance, fabrication, and periodic leak tests of the RT-100 based on partial pressure of helium and ambient temperatures used in the test. If the measured leakage rate is below the value shown in Figure 4.3.1-2, then the leaktight criteria has been met.

4.4 Hydrogen Gas Generation

Hydrogen gas buildup in loads containing waste material typically occurs due to radiolysis of hydrogenous material in the contents. As hydrogen is generated, it could potentially accumulate within the cask cavity in flammable concentrations. Based on USNRC guidance, the flammability limit of 0.05 volume fraction (mole fraction and volume fraction is interchangeable when discussing ideal gas buildup) hydrogen in air was measured in accordance with NUREG/CR-6673 “Hydrogen Generation in TRU Waste Transportation Packages” [Ref. 16], and supplemented with data from EPRI NP-5977 “Radwaste Radiolytic Gas Generation Literature Review” [Ref. 21].

Materials that make up the contents that can undergo radiolysis include primarily ion exchange resins, with lesser quantities of polystyrene and polyamides (nylon). Materials that make up the secondary container and shoring that can undergo radiolysis include polyethylene, wood, and polypropylene. Free water in the contents and moisture in the resin beads are also included in the analysis. In order to provide a bounding analysis, it is assumed that all of the decay energy in the contents produces gas generation in the waste or secondary container.

The rate of gas generation by radiolysis in these materials is dependent upon the type of incident radiation. Alpha emitters tend to generate more hydrogen per unit of energy deposited than gamma/beta emitters. Typical resin and filter waste produced at commercial nuclear power reactor facilities contains a high percentage of gamma in relation to alpha emitters. Typical examples of historical shipment data are provided with RT100-REF-01-01 "*Historical Cask Summaries by Waste Category*" [Ref. 22]. Because NUREG/CR-6673 is primarily focused on the alpha radiation predominant in TRU waste, EPRI NP-5977 is utilized to obtain gamma radiation G Values for these primary waste materials.

The typical shipment data referenced above indicates that the decay energy is approximately 90~100% from gamma radiation. In order to bound these shipments and to facilitate the utilization of a loading curve as a function of decay heat and waste volume in the cask, a decay energy distribution of 80% gamma and 20% alpha decay energy is assumed. The evaluation presented in Sections 4.4.1, 4.4.2, and 4.4.3 utilize this distribution as a way of illustrating the calculational method. Section 4.4.4 provides the user with a simplified model used to develop the loading curve (Figure 4.4.4-1) in order to determine the maximum allowable decay heat as a function of waste volume. Section 4.4.5 provides the user with an analytical model along with a set of G Values for the bounding waste material as a function of the gamma and alpha decay energy distribution for cases that do not fit the loading curve.

Package material and content that can generate flammable gas shall be appropriately assigned as part of the ionic resin bead waste or polyethylene container when using the Loading Curve (Figure 4.4.4-1) or detailed analysis (Section 4.4.5) to determine acceptable hydrogen gas generation-related parameters of shipping time and decay heat. For example, waste filters (made of material other than polypropylene or polyethylene) shall be grouped as ionic bead waste and wood shoring would be grouped as part of the polyethylene container. If filters are made of polyethylene or polypropylene, they are to be included in the secondary container volume for the hydrogen gas generation detailed analysis.

4.4.1 Determination of Bounding G Values

The first step in performing a gas generation calculation is to determine the G Values. As such, the following sections describe the steps in this process.

4.4.1.1 G Values for Waste and Secondary Container Materials

A list of G Values is provided in Table 4.4-1 and are taken from NUREG/CR-6673 [Ref. 16], EPRI NP-5977 [Ref. 21], and RH-TRU 72-B SAR [Ref. 23]. These materials represent all potential cask contents as indicated in Section 1.2.2.3, *Physical and Chemical Form – Density, Moisture Content and Moderators*. Potential materials in the waste that can undergo radiolysis are polystyrene, nylon, polyamides, ion exchange resins, and any residual water. Secondary container and shoring materials include polyethylene, wood and polypropylene.

Table 4.4-1 G Values (Molecules/100eV) for Potential Content Materials

Material	G_H G (H ₂)	G_{FG} G (flammable gas)	G_T G (net gas)
Waste Materials			
Polystyrene (Alpha Radiation)	0.20	0.20	0.20
Polyamides/Nylon ⁵	1.10	1.20	1.50
Ion Exchange Resins (Alpha Radiation)	1.70	1.70	2.10
Ion Exchange Resins (Gamma/Beta Radiation) ⁶	0.62	0.62	0.62
Water (Liquid Phase, Gamma Radiation) ⁷	0.45	0.45	0.45 ⁽⁸⁾
Water (Liquid Phase, Alpha Radiation)	1.60	1.60	1.60 ⁽⁸⁾
Paper	0.90	0.90	1.50
Polyethylene Filter	4.00	4.10	4.10
Polypropylene Filter	3.30	3.40	3.40
Secondary Container / Shoring			
Polyethylene	4.00	4.10	4.10
Wood (Cellulose)	3.20	3.20	10.20
Polypropylene	3.30	3.40	3.40

The ion exchange resin has the highest flammable gas G Value due to alpha radiation when compared to the other hydrogenous materials that could be contained within the waste. The G Value of ionic resin for gamma radiation is taken from EPRI NP-5977, which indicates that fully swollen ionic exchange resins have flammable gas G Values of up to 0.62.

⁵ Based on NUREG/CR-6673, Section D.7.22 [Ref. 16], nylon is a polyamide. Polyamides are bounded by these values.

⁶ The G_{FG} value for ionic resin is used for G_T because no value is provided in EPRI NP-5977 [Ref. 21]. Less non-flammable gas production will decrease the amount of time required to achieve a flammable mixture, making this a bounding assumption.

⁷ Based on NUREG/CR-6673 Table D.1 [Ref. 16], the largest G(H₂) for liquid water subjected to gamma radiation is 0.45 molecules/100eV.

⁸ For water, The G_T value is set to the G_{FG} value, as explained later in Section 4.4.1.1.

Ionic resins are dewatered before transport, meaning most of the free water is removed. Even in a fully “dewatered” state, ion exchange resin beads can contain from 50% to 66% moisture, per NUREG/CR-6673 and EPRI NP-5977. The term “dewatered” should not be confused with the term “dry” for ionic resins. Based on Section 4 of EPRI NP-5977, the G Values for fully dried resins are a factor of 10 less than swollen resin beads (from 0.001 to 0.067 in recorded experiments). As such, it can be concluded that the G values for ionic resins are primarily driven by moisture content and the values utilized in Table 4.4-1 already take into consideration the moisture content in the resin.

Only hydrogen gas was considered as a byproduct of the radiolysis of water. This results in the fraction of flammable gas to the total gas generated (α) of 1.0 in Equation 4.8 of NUREG/CR-6673 [Ref. 16]. Including oxygen in the total gas generation from the radiolysis of water would decrease the mole fraction of hydrogen (X_H) in the free gas volume. This is because the alpha term would be less than 1.0. Thus, using the value of 1.0 would yield the most bounding result.

4.4.1.2 Calculation of Effective G Values

Table 4.4-1 lists the G Values for the material that could be transported in the cask. Both alpha and gamma G Values are provided for the most predominant waste contents of resin and water. For other materials, the more conservative alpha radiation values are utilized. As noted in Section 4.4, hydrogen gas generation calculations for typical resin waste contents are performed assuming that the decay energy of the waste is 80% gamma and 20% alpha. The effective G Values for these materials is calculated using these fractions applied to the corresponding G Value. Materials without a gamma G Value are taken as the alpha G Value. The effective G Values are provided in Table 4.4-2.

Table 4.4-2 Effective G Values (Molecules/100eV) for Potential Content Materials

Material	Effective G_H G (H ₂)	Effective G_{FG} G (flam. gas)	Effective G_T G (net gas)
Waste Materials			
Polystyrene	0.20	0.20	0.20
Polyamides/Nylon	1.10	1.20	1.50
Ion Exchange Resins	0.84	0.84	0.92
Water	0.68	0.68	0.68
Paper	0.90	0.90	1.50
Polyethylene Filter	4.00	4.10	4.10
Polypropylene Filter	3.30	3.40	3.40
Secondary Container / Shoring			
Polyethylene	4.00	4.10	4.10
Wood (Cellulose)	3.20	3.20	10.20
Polypropylene	3.30	3.40	3.40

4.4.1.3 Operating Temperature G Value Adjustment

As described in Section 2.4.2 of NUREG/CR-6673 [Ref. 16], the hydrogen gas generation rate of some materials is noticeably affected by the temperature in the container during transport. This is contingent upon the activation energy of the material being shipped in the cask. The activation energies for the materials used in the hydrogen generation calculations are shown in Table 4.4-3, and are based on Table 3.11 of NUREG/CR-6673 and RH-TRU 72-B Appendices [Ref. 23]. The activation energy for ionic resin is not specifically listed in NUREG/CR-6673, but RH-TRU 72-B SAR specifies that organic resins have an activation energy of 2.1 kcal/mole.

Table 4.4-3 Activation Energy

Material	Activation Energy (kcal/mole)
Waste Materials	
Polystyrene	0.8
Polyamides/Nylon	0.8
Resins	2.1
Water	0.0
Paper	1.3
Polyethylene Filter	0.8
Polypropylene Filter	0.8
Secondary Container / Shoring	
Polyethylene	0.8
Wood	2.1
Polypropylene	0.8

The G value at NCT temperatures is determined using Equation 2.2 of NUREG/CR-6673.

$$G_{T_2} = G_{T_1} \exp \left[\left(\frac{E_a}{R} \right) \left(\frac{T_2 - T_1}{T_2 T_1} \right) \right]$$

- where:
- G_{T_1} = radiolytic G value at 298 K [molecules/100eV]
 - G_{T_2} = radiolytic G value at transport temperature [molecules/100eV],
 - E_a = activation energy for radiolytic gas generation [kcal/gmol],
 - R = gas law constant [1.987×10^{-3} kcal/gmol-K],
 - T_1 = 298 K
 - T_2 = temperature of contents during transport [K]

Based on Table 3.1.3-1, the maximum inner shell temperature during NCT is 73.1 °C. Therefore, a bounding value of 80 °C (353.15 K) is utilized for the contents in this analysis. For example, the resultant G_{FG} value (and G_T value because they are the same for polyethylene) for

polyethylene at 353.15 K is equivalent to:

$$G_{FG} = (4.1 \text{ molecules}/100\text{eV}) \exp \left[\left(\frac{0.8 \text{ kcal/gmol}}{1.987 \times 10^{-3} \text{ kcal/gmolK}} \right) \left(\frac{353.15\text{K} - 298\text{K}}{(353.15\text{K})(298\text{K})} \right) \right]$$

$$= 5.06 \text{ molecules}/100\text{eV}$$

The final G values used in the hydrogen generation calculations are shown in Table 4.4-4.

Table 4.4-4 Bounding G Values for Contents at Maximum NCT Temperature

Material	G (H ₂), G _H	G (flammable gas), G _{FG}	G (net gas), G _T
Waste Materials			
Polystyrene	0.25	0.25	0.25
Polyamides	1.36	1.48	1.85
Ion Exchange Resins	1.45	1.45	1.59
Water	0.68	0.68	0.68
Paper	1.27	1.27	2.11
Polyethylene Filter	4.94	5.06	5.06
Polypropylene Filter	4.08	4.20	4.20
Secondary Container / Shoring			
Polyethylene	4.94	5.06	5.06
Wood	5.57	5.57	17.75
Polypropylene	4.08	4.20	4.20

Of the materials that could comprise the waste, resin and water are present in the greatest quantities. While polyamides have a slightly higher G(flammable gas) value than the resins, resins were chosen as the bounding contents because resins have a much higher density when loaded than the polyamides which form a small part of filters. In addition, hydrolysis of polyamides produces nonflammable gas which would tend to dilute hydrogen concentration. If polyethylene or polypropylene filters are loaded into the cask, their volumes shall be accounted for as a polyethylene secondary container in the calculation. Therefore, resin and water are selected for utilization in the gas generation calculations.

The secondary container and shoring materials are assumed to be polyethylene. Like polyamides in the waste, wood has a slightly higher G Value than polyethylene. However, wood has a significantly higher total gas G Value, which offsets the impact of flammable gas generation by generating more than 2 moles of non-flammable gas for every mole of flammable gas. Additionally, the wood would be present only in limited quantities as shoring material on the outside of the secondary container.

As described in Section 4.4, the gas generation analysis is performed assuming that all decay energy is absorbed in either the waste or the secondary container, maximizing the amount of gas generated through radiolysis. In fact, much of the gamma radiation emitted from the waste escapes the cavity and is absorbed in the cask's lead shielding material.

These G values are then utilized to calculate the hydrogen gas generation rates as described in Section 4.4.3.

4.4.2 Hydrogen Gas Generation by Radiolysis

For the hydrogen generation evaluation, the RT-100 is treated as a single rigid non-leaking enclosure. Using Equation 4.8 on page 31 of NUREG/CR-6673 [Ref. 16], an equation characterizing the mole fraction of hydrogen (or flammable gas) in the RT-100 over time for a single material generating hydrogen is shown below.

Equation 4.4

$$X_H = \frac{n_H}{n_0 + n_{net}} = \frac{\frac{D_H}{100} \frac{\alpha G_T t}{A_N}}{\frac{P_0 V}{R_g T_0} + \frac{D_H}{100} \frac{G_T t}{A_N}}$$

where: X_H = mole fraction of hydrogen,
 n_H = number of moles of hydrogen [gmol],
 n_0 = initial number of gas moles in the container when the vessel was closed [gmol],
 n_{net} = number of moles of gas generated [gmol],
 G_T = total radiolytic G value [molecules/100eV],
 D_H = decay heat that is absorbed by the radiolytic materials [eV/s],
 α = fraction of G_T that is equivalent to G_{FG} , flammable gas released,
 A_N = Avogadro's constant [6.022×10^{23} molecules/gmol],
 P_0 = pressure when the container is sealed [atm],
 T_0 = temperature when the container is sealed [K],
 V = is the container void volume [cm^3],
 R_g = gas law constant [$82.05 \text{ cm}^3 \text{ atm/gmolK}$],
 t = time [seconds]

Based on Section 5 of NUREG/CR-6673 [Ref. 16], shipping periods other than one year need to be defined as one half the time it takes for hydrogen to accumulate in the package to a concentration equivalent to the lower flammability limit. To ensure that this is taken into consideration in the calculations, the equation above has been adjusted to incorporate a multiple of 2 times the shipping period required. Equation 4.4 is also limited to providing hydrogen mole fraction over time for one hydrogenous material. In this analysis there are three hydrogenous materials that are taken into consideration, water in the waste material, the resin, and the

polyethylene container. The resultant equation generated once these parameters are taken into consideration (the increase in shipping time and the number of hydrogenous materials) is shown below in Equation 4.5.

Equation 4.5

$$X_H = \frac{\frac{D_i \alpha_i G_{Ti}(2t)}{100 A_N} + \frac{D_C \alpha_C G_{TC}(2t)}{100 A_N} + \frac{D_W \alpha_W G_{TW}(2t)}{100 A_N}}{\frac{P_0 V}{R_g T_0} + \frac{D_i G_{Ti}(2t)}{100 A_N} + \frac{D_C G_{TC}(2t)}{100 A_N} + \frac{D_W G_{TW}(2t)}{100 A_N}}$$

$$X_H = \frac{\frac{D_H \alpha_i G_{Ti}(2t) F_i}{100 A_N} + \frac{D_H \alpha_C G_{TC}(2t) F_C}{100 A_N} + \frac{D_H \alpha_W G_{TW}(2t) F_W}{100 A_N}}{\frac{P_0 V}{R_g T_0} + \frac{D_H G_{Ti}(2t) F_i}{100 A_N} + \frac{D_H G_{TC}(2t) F_C}{100 A_N} + \frac{D_H G_{TW}(2t) F_W}{100 A_N}}$$

- where:
- X_H = mole fraction of hydrogen,
 - G_{Ti} = total radiolytic G value for ionic resin and stainless steel filters [molecules/100eV],
 - G_{TC} = total radiolytic G value for polyethylene container, shoring, and polyethylene or polypropylene filters [molecules/100eV],
 - G_{TW} = total radiolytic G value for water in waste [molecules/100eV],
 - D_H = decay heat that is absorbed by the radiolytic materials [eV/s],
 - D_i = decay heat that is absorbed by the ionic resin and stainless steel filters [eV/s],
 - D_C = decay heat that is absorbed by the polyethylene container, shoring, and polyethylene or polypropylene filters [eV/s],
 - D_W = decay heat that is absorbed by the water [eV/s],
 - α_i = fraction of G_{Ti} that is equivalent to G_{FGi} , flammable gas released, for the ionic resin and stainless steel filters,
 - α_C = fraction of G_{TC} that is equivalent to G_{FGC} , flammable gas released, for the secondary container, shoring, and polyethylene or polypropylene filters in the waste,
 - α_W = fraction of G_{TW} that is equivalent to G_{FGW} , flammable gas released, for the water in waste,
 - F_W = fraction of decay heat energy absorbed by the water in the waste material,
 - F_i = fraction of decay heat energy absorbed by the ionic resin and stainless steel filters in the waste material,
 - F_C = fraction of decay heat energy absorbed by the polyethylene container, shoring, and polyethylene or polypropylene filters,
 - A_N = Avogadro's constant [6.022×10^{23} molecules/gmol],
 - P_0 = pressure when the container is sealed [atm],
 - T_0 = temperature when the container is sealed [K],
 - V = is the container void volume [cm^3],
 - R_g = gas law constant [$82.05 \text{ cm}^3 \text{ atm/gmol-K}$],
 - t = time [seconds]

4.4.3 Hydrogen Generation – Radiolysis in Waste, Water and Polyethylene Container

In order to determine the time available to transport the RT-100, Equation 4.5 must be manipulated to provide time limit versus waste volume and decay heat of inventory. Given the decay heat and other cask content parameters, the time to reach 5% by volume of combustible gases is determined as follows.

Solve for t,

$$X_H = \frac{\frac{D_H \alpha_i G_{Ti}(2t)F_i}{100 A_N} + \frac{D_H \alpha_C G_{TC}(2t)F_C}{100 A_N} + \frac{D_H \alpha_W G_{TW}(2t)F_W}{100 A_N}}{\frac{P_0 V}{R_g T_0} + \frac{D_H G_{Ti}(2t)F_i}{100 A_N} + \frac{D_H G_{TC}(2t)F_C}{100 A_N} + \frac{D_H G_{TW}(2t)F_W}{100 A_N}}$$

$$X_H \left(\frac{P_0 V}{R_g T_0} + \frac{D_H G_{Ti}(2t)F_i}{100 A_N} + \frac{D_H G_{TC}(2t)F_C}{100 A_N} + \frac{D_H G_{TW}(2t)F_W}{100 A_N} \right) = \frac{\frac{D_H \alpha_i G_{Ti}(2t)F_i}{100 A_N} + \frac{D_H \alpha_C G_{TC}(2t)F_C}{100 A_N} + \frac{D_H \alpha_W G_{TW}(2t)F_W}{100 A_N}}{\frac{D_H \alpha_i G_{Ti}(2t)F_i}{100 A_N} + \frac{D_H \alpha_C G_{TC}(2t)F_C}{100 A_N} + \frac{D_H \alpha_W G_{TW}(2t)F_W}{100 A_N}}$$

$$t = \frac{50 A_N X_H \frac{P_0 V}{R_g T_0}}{F_i G_{Ti} D_H [\alpha_i - X_H] + F_C G_{TC} D_H [\alpha_C - X_H] + F_W G_{TW} D_H [\alpha_W - X_H]}$$

Alternatively, given the limiting transport time and other cask parameters, the Equation 4.5 must be manipulated to provide decay heat limit versus the waste volume and the shipping period. The decay heat limit versus the free gas volume and shipping period (all decay heat energy deposited into the waste material and the polyethylene container) is determined as follows.

Solve for D_H ,

$$X_H = \frac{\frac{D_H \alpha_i G_{Ti}(2t)F_i}{100 A_N} + \frac{D_H \alpha_C G_{TC}(2t)F_C}{100 A_N} + \frac{D_H \alpha_W G_{TW}(2t)F_W}{100 A_N}}{\frac{P_0 V}{R_g T_0} + \frac{D_H G_{Ti}(2t)F_i}{100 A_N} + \frac{D_H G_{TC}(2t)F_C}{100 A_N} + \frac{D_H G_{TW}(2t)F_W}{100 A_N}}$$

$$X_H \left(\frac{P_0 V}{R_g T_0} + \frac{D_H G_{Ti}(2t)F_i}{100 A_N} + \frac{D_H G_{TC}(2t)F_C}{100 A_N} + \frac{D_H G_{TW}(2t)F_W}{100 A_N} \right) = \frac{\frac{D_H \alpha_i G_{Ti}(2t)F_i}{100 A_N} + \frac{D_H \alpha_C G_{TC}(2t)F_C}{100 A_N} + \frac{D_H \alpha_W G_{TW}(2t)F_W}{100 A_N}}{\frac{D_H \alpha_i G_{Ti}(2t)F_i}{100 A_N} + \frac{D_H \alpha_C G_{TC}(2t)F_C}{100 A_N} + \frac{D_H \alpha_W G_{TW}(2t)F_W}{100 A_N}}$$

$$D_H = \frac{50 A_N X_H \frac{P_0 V}{R_g T_0}}{F_i G_{Ti} t [\alpha_i - X_H] + F_C G_{TC} t [\alpha_C - X_H] + F_W G_{TW} t [\alpha_W - X_H]}$$

where: X_H = mole fraction of hydrogen,
 G_{Ti} = total radiolytic G value for ionic resin and stainless steel filters [molecules/100eV],
 G_{TC} = total radiolytic G value for polyethylene container, shoring, and polyethylene or polypropylene filters [molecules/100eV],
 G_{TW} = total radiolytic G value for water in waste [molecules/100eV],
 D_H = decay heat that is absorbed by the radiolytic materials [eV/s],
 D_i = decay heat that is absorbed by the ionic resin and stainless steel filters [eV/s],
 D_C = decay heat that is absorbed by the polyethylene container, shoring, and polyethylene or polypropylene filters [eV/s],
 D_W = decay heat that is absorbed by the water [eV/s],
 α_i = fraction of G_{Ti} that is equivalent to G_{FGi} , flammable gas released, for the ionic resin and stainless steel filters,
 α_C = fraction of G_{TC} that is equivalent to G_{FGC} , flammable gas released, for the secondary container, shoring, and polyethylene or polypropylene filters in the waste,
 α_W = fraction of G_{TW} that is equivalent to G_{FGW} , flammable gas released, for the water in waste,
 F_W = fraction of decay heat energy absorbed by the water in the waste material,
 F_i = fraction of decay heat energy absorbed by the ionic resin and stainless steel filters in the waste material,
 F_C = fraction of decay heat energy absorbed by the polyethylene container, shoring, and polyethylene or polypropylene filters,
 A_N = Avogadro's constant [6.022×10^{23} molecules/gmol],
 P_0 = pressure when the container is sealed [atm],
 T_0 = temperature when the container is sealed [K],
 V = is the container void volume [cm^3],
 R_g = gas law constant [$82.05 \text{ cm}^3 \text{ atm/gmolK}$],
 t = time [seconds]

The next step is to determine the values of the variables in this equation. Avogadro's constant and the gas law constant are known values set at 6.022×10^{23} molecules/gmol and $82.05 \text{ cm}^3 \text{ atm/gmolK}$, respectively, in this analysis. Initial gas temperature and pressure have been set at maximum NCT conditions (311 K and 1 atm). Based on USNRC guidance, the flammability limit of 0.05 volume fraction hydrogen in air was measured NUREG/CR-6673 [Ref. 16]. The radiolytic G values and α values utilized are as provided in Table 4.4-5. The time required has been arbitrarily set at 10 days (864,000 seconds) in this analysis (reminder that equations automatically double the time entered into the equation based on guidance suggested in NUREG/CR-6673 [Ref. 16]).

Table 4.4-5 Effective G Values and Corresponding α Values for Contents

Gamma Frac.	Alpha Frac.	Material	G (flam gas), G_{FG}	G (net gas), G_T	α
80%	20%	Polyethylene	5.06	5.06	1.00
80%	20%	Resin	1.45	1.59	0.91
80%	20%	Water	0.68	0.68	1.00 ⁽⁹⁾

Determining the fraction of decay heat energy absorbed by the free water in the waste material (F_W), ionic resin and stainless steel filters in the waste material (F_i), and by the polyethylene container, shoring, and polyethylene or polypropylene filters in the waste material (F_C) is approximated by assuming that the energy absorbed is proportional to the volume of the material in question divided by the total volume of hydrogenous material being shipped in the cask. Thus, the fractions can be described as follows:

$$F_W = \frac{V_W}{V_W + V_i + V_C}$$

$$F_i = \frac{V_i}{V_W + V_i + V_C}$$

$$F_C = \frac{V_C}{V_W + V_i + V_C}$$

where: V_W = volume of free water in the waste
 V_i = volume of dewatered¹⁰, ionic resin in the waste, including absorbed moisture, and stainless steel filters in the waste material
 V_C = volume occupied by the secondary container, shoring, and polyethylene or polypropylene filters in the waste material

Water is present in resin bead shipments in two distinct forms; one is “absorbed moisture” within the resin bead itself; the other is “free water” that is present between the resin beads. The absorbed moisture within the resin bead is considered in the hydrogen generation analysis as it is incorporated into G Value of the resins.

The volume occupied by the waste (V_{waste}) is assumed to be 99% ionic resin and 1% free water.

⁹ For water, The G_T value is set to the G_{FG} value to obtain an α value of 1.0.

¹⁰ The term “dewatered resin” refers to resins in which free water has been removed from between the resin beads at the time of preparation for storage or transportation. The amount of free water in “dewatered” resins is typically around 1% after mechanical draining (EPRI NP-5977 “Radwaste Radiolytic Gas Generation Literature Review”, page 10 [Ref. 21]). The term “dewatered” should not be confused with “dry”. Dewatered resin beads shipped in the RT-100 could have a moisture content up to 50~66% based on NUREG/CR-4062 “Extended Storage of Low-Level Radioactive Waste, Potential Problem Areas” [Ref. 20], and EPRI NP-5977.

The ionic resin beads are assumed to be uniform spheres. Since the random packing fraction for uniform spheres is 0.64 [Ref. 5], the remaining free space (0.36) of the waste volume is assumed to be 0.11 air and 0.25 water to account for grossly dewatered material content. Thus, the volumes of ionic resin and water in the waste can be described as follows:

$$V_W = (0.99)(0.25)V_{waste} + (0.01)V_{waste} = (0.2575)V_{waste}$$

$$V_i = (0.99)(0.64)V_{waste} = (0.6336)V_{waste}$$

As noted, the assumed content is either dewatered resin or grossly dewatered resin. The amount of free water in “dewatered resins”¹⁰ is typically around 1% after mechanical draining, by regulation no more than 1% to meet disposal requirements. Grossly dewatered resins have a higher free water amount that shall be limited to 20% of the ionic resin volume (20.75% of the waste volume). Therefore, the amount of “free water” assumed (25.75% of waste volume) thus represents a free water volume that bounds the dewatered resin state by an order of magnitude, and bounds the grossly dewatered resin state by around 25%, and was chosen to represent a bounding condition for hydrogen generation.

Therefore, the fraction of decay heat energy absorbed by the water in the waste volume (F_W), ionic resin and stainless steel filters the waste volume (F_i), and by the polyethylene container, shoring, and polyethylene or polypropylene filter (F_C) are equivalent to:

$$F_W = \frac{0.2575V_{waste}}{(0.2575V_{waste} + 0.6336V_{waste} + V_C)}$$

$$F_i = \frac{0.6336V_{waste}}{(0.2575V_{waste} + 0.6336V_{waste} + V_C)}$$

$$F_C = \frac{V_C}{(0.2575V_{waste} + 0.6336V_{waste} + V_C)}$$

The remaining 0.11 fraction of ionic resin volume is air. The remaining fraction of air volume in the ionic resin is taken into consideration in the total free gas volume (V). Where the free gas volume (V) is equivalent to the total cavity volume ($4.60 \times 10^6 \text{ cm}^3$) minus the sum of the container, shoring, and polyethylene or polypropylene filter volume (V_C), water volume (V_W), and the ionic resin and stainless steel filter volume (V_i).

$$V = (4.60 \times 10^6 \text{ cm}^3) - (V_C + V_W + V_i)$$

$$V = (4.60 \times 10^6 \text{ cm}^3) - (V_C + 0.2575V_{waste} + 0.6336V_{waste})$$

$$V = (4.60 \times 10^6 \text{ cm}^3) - V_C - 0.8911V_{waste}$$

Incorporating the equations for fraction of decay heat energy absorbed by the water in the waste volume, ionic resin in the waste volume and by the polyethylene container into the derivation of time limit and decay heat limit results in the following equations.

Equation 4.6

$$t = \frac{50A_N X_H \frac{P_0 V}{R_g T_0} (0.2575V_{waste} + 0.6336V_{waste} + V_C)}{(0.6336V_{waste})G_{Ti}D_H[\alpha_i - X_H] + (V_C)G_{TC}D_H[\alpha_C - X_H] + (0.2575V_{waste})G_{TW}D_H[\alpha_W - X_H]}$$

Equation 4.7

$$D_H = \frac{50A_N X_H \frac{P_0 V}{R_g T_0} (0.2575V_{waste} + 0.6336V_{waste} + V_C)}{(0.6336V_{waste})G_{Ti}t[\alpha_i - X_H] + V_C G_{TC}t[\alpha_C - X_H] + (0.2575V_{waste})G_{TW}t[\alpha_W - X_H]}$$

The final step to solving the equation is determining the free gas volume which will vary based on the inventory in the RT-100. The maximum cavity volume is known to be $4.60 \times 10^6 \text{ cm}^3$ (162.37 ft^3) based on Table 4.1.5-2. In order to determine the free gas volume an approximation of the volume occupied by the polyethylene liner needs to be made. The guiding technical issue in determining the free gas volume is to maximize the hydrogen gas mole fraction buildup rate that then results in a conservative shipping time (limiting the allowable shipping time). A greater hydrogen mole fraction buildup rate in the cavity is produced by minimizing the free gas volume of the cavity. Minimizing the available free gas volume is accomplished by using the polyethylene container with the largest container volume. "Exhibit A of Cask Procurement Agreement dated April 10, 2012" [Ref. 17], provides the burial volume, maximum internal volume, and empty weight of various containers, and is shown in Table 4.4.3-6.

The container volume may be calculated from the empty weight and material density. In order to calculate the largest container volume, a minimum material density is used. The material density of high density polyethylene is 0.959 g/cm^3 , while the material density of plain carbon steel is 7.85 g/cm^3 [Ref. 24]. For a bounding assumption, and to take into account empty liner weight tolerances, the densities were reduced by 10%, resulting in a density of 0.863 g/cm^3 (53.88 lb/ft^3) for polyethylene and 7.065 g/cm^3 (441.05 lb/ft^3) for steel. The result is that the EL-142 container has the largest container volume of 27.02 ft^3 . A volume of 30.1 ft^3 was used in the analysis to represent the volume occupied by the secondary container and any shoring. Therefore, the maximum free gas volume (no waste volume) is 132.27 ft^3 . If a different container is used in the RT-100 transport cask, the equations generated in this section of the SAR can be adjusted.

The analysis assumes use of a polyethylene container. As described in Section 4.4.1.3 this is considered a bounding assumption based on material G Values. Use of a steel liner listed in Table 4.4.3-6 is considered acceptable because steel does not contribute to hydrogen gas generation.

Given the 10 day limiting transport time, the concern is how much waste volume and decay heat is acceptable for the individual shipments. The waste volume is then equal to the maximum cavity volume subtracted by the free gas volume and the polyethylene container volume.

A loading curve of allowable decay heat as a function of waste volume is provided in Section 4.4.4 for a specific set of waste parameters, including G-Values based on a bounding decay heat distribution of 80% gamma and 20% alpha. Additionally, in case a detailed analysis is performed, a procedure is given in Section 4.4.5, and a list of effective G Values for other distributions of gamma and alpha radiation is provided in Table 4.4.5-2.

Table 4.4.3-6 Secondary Container Volumes and Allowable Shoring Volume

Container	Material Type	Empty Weight ¹¹ (lbs)	Density ¹² (lb/ft ³)	Volume Occupied by Container ¹³ (ft ³)	Allowable Shoring Volume (ft ³)
PL 6-80 MT	Polyethylene	500	53.88	9.28	20.82
PL 6-80 MTIF	Polyethylene	525	53.88	9.74	20.36
PL 6-80 FR	Polyethylene	550	53.88	10.21	19.89
PL 6-80 FP/FEDX	Polyethylene	625	53.88	11.60	18.50
PL 8-120 MT	Polyethylene	600	53.88	11.14	18.96
PL 8-120 MTIF	Polyethylene	625	53.88	11.60	18.50
PL 8-120 FR	Polyethylene	650	53.88	12.06	18.04
PL 8-120 FP/FEDX	Polyethylene	725	53.88	13.46	16.64
PL 8-120 CMT	Polyethylene	720	53.88	13.36	16.74
PL 14-150	Polyethylene	800	53.88	14.85	15.25
PL 10-160 MT	Polyethylene	700	53.88	12.99	17.11
PL 10-160 MTIF	Polyethylene	735	53.88	13.64	16.46
PL 10-160 FR	Polyethylene	750	53.88	13.92	16.18
PL 10-160 FP/FEDX	Polyethylene	825	53.88	15.31	14.79
NUHIC-55	Polyethylene	150	53.88	2.78	27.32
NUHIC-136	Polyethylene	600	53.88	11.14	18.96
Radlok 500	Polyethylene	680	53.88	12.62	17.48
EL-50	Polyethylene	909	53.88	16.87	13.23
EL-142	Polyethylene	1456	53.88	27.02	3.08
L 6-80 MT	Steel	1000	441.05	2.27	27.83
L 6-80 CMT	Steel	1150	441.05	2.61	27.49
L 6-80 IN-SITU	Steel	3500	441.05	7.94	22.16
L 6-80 FP	Steel	1050	441.05	2.38	27.72
L 6-80 FP/FEDX	Steel	1225	441.05	2.78	27.32
L 8-120 MT	Steel	1200	441.05	2.72	27.38
L 8-120 CMT	Steel	1350	441.05	3.06	27.04
L 8-120 IN-SITU	Steel	4200	441.05	9.52	20.58
L 8-120 FR	Steel	1250	441.05	2.83	27.27
L 8-120 FP/FEDX	Steel	1325	441.05	3.00	27.10
ES-50	Steel	250	441.05	0.57	29.53
ES-142	Steel	1100	441.05	2.49	27.61

¹¹ From Exhibit A of Cask Procurement Agreement dated April 10, 2012 by and between Waste Control Specialists LLC and Robatel Technologies, LLC et al [Ref. 17].

¹² The bounding calculation assumes a maximum container volume. Therefore, lower density values of 0.863 g/cm³ and 7.065 g/cm³ were chosen for polyethylene and steel.

¹³ Calculated as the Empty Weight divided by the Density, neglecting void space.

4.4.4 Hydrogen Gas Generation – Simplified Model used to develop Loading Curve

Using Equation 4.7, the decay heat limit versus waste volume can be determined for a limit of 5% in the cavity free volume. Figure 4.4.4-1 provides a curve illustrating the waste volume to decay heat value that would result in the generation of a flammable gas mixture within 10 days assuming that all decay heat is absorbed by the waste material and the polyethylene container. The calculation assumes that the hydrogen generation occurs over a period of time that is twice the allowable shipping time.

For most shipments, this simplified graphical model (Loading Curve) can be used to determine the maximum heat load. However, use of the Loading Curve is limited to the restrictions noted in Table 4.4.4-1. One restriction of using the Loading Curve is that the secondary container is listed in Table 4.4.3-6, or is a container of equivalent material volume.

If the waste volume and decay heat values for the contents fall below the Loading Curve illustrated in Figure 4.4.4-1, and the restrictions listed in Table 4.4.4-1 are met, the load would not generate a flammable gas mixture during shipment. Otherwise, the user must perform a more detailed calculation of hydrogen generation for their specific contents and expected shipping time using the information provided in Section 4.4.5. The use of this calculation ensures that the requirements of NUREG/CR-6673 [Ref. 16] are met.



Figure 4.4.4-1 Package Loading Curve for Hydrogen Generation – Decay Heat Limit Versus Waste Volume

**Table 4.4.4-1 Conditions and Justifications for using Package Loading Curve
 (Figure 4.4.4-1)**

Condition for Shipper to use Loading Curve	Justification
Waste consisting of resins and filters from commercial power plants	Historically shipments of commercial resins and filters have consisted of approximately 90-100% gamma radiation [Ref. 22]. To bound these shipments, the calculation assumes a decay energy distribution of 80% gamma and 20% alpha radiation. This results in effective G-Values for resin beads of 0.836 and for water of 0.68 molecules/100eV at 298K. These values are adjusted for maximum NCT temperature of 80 °C, and bound the expected G-Values for resins and filters from commercial reactors.
Waste has been dewatered or grossly dewatered	The loading curve assumes a free water volume of 25.75%. The main effect of free water is to limit the void volume in the cavity, thereby increasing the hydrogen mole fraction. Since the loading curve assumes 25.75% free water for a hydrogen concentration of 5% or less, shippers must ensure that the limit is not exceeded.
No limit on moisture content of resin	The G-values for resins, as noted in Table 5.3 of EPRI NP-5977, are for resins with high moisture contents (i.e., swollen resin).
Use of a liner (or equivalent) listed in Table 4.4.3-6 with maximum shoring volume as specified	The calculation determines the free volume for waste by subtracting the maximum liner and shoring volume from the cask cavity volume. Equivalent liners may be used provided the volume occupied by the liner and shoring material does not exceed 30.1 ft ³ .
Shipment time not greater than 10 days	Shipment time calculated for 20 days (allowing a shipment within 10 days following regulation).
Loading at temperature not to exceed 38 °C and standard pressure (1 atm)	The maximum ambient NCT temperature is 38 °C per 10 CFR 71.
Secondary containers are passively vented within the cask cavity during shipment.	Secondary containers are required to be passively vented within the cask cavity. The loading curve assumes the gases generated are free to occupy the cask cavity volume inside and outside the secondary container.
Filters are not made of polyethylene or polypropylene	Polyethylene or polypropylene filters have higher G Values than resins, therefore, they require performing the detailed analysis and addition of their volume to the secondary container volume (V_C).
Waste volume not greater than 130 ft ³	Extrapolation beyond the curve is not allowed.

4.4.5 Hydrogen Gas Generation – Analytical Model used for Detailed Analysis

If Figure 4.4.4-1 is not applicable to a shipment, or if further analysis is required, the equations derived in Section 4.4.3 can be used. With substitution and further simplification of Equation 4.6 and Equation 4.7, the maximum allowable shipping time (t_{max}) or the maximum allowable decay heat ($D_{H,max}$) can be described as:

Equation 4.8

$$t_{max} = \frac{(2.5A_N P_0)(4.6E6 - V_C - 0.8911V_{WASTE})(0.8911V_{WASTE} + V_C)}{(R_g T_0 D_H)[0.6336V_{WASTE} G_{Ti}(\alpha_i - 0.05) + V_C G_{TC}(\alpha_C - 0.05) + 0.2575V_{WASTE} G_{TW}(\alpha_W - 0.05)]}$$

Equation 4.9

$$D_{H,max} = \frac{(2.5A_N P_0)(4.6E6 - V_C - 0.8911V_{WASTE})(0.8911V_{WASTE} + V_C)}{(R_g T_0 t)[0.6336V_{WASTE} G_{Ti}(\alpha_i - 0.05) + V_C G_{TC}(\alpha_C - 0.05) + 0.2575V_{WASTE} G_{TW}(\alpha_W - 0.05)]}$$

- where:
- A_N = Avogadro's constant [6.022x10²³ molecules/gmol]
 - R_g = gas law constant [82.05 cm³·atm/gmol·K]
 - P_0 = pressure when the container is sealed [atm]
 - T_0 = temperature when the container is sealed [K]
 - D_H = decay heat of cask contents [eV/s]
 - t = shipment time [s]
 - V_C = volume occupied by the secondary container, shoring, and polyethylene or polypropylene filters in the waste [cm³]
 - V_{WASTE} = volume occupied by the ionic resin and stainless steel filters in the waste material [cm³]
 - G_{Ti} = total radiolytic G value for the ionic resin and stainless steel filters [molecules/100eV]
 - G_{TC} = total radiolytic G value for the secondary container, shoring, and polyethylene or polypropylene filters in the waste [molecules/100eV]
 - G_{TW} = total radiolytic G value for water in waste [molecules/100eV]
 - α_i = fraction of G_{Ti} that is equivalent to G_{FGi} , flammable gas released, for the ionic resin and stainless steel filters
 - α_C = fraction of G_{TC} that is equivalent to G_{FGC} , flammable gas released, for the secondary container, shoring, and polyethylene or polypropylene filters in the waste
 - α_W = fraction of G_{TW} that is equivalent to G_{FGW} , flammable gas released, for water in the waste

NOTE: Use of Equation 4.8 and Equation 4.9 are valid only when the conditions listed in Table 4.4.5-1 are met.

Table 4.4.5-1 Conditions for Shipper to use the Detailed Analysis

1	Waste consists of resins and filters from commercial power plants.
2	Waste has been grossly dewatered.
3	Secondary containers are passively vented within the cask cavity during shipment.

The user may measure the decay heat of the cask contents (D_H) in order to calculate the maximum allowable shipping time (t_{max}) using Equation 4.8.

Alternately, the user may know the shipment time (t) and calculate the maximum allowable decay heat of the cask contents ($D_{H,max}$) using Equation 4.9.

Initial pressure (P_0) and initial temperature (T_0) may be measured by the user at the time of loading. The volume occupied by the secondary container, shoring, and polyethylene or polypropylene filters in the waste (V_C) and the volume occupied by the ionic resin and stainless steel filters in the waste material (V_{WASTE}) are known.

The use of different G-values (G_{Ti} , G_{TC} , G_{TW}) and α fractions (α_i , α_C , α_W) must be justified by the user based on waste characterization. These variables must be adjusted for the transport temperature of 80 °C as described in Section 4.4.1.3, in order to meet the requirements of NUREG/CR-6673 [Ref. 16].

The values must also be adjusted for the appropriate alpha/gamma radiation distribution. One example of this adjustment is provided in Table 4.4.5-2 for the same G-values in the bounding case loading curve for the 80% gamma/20% alpha decay heat distribution.

Table 4.4.5-2 G-values and α -Fractions for a Range of Alpha/Gamma Decay Heat Distributions

Gamma Frac	Alpha Frac	Material	G (H ₂), G _H	G (flam gas), G _{FG}	G (net gas), G _T	α
0.0	1.0	Polyethylene	4.94	5.06	5.06	1.00
		Resin	2.96	2.96	3.65	0.81
		Water	1.60	1.60	1.60	1.00 ⁽¹⁴⁾
0.1	0.9	Polyethylene	4.94	5.06	5.06	1.00
		Resin	2.77	2.77	3.40	0.82
		Water	1.49	1.49	1.49	1.00 ⁽¹⁴⁾
0.2	0.8	Polyethylene	4.94	5.06	5.06	1.00
		Resin	2.58	2.58	3.14	0.82
		Water	1.37	1.37	1.37	1.00 ⁽¹⁴⁾
0.3	0.7	Polyethylene	4.94	5.06	5.06	1.00
		Resin	2.39	2.39	2.88	0.83
		Water	1.26	1.26	1.26	1.00 ⁽¹⁴⁾
0.4	0.6	Polyethylene	4.94	5.06	5.06	1.00
		Resin	2.21	2.21	2.62	0.84
		Water	1.14	1.14	1.14	1.00 ⁽¹⁴⁾
0.5	0.5	Polyethylene	4.94	5.06	5.06	1.00
		Resin	2.02	2.02	2.37	0.85
		Water	1.03	1.03	1.03	1.00 ⁽¹⁴⁾
0.6	0.4	Polyethylene	4.94	5.06	5.06	1.00
		Resin	1.83	1.83	2.11	0.87
		Water	0.91	0.91	0.91	1.00 ⁽¹⁴⁾
0.7	0.3	Polyethylene	4.94	5.06	5.06	1.00
		Resin	1.64	1.64	1.85	0.89
		Water	0.80	0.80	0.80	1.00 ⁽¹⁴⁾
0.8	0.2	Polyethylene	4.94	5.06	5.06	1.00
		Resin	1.45	1.45	1.59	0.91
		Water	0.68	0.68	0.68	1.00 ⁽¹⁴⁾
0.9	0.1	Polyethylene	4.94	5.06	5.06	1.00
		Resin	1.27	1.27	1.34	0.95
		Water	0.57	0.57	0.57	1.00 ⁽¹⁴⁾
0.95	0.05	Polyethylene	4.94	5.06	5.06	1.00
		Resin	1.17	1.17	1.21	0.97
		Water	0.51	0.51	0.51	1.00 ⁽¹⁴⁾
1.0	0.0	Polyethylene	4.94	5.06	5.06	1.00
		Resin	1.08	1.08	1.08	1.00
		Water	0.45	0.45	0.45	1.00 ⁽¹⁴⁾

¹⁴ For water, the α value is set to 1.0.

4.5 Appendix

Attachment 4.5-1 EPDM Temperature Specifications [Ref. 10]

Not compatible with:

- Fuels of high aromatic content (for flex fuels a special compound must be used).
- Aromatic hydrocarbons (benzene).
- Chlorinated hydrocarbons (trichloroethylene).
- Polar solvents (ketone, acetone, acetic acid, ethylene-ester).
- Strong acids.
- Brake fluid with glycol base.
- Ozone, weather and atmospheric aging.

2.2.2 Carboxylated Nitrile (XNBR)

Carboxylated Nitrile (XNBR) is a special type of nitrile polymer that exhibits enhanced tear and abrasion resistance. For this reason, XNBR based materials are often specified for dynamic applications such as rod seals and rod wipers.

Heat resistance

- Up to 100°C (212°F) with shorter life @ 121°C (250°F).

Cold flexibility

- Depending on individual compound, between -18°C and -48°C (0°F and -55°F).

Chemical resistance

- Aliphatic hydrocarbons (propane, butane, petroleum oil, mineral oil and grease, diesel fuel, fuel oils) vegetable and mineral oils and greases.
- HFA, HFB and HFC hydraulic fluids.
- Many diluted acids, alkali and salt solutions at low temperatures.

Not compatible with:

- Fuels of high aromatic content (for flex fuels a special compound must be used).
- Aromatic hydrocarbons (benzene).
- Chlorinated hydrocarbons (trichloroethylene).
- Polar solvents (ketone, acetone, acetic acid, ethylene-ester).
- Strong acids.
- Brake fluid with glycol base.
- Ozone, weather and atmospheric aging.

2.2.3 Ethylene Acrylate (AEM, Vamac)

Ethylene acrylate is a terpolymer of ethylene and methyl acrylate with the addition of a small amount of carboxylated curing monomer. Ethylene acrylate rubber is not to be confused with polyacrylate rubber (ACM).

Heat resistance

- Up to 149°C (300°F) with shorter life up to 163°C (325°F).

Cold flexibility

- Between -29°C and -40°C (-20°F and -40°F).

Chemical resistance

- Ozone.
- Oxidizing media.
- Moderate resistance to mineral oils.

Not compatible with:

- Ketones.
- Fuels.
- Brake fluids.

2.2.4 Ethylene Propylene Rubber (EPR, EPDM)

EPR copolymer ethylene propylene and ethylene-propylene-diene rubber (EPDM) terpolymer are particularly useful when sealing phosphate-ester hydraulic fluids and in brake systems that use fluids having a glycol base.

Heat resistance

- Up to 150°C (302°F) (max. 204°C (400°F)) in water and/or steam).

Cold flexibility

- Down to approximately -57°C (-70°F).

Chemical resistance

- Hot water and steam up to 149°C (300°F) with special compounds up to 260°C (500°F).
- Glycol based brake fluids (Dot 3 & 4) and silicone-based brake fluids (Dot 5) up to 149°C (300°F).
- Many organic and inorganic acids.
- Cleaning agents, sodium and potassium alkalis.
- Phosphate-ester based hydraulic fluids (HFD-R).
- Silicone oil and grease.
- Many polar solvents (alcohols, ketones, esters).
- Ozone, aging and weather resistant.

Not compatible with:

- Mineral oil products (oils, greases and fuels).

2.2.5 Butyl Rubber (IIR)

Butyl (isobutylene, isoprene rubber, IIR) has a very low permeability rate and good electrical properties.

Heat resistance

- Up to approximately 121°C (250°F).

Cold flexibility

- Down to approximately -59°C (-75°F).

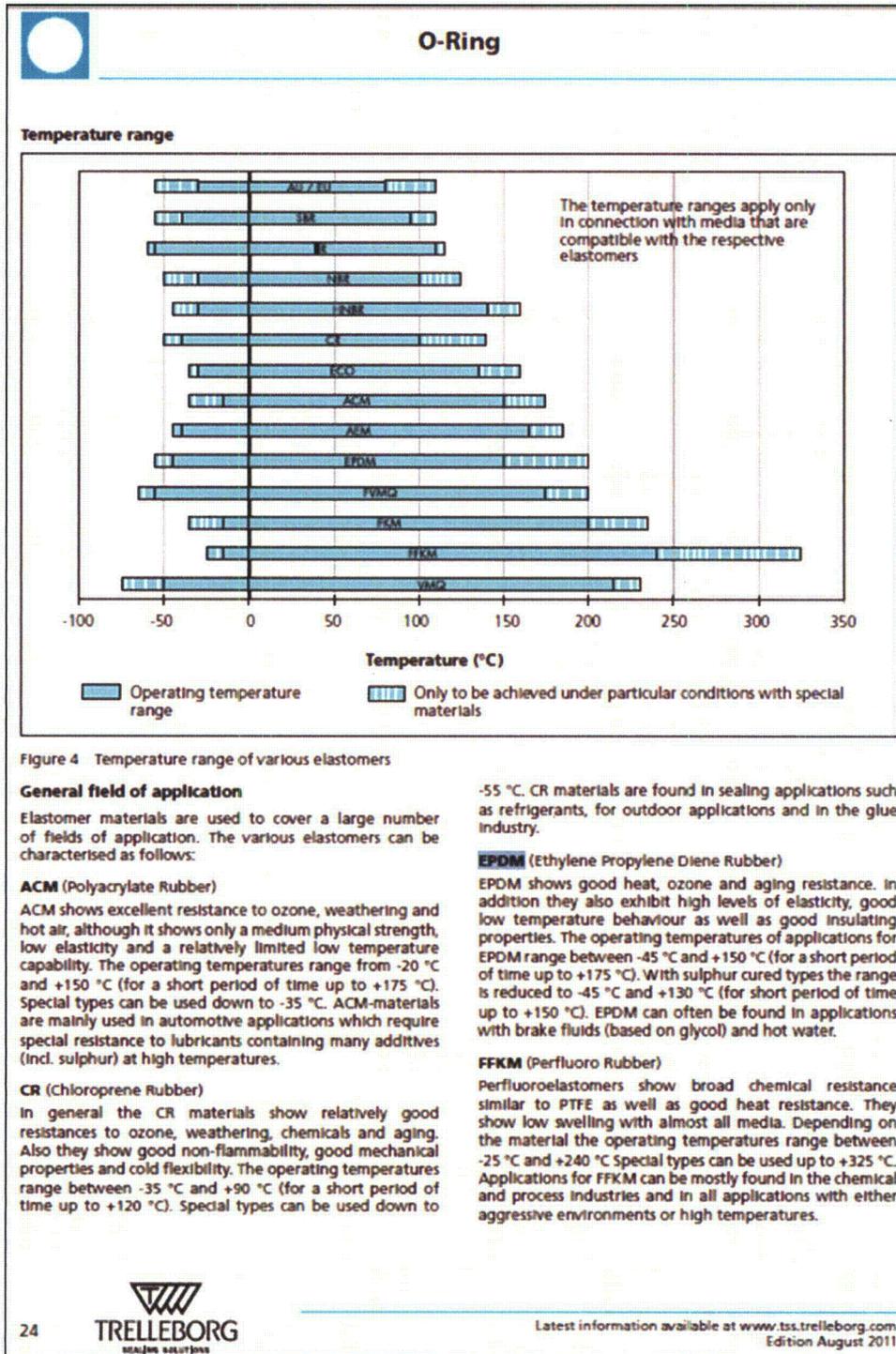
Chemical resistance

- Hot water and steam up to 121°C (250°F).
- Brake fluids with glycol base (Dot 3 & 4).
- Many acids (see Fluid Compatibility Tables in Section VII).
- Salt solutions.
- Polar solvents, (e.g. alcohols, ketones and esters).
- Poly-glycol based hydraulic fluids (HFC fluids) and phosphate-ester bases (HFD-R fluids).
- Silicone oil and grease.
- Ozone, aging and weather resistant.

Not compatible with:

- Mineral oil and grease.
- Fuels.
- Chlorinated hydrocarbons.

Attachment 4.5-2 Seal Material EPDM Working Temperature
 [Ref. 11]



Attachment 4.5-3 Seal Material EPDM Helium gas permeation rate
 [Ref. 11]



O-Ring

Materials

FEP sheath

FEP is the abbreviated designation for Tetrafluoroethylene-hexafluoropropylene. This material has similar properties to those of Polytetrafluoroethylene (PTFE). It also has a very high chemical resistance and exhibits a good resistance to abrasion.

In contrast to PTFE, however, FEP is thermoplastically moldable. This allows the material to be processed to form flexible semifinished products, such as thin-walled hoses.

PFA sheath

PFA is the abbreviation for Perfluoralkoxy. This material is a type of Fluoropolymer with properties similar to Polytetrafluoroethylene (PTFE). Differing from PTFE, like FEP, PFA it is melt-processable but shares PTFE's useful properties of low coefficient of friction and non-reactivity.

PFA is preferable to FEP in high temperature situations. PFA is more affected by water absorption and weathering than FEP, but is superior in terms of salt spray resistance.

Inner ring

A choice of three materials is available for the elastomer inner rings with FEP encapsulation and two materials for the inner ring with PFA encapsulation. The choice of the material also determines the service temperature range.

- Fluorocarbon rubber (FKM),
 temperature range -20 °C up to +200 °C
 material code with FEP sheath: VZ00R
 material code with PFA sheath: VZ01R
- Silicone Rubber (VMQ),
 temperature range: -50 °C up to +175 °C
 material code with FEP sheath: SZ00R
 material code with PFA sheath: SZ01R
- Ethylene Propylen Dien Rubber,
 temperature range: -45 °C up to +150 °C
 material code with FEP sheath: EZ00R

The specified temperature ranges are limits which must always be considered in conjunction with the medium to be sealed and the working pressure. The permissible continuous operating temperatures are always lower than the given upper limits.

Design recommendations

FEP encapsulated O-Rings are fully interchangeable with standard O-Ring seals. There is no need to modify the groove dimensions. The FEP sheath is relatively thin-walled.

All the specifications given in this catalogue therefore refer to the installation dimensions of elastomer O-Rings.

As a result of the FEP sheath, the O-Rings are less flexible than elastomer O-Rings. They have limited stretch and higher permanent deformation.

Split grooves are recommended, especially for outside sealing FEP encapsulated O-Rings, in order to avoid overstretching during installation.

The general information on the construction, design and surfaces given for the elastomer O-Rings applies also to FEP encapsulated O-Rings.

At higher pressures, additional concave Back-up Rings should be used.

Application in gases

Where the O-Ring is used to seal gases, the permeation rate must be taken into consideration. In this case the material of the inner ring must also have a good resistance to the medium to be sealed. The permeation rate depends on the exposed surface area, the temperature, the working pressure and the thickness of the FEP sheath.

The thickness of the FEP sheath can be found in Table 32.

Compliances and approvals

The FEP-sheath of material VZ00R, SZ00R and EZ00R is in compliance with the following regulations governing plastic materials for food contact applications:

- Commission Directive 2002/72/EC and amendments 2004/1/EC, 2004/19/EC 2005/79/EC, 2007/19/EC, 2008/39/EC, Reg. (EC) 975/2009
- Requirement of the German Food and Feed Code, LFGB and regulation (EC) 1935/2004, article 5

OML (Overall Migration Limits):
 Migration testing was done according to 82/711/EEC and 85/572/EEC and amendments. The OML was below the required limit of 10 mg/dm² in aqueous, acidic and fatty food in repeated contact.

Sensory Tests:
 The material meets the requirements of the LFGB and Regulation (EC) 1935/2004 for aqueous, acidic and fatty food in repeated contact. Test condition: 30 min at 95 °C. Surface volume ratio: 30 cm²/1000 ml.

Both the FEP and the PFA sheath are also in compliance with the FDA Regulation 21 CFR Part 177.1550.

Table 32 Thickness of the FEP and PFA sheath

O-Ring		Thickness of the FEP/PFA Sheath
Cross section d ₂	Tolerance ±	
1.78 1.80	0.10	0.20
2.62 2.65	0.10	0.30
3.53 3.55	0.12	0.38
5.34 5.30	0.25	0.50
7.00	0.38	0.50

Latest information available at www.tss.trelleborg.com
Edition August 2011



75

Attachment 4.5-3 Seal Material EPDM Helium gas permeation rate (Continued)
 [Ref. 11]

O-Ring

The diagram (Figure 37) gives guide values for the permeation of different gases.

Figure 37 Gas permeation rates for FEP O-Rings

The diagram (Figure 38) gives guide values for the permeation of water vapour.

Figure 38 Water vapour permeation for FEP O-Rings

Methods of installation

The same recommendations apply to the installation of FEP/PFA encapsulated O-Rings as for standard elastomer O-Rings. It should be noted, however, that the O-Rings have only limited stretch due to the FEP/PFA sheath.

If, for design reasons, a split groove is not possible, auxiliary tools must be used for installation.

For inside sealing applications (e.g. rod), FEP/PFA encapsulated O-Rings can be installed with larger diameters without tools. On no account should the seal ring be forced into the groove (e.g. by bending), otherwise the sealing function cannot be assured.

Dimensions

FEP/PFA encapsulated O-Rings are available in the same sizes as the elastomer O-Rings. Table 34 shows the smallest available inside diameters for the different cord diameters.

Table 33 Tolerances inside diameter (d₁)

Inside diameter d ₁	Tolerance a
d ₁ > 7.64	not available
7.64 ≤ d ₁ ≤ 30.00	0.25
30.00 < d ₁ ≤ 130.00	0.38
130.00 < d ₁ ≤ 170.00	0.51
170.00 < d ₁ ≤ 380.00	0.64
380.00 < d ₁ ≤ 650.00	0.76
650.00 < d ₁ ≤ 1000.00	1.52
d ₁ > 1000.00	on request

Table 34 Smallest available sizes and cross section tolerances

O-Ring		Minimum inside diameter d ₂
Cross section d ₂	Tolerance a	
1.60	0.10	7.60
1.78		7.64
2.00		8.00
2.40		9.30
2.50		10.00
2.62		9.19
2.80		10.50
3.00	0.13	10.00
3.10		10.00
3.20		12.00
3.53		12.00
3.75		12.00
		12.00

76

Latest information available at www.tss.trelleborg.com
 Edition August 2011

Robatel Technologies, LLC

Page 4-39

Attachment 4.5-4 Seal Material EPDM Characteristics With Respect to Damage by
Radiation and Hardness Concerns
[Ref. 11]

A General quality criteria

The cost-effective use of seals and bearings is highly influenced by the quality criteria applied in production. Seals and bearings from Trelleborg Sealing Solutions are continuously monitored according to strict quality standards from material acquisition through to delivery.

Certification of our production plants in accordance with international standards QS 9000/ISO 9000 meets the specific requirements for quality control and management of purchasing, production and marketing functions.

Our quality policy is consistently controlled by strict procedures and guidelines which are implemented within all strategic areas of the company.

All testing of materials and products is performed in accordance with accepted test standards and specifications, e.g. random sample testing in accordance with ISO 2859-1:2004-01 AQL 1.0 general inspection level II, normal inspection.

Inspection specifications correspond to standards applicable to individual product groups (e.g. for O-Rings: ISO 3601).

Our sealing materials are produced free of chlorofluorinated hydrocarbons and carcinogenic elements.

B Guidelines for the storage of polymer products based on ISO 2230

Many polymer products and components are stored for long periods of time before being put into service, so it is important they are stored in conditions that minimize unwanted changes in properties. Such changes may result from degradation, in which case they may include excessive hardening, softening, cracking, crazing and other surface effects. Other changes may be caused by deformation, contamination or mechanical damage.

Packaging

Unless otherwise specified in the appropriate product specification, rubber products should be enclosed in individual sealed envelopes. The packaging should be carried out in an atmosphere in which the relative humidity is less than 70 %, or if polyurethanes are being packed, less than 65 %. Where there is serious risk of ingress of moisture (e.g. rubber-metal-bonded parts), aluminum foil/paper/polyethylene laminate or other similar means of protection should be used to ensure protection from ingress of moisture.

Temperature

The storage temperature should be below 25 °C and the products should be stored away from direct sources of heat such as boilers, radiators and direct sunlight. If the storage temperature is below 15 °C, care should be

exercised during handling of stored products, as they may have stiffened and have become susceptible to distortion if not handled carefully.

Humidity

The relative humidity should be such that, given in the variations of temperature in storage, condensation does not occur. In all cases, the relative humidity of the atmosphere in storage should be less than 70 %, or if polyurethanes are being stored, less than 65 %.

Light

Rubber should be protected from light sources, in particular direct sunlight or intense light having a high ultraviolet content. It is advisable that any windows of storage rooms be covered with a red or orange coating or screen.

Radiation

Precautions should be taken to protect stored products from all sources of ionizing radiation likely to cause damage to the products.

Ozone

Ozone has a particularly harmful effect on rubber. Storage rooms should not contain any equipment that is capable of generating ozone, such as mercury vapor lamps or high-voltage electrical equipment giving rise to electric sparks or electrical discharges. Combustion gases and organic vapors should also be excluded, as they may give rise to ozone via photo-chemical processes. When equipment such as a fork-lift truck is used to handle large rubber products, care needs to be taken to ensure this equipment is not a source of pollution that may affect the rubber. Combustion gases should be considered separately. While they are responsible for generating ground-level ozone, they may also contain unburned fuel which, by condensing on rubber products, can cause additional deterioration.

Deformation

Rubber should be stored free from tension, compressive stresses or other causes of deformation. Where products are packaged in a strain-free condition, they should be stored in their original packaging. In case of doubt, the manufacturer's advice should be sought. It is advisable that rings of large internal diameter are formed into three equal loops so as to avoid creasing or twisting. It is not possible to achieve this condition by forming just two loops.

Contact with liquids and semi-liquid materials

Rubber should not be allowed to come into contact with liquid or semi-liquid materials (for example, petrol, greases, acids, disinfectants, cleaning fluids) or their vapors at any time during storage, unless these materials are by design an integral part of the product or the manufacturer's packaging. When rubber products are received coated with their operational media, they should be stored in this condition.

Latest information available at www.tss.trelleborg.com
Edition August 2011


TRELLEBORG
SEALING SOLUTIONS

135

Attachment 4.5-4 Seal Material EPDM Characteristics With Respect to Damage by Radiation and Hardness Concerns (Continued)

[Ref. 11]

B.1.3 Characteristics and inspection of elastomers

Hardness

One of the most often named properties regarding Polymer materials is hardness. Even so the values can be quite misleading.

Hardness is the resistance of a body against penetration of an even harder body - of a standard shape defined pressure.

There are two procedures for hardness tests regarding test samples and finished parts made out of elastomer material:

1. Shore A / D according to ISO 868 / ISO 7619 / DIN 53505 / ASTM D 2240
 Measurement for test samples
2. Durometer IRHD (International Rubber Hardness Degree) according to ISO 48 / ASTM 1414 and 1415
 Measurement of test samples and finished parts

The hardness scale has a range of 0 (softest) to 100 (hardest). The measured values depend on the elastic qualities of the elastomers, especially on the tensile strength.

The test should be carried out at temperatures of 23 ± 2 °C - not earlier than 16 hours after the last vulcanisation process (manufacturing stage). If other temperatures are being used this should be mentioned in the test report.

Tests should only be carried out with samples which have not been previously stressed mechanically.

Hardness tests according to Shore A / D

The hardness test device Shore A (indenter with pyramid base) is a sensible application in the hardness range 10 to 90. Samples with a larger hardness should be tested with the device Shore D (indenter with spike).

Test specimen:
 Diameter min. 1.181 inches (30 mm)
 Thickness min. .240 inches (6 mm)
 Upper and lower sides smooth and flat

When thin material is being tested it can be layered providing minimal sample thickness is achieved by a maximum of 3 layers. All layers must be at minimum .080 inches (2 mm) thick.

The measurement is done at three different places at a defined distance and time.

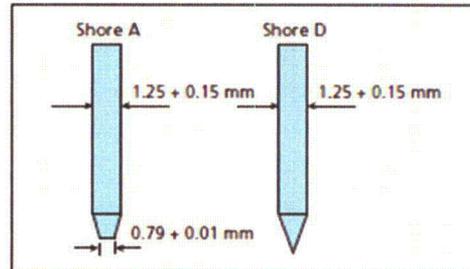


Figure 5 Indentor according to Shore A / D

Hardness test according to IRHD

The test of the Durometer according to IRHD is used with test samples as well as with finished goods.

The thickness of the test material has to be adjusted according to the range of hardness. According to ISO 48 there are two hardness ranges:

- Soft: 10 to 35 IRHD ⇒ Sample thickness
 .394 to .591 inches
 (10 to 15 mm) / procedure "L"
- Normal: over 35 IRHD ⇒ Sample thickness
 .315 to .394 inches
 (8 to 10 mm) / procedure "N"
 Sample thickness
 .059 to .098 inches
 (1.5 to 2.5 mm) /
 procedure "M"

The hardness determined with finished parts or samples usually vary in hardness determined from specimen samples, especially those with a curved surface.

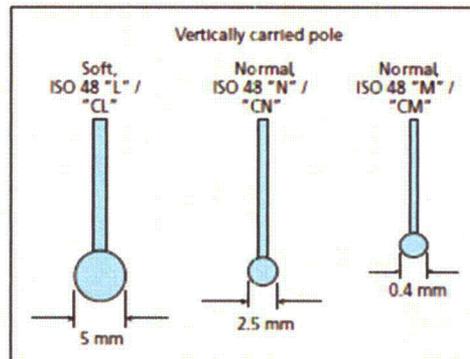


Figure 6 Indentor according to IRHD

Attachment 4.5-4 Seal Material EPDM Characteristics With Respect to Damage by Radiation and Hardness Concerns (Continued)

[Ref. 11]

Influencing parameters on the hardness test for polymer materials

Various sample thicknesses and geometries as well as various tests can show different hardness values even though the same materials have been used.

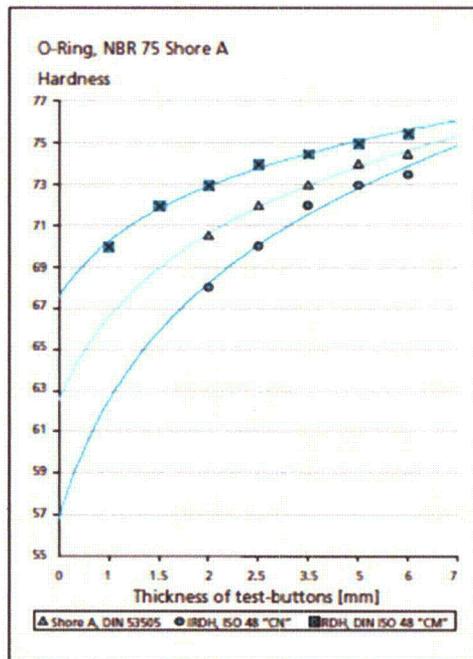


Figure 7 Ranges of hardness depending on sample thickness and test method

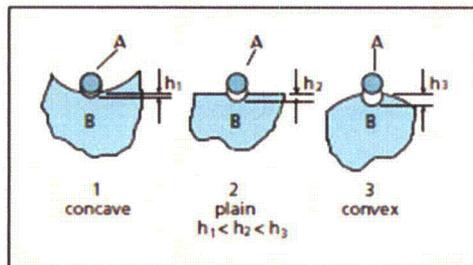


Figure 8 Range of hardness depending on surface geometry for the equivalent material characteristics

With equivalent material characteristics of the elastomer sample B, the indenter penetrates the deepest at the surface 3 (convex) and therefore establishes the softest area.

As the convex geometry (3) has a stronger effect on smaller width O-Rings, the tolerances on hardness for widths under 2.0 mm should be increased up to +5 / -8 IRHD based on the valid IRHD nominal value.

Compression set

An important parameter regarding the sealing capability is the compression set (CS) of the O-Ring material. Elastomers when under compression show aside from an elastic element also a permanent plastic deformation (Figure 9).

The compression set is determined in accordance with ISO 815 as follows:

- Standard test piece: Cylindrical disc, diameter .512 and height .236 inches (13 mm and height 6 mm)
 Deformation: 25 %
 Tension release time: 30 minutes

$$CS = \frac{h_0 - h_2}{h_0 - h_1} \cdot 100(\%)$$

- Where h_0 = Original height (cross section d_2)
 h_1 = Height in the compressed state
 h_2 = Height after tension release

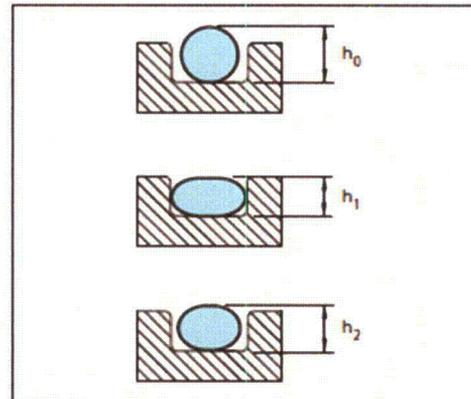


Figure 9 Illustration of the compression set

Attachment 4.5-4 Seal Material EPDM Characteristics With Respect to Damage by Radiation and Hardness Concerns (Continued)

[Ref. 11]

The accuracy of the measured value depends on:

- Test sample thickness
- Deformation
- Measurement deviations

Therefore the values which have been identified with the test sample cannot be transferred onto the finished part. The result of the measured finished parts are strongly influenced by geometrics and measurements as well as the measuring accuracy of the test equipment.

The following illustration shows the influence of various measuring deviations (in mm) in respect to the established compression set CS depending on the cross section of the measured O-Rings.

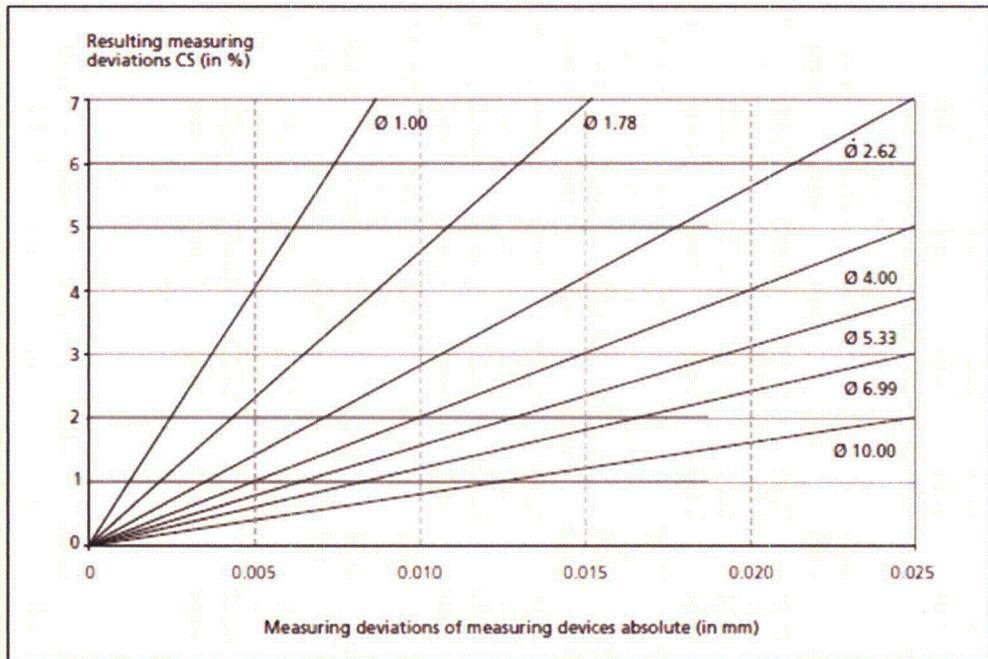


Figure 10 Measuring deviations CS depending on O-Ring cross section and measuring accuracy of the test equipment (schematic illustration)

Attachment 4.5-5 Additional Support Information about EPDM Resistance to Radiation Up to 5×10^8 Rads While Retaining Reasonable Flexibility and Strength, Hardness and Very Good Compression Set Resistance
[Ref. 12]

© 1985 IEEE. Personal use of this material is permitted. However, permission to reprint/republish this material for advertising or promotional purposes or for creating new collective works for resale or redistribution to servers or lists, or to reuse any copyrighted component of this work in other works must be obtained from the IEEE.

IEEE Transactions on Nuclear Science, Vol. NS-32, No. 5, October 1985

3826

RADIATION RESISTANCE OF ELASTOMERS

Glenn Lee

Fermi National Accelerator Laboratory*
P.O. Box 500
Batavia, Illinois 60510

Abstract

Various data has indicated that some elastomers have much higher radiation resistance than Viton. Nine samples of elastomers were irradiated with gamma rays. Two Ethylene Propylene Diene compounds, EPDM's, were found to exhibit acceptable properties for o-rings after radiation levels of 5×10^8 rads, while Viton failed at 1×10^7 rads. Vacuum tests also were favorable so EPDM o-rings were chosen as seals in the Energy Saver cryostat vacuum system.

Introduction

Viton is commonly used for o-ring seals in high vacuum systems, and failures have occurred in radiation areas such as particle beam transport lines due to radiation from beam loss. In a search for radiation resistant seals suitable for vacuum systems, nine elastomer samples were obtained from Minnesota Rubber Company and irradiated with gamma rays.

Materials Tested

The samples tested were:

Compound #	Material
5599	EPDM (Ethylene Propylene Diene)
5599Q	EPDM (Ethylene Propylene Diene)
3657	NBR (Nitrile)
514AD	Viton
71417	Silicone
512AJ	Sulfur Cured Urethane
482BJ	Neoprene
560ND	EPDM (tightly cured)
564FP	Peroxide Cured Urethane
564PB	Sulfur Cured Urethane

Affect of Radiation

Minnesota Rubber Company tested the elastomers after irradiation. There are some variances of data due to the size of the samples tested and the results are as follows.

The compound, 512AJ, sulfur cured Urethane, appears to have the best radiation resistance. Even after 10^8 rads 512AJ has some elongation and tensile and little change in hardness. However, the compression set of 512AJ, even originally, is poor which is typical of sulfur cured Urethanes. In a seal application, compression set is a critical property and such extremely poor set resistance will cause part failure.

The EPDM compounds 5599 and 5599Q show the best all around properties with radiation levels up to 5.0×10^8 rads. They exhibit good tensile and are still elastomeric though elongation is low and hardness is high. Compression set is excellent even at 5.0×10^8 rads. The EPDM's are not good at levels of 10^9 rads since in the compression set test both samples disintegrated.

The other compounds were brittle at or before 3.0×10^8 rads. Compound 3657, a NBR, retains good properties at 10^8 rads. Compound 482BJ, a Neoprene; was brittle at 3×10^8 rads though it had good properties at 10^7 rads. Both 71417, silicone, and 514AD, Viton, were significantly affected by the radiation, becoming hard even at 5×10^7 rads and brittle at 3×10^8 rads.

For all radiation applications up to 5.0×10^8 rads the best compounds are 5599 or 5599Q, the EPDM's. If radiation levels are higher than 5.0×10^8 rads, then compound 512AJ could be used, but difficulty would be encountered in designing a functional part because of the high set it exhibits.

The test results confirmed that EPDM compounds have the best all around properties with radiation levels up to 5.0×10^8 rads. They retain reasonable flexibility and strength, hardness, and very good compression set resistance.

A Urethane that is sulfur cured has the best flexibility, strength and hardness even up to 2×10^8 rads. However, they have very poor compression set qualities even before treatment of radiation. The sulfur cured Urethane fail completely by $.85 \times 10^8$ rads in compression set.

The peroxide cured Urethanes have an initial change of properties but seem to stabilize through to 2.0×10^8 rads and is very brittle at 3×10^8 rads. The initial compression set characteristics is much better than the sulfur cured Urethanes but again failure is seen at $.85 \times 10^8$ rads.

There are many new compounds now that have not been tested. Quite possibly elastomers with properties superior to the EPDM's could be found.

Vacuum Tests at Fermilab

Urethane o-rings have been used for a few vacuum applications in high radiation areas, but extreme outgassing eliminated their use in high vacuum apparatus. Samples of compounds 560ND, 564FP, 564PB, Viton, and polyurethane cord purchased from Eagle Belting Company were tested for outgassing in a very simple vacuum chamber. The chamber consisted of a spare Fermilab main ring ion pump with a short tube extension and a roughing valve. Equal weights of elastomer samples were placed in the tube extension and the chamber was then roughed down and the ion pump started. The ion pump power supply frequency was used as the pressure indicator since an ion gauge was not available. A frequency of 10 KHz indicated a pressure of approximately 1×10^{-8} Torr. A table of test results indicates the extreme outgassing of the Urethane materials as compared to Viton, while the ethylene propylene compound wasn't so bad. No data was obtained as to actual outgassing rates due to lack of personnel, time, and equipment.

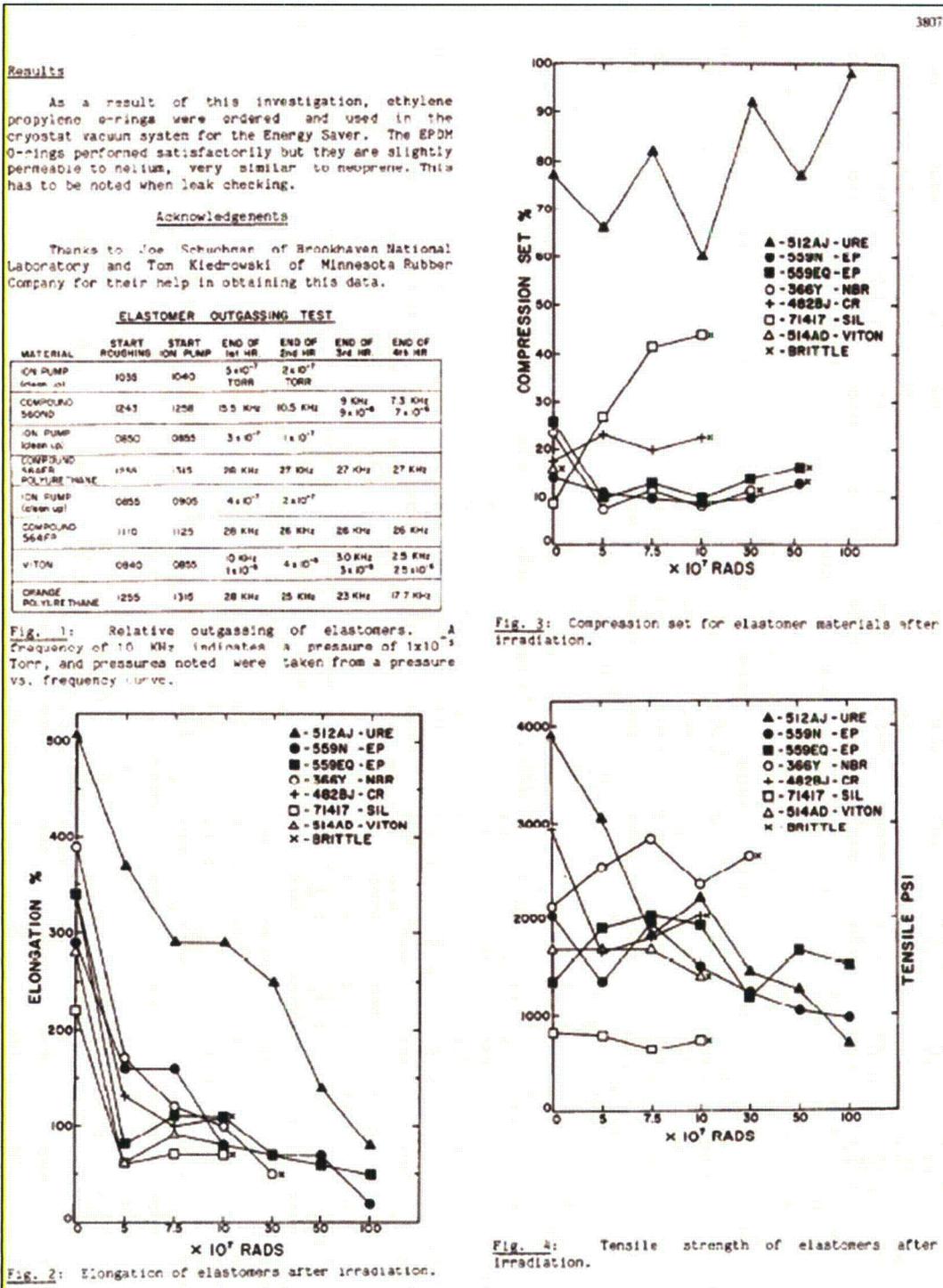
Figure 1 shows the pump-down data for six of the compounds tested. Figures 2, 3, 4, and 5 show respectively, the elongation, compression set, tensile, and hardness properties.

*Operated by Universities Research Association, Inc. under contract with the U.S. Department of Energy.

0018-9499/85/1000-3806\$01.00 © 1985 IEEE

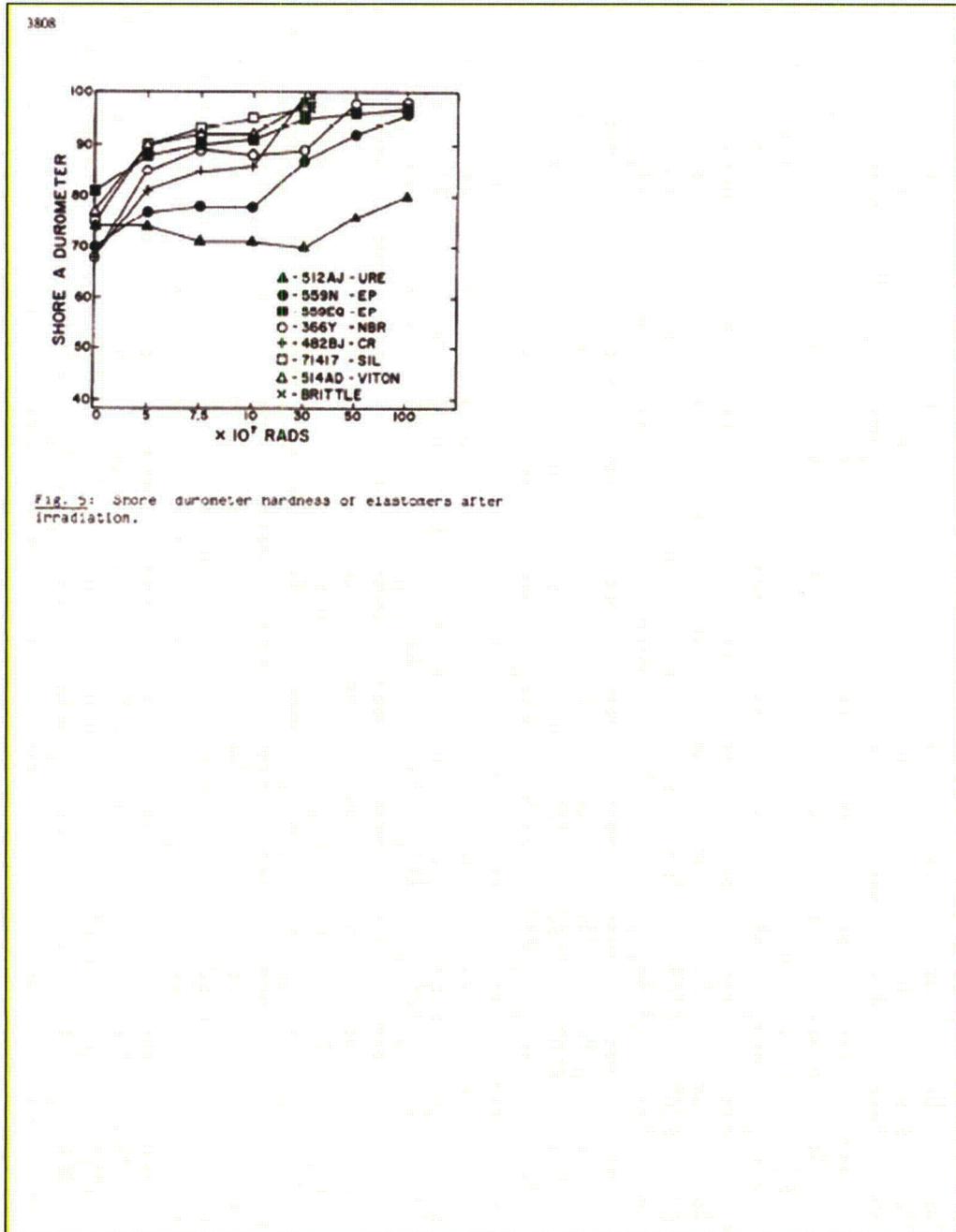
Attachment 4.5-5 Additional Support Information about EPDM Resistance to Radiation Up to 5x10⁸ Rads While Retaining Reasonable Flexibility and Strength, Hardness and Very Good Compression Set Resistance (Continued)

[Ref. 12]



**Attachment 4.5-5 Additional Support Information about EPDM Resistance to Radiation
Up to 5×10^8 Rads While Retaining Reasonable Flexibility and Strength, Hardness and
Very Good Compression Set Resistance (Continued)**

[Ref. 12]



4.6 References

1. Robatel Technologies, LLC, Quality Assurance Program for Packaging and Transportation of Radioactive Material, 10 CFR 71 Subpart H, Dated January 31, 2012 and NRC Approved on March 21, 2012
2. U.S. Nuclear Regulatory Commission, 10 CFR Part 71--PACKAGING AND TRANSPORTATION OF RADIOACTIVE MATERIAL, dated March 7, 2012 and the following specific Sections:

71.31(a)(1)	71.31(a)(2)	71.33	71.35(a)
71.31(c)	71.43(c)	71.73(d)	71.4(e)
71.71	71.43(f)	71.51(a)(1)	71.43(h)
71.51(a)(2)	71.51	71.63	71.63(b)
71.51(a)(1)	71.51(a)(2)	71.73	

3. ANSI N14.5-1997, "American National Standard for Radioactive Materials – Leakage Tests on Packages for Shipment," American National Standards Institute, Inc., 11 West 42nd Street, New York, NY, www.ansi.org.
4. U.S. Nuclear Regulatory Commission, "Containment Analysis for Type B Packages Used to Transport Various Contents," NUREG/CR-6487, November 1996.
5. "Particle-size distribution and packing fraction of geometric random packings." H. J. H. Brouwers, *Physical Review E* 74, 031309, 2006.
6. DOE Handbook, *Airborne Release Fractions/Rates and Respirable Fractions for Nonreactor Nuclear Facilities*, "Volume I - Analysis of Experimental Data," U.S. Department of Energy, Washington, D.C., 1994.
7. NUREG/CR-6487, "Containment Analysis for Type B Packages Used to Transport Various Contents," Anderson, B., Carlson, R., & Fischer, L., Lawrence Livermore National Laboratory, Livermore, CA, November 1996, Retrieved on August 28, 2013, Retrieved from http://rampac.energy.gov/docs/nrcinfo/NUREG_6487.pdf.
8. RTL-001-CALC-TH-0102, Rev. 6, "RT-100 Cask Maximum Normal Operating Pressure Calculation" (PROPRIETARY)
9. RTL-001-CALC-TH-0202, Rev. 6, "RT-100 Cask Hypothetical Accident Condition Maximum Pressure Calculation" (PROPRIETARY)
10. Parker O-Ring Handbook ORD 5700, Retrieved on August 28, 2013, Retrieved from http://www.parker.com/literature/ORD%205700%20Parker_O-Ring_Handbook.pdf.
11. TRELLEBORG Sealing Solutions O-Ring and Backup Rings Catalog, August 2011 Edition
12. Glenn Lee, Radiation Resistance of Elastomers, *IEEE Transactions on Nuclear Science*, Vol. NS-32, No. 5, October 1985.

13. Lamarsh, J. & Baratta, A., "Introduction to Nuclear Engineering", 3rd Edition, 2001.
14. Fundamentals of Fluid Mechanics, B. Munson, D. Young and T. Okiishi, 5th ed., John Wiley & Sons, Inc., 2006.
15. Brookhaven National Laboratory, "Selected Cryogenic Data Notebook", August 1980.
16. NUREG/CR-6673, "Hydrogen Generation in TRU Waste Transportation Packages," Anderson, B., Sheaffer, M., & Fischer, L., Lawrence Livermore National Laboratory, Livermore, CA, May 2000.
17. "Exhibit A of Cask Procurement Agreement dated April 10, 2012 by and between Waste Control Specialists LLC and Robatel Technologies, LLC et al."
18. RTL-001-CALC-SH-0301, Rev 4, "Application of RT-100 Loading Table in Shielding Evaluations" (PROPRIETARY)
19. RTL-001-CALC-CN-0101, Rev 6, "Containment Evaluation for the RT-100" (PROPRIETARY)
20. NUREG/CR-4062 "Extended Storage of Low-Level Radioactive Waste: Potential Problem Areas", B. Siskind D.R. Dougherty, D. R. MacKenzie.
21. EPRI NP-5977, "Radwaste Radiolytic Gas Generation Literature Review", Electric Power Research Institute, September 1988.
22. RT100-REF-01-01, Rev. 0, "*Historical Cask Summaries by Waste Category*" (PROPRIETARY)
23. "RH-TRU 72-B SAR Payload Appendices", Rev. 0, June 2006.
24. "Materials Science and Engineering", W. Callister, Jr., 6th Edition, John Wiley & Sons, Inc., 2003.