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Technical Memorandum

Justification of the R7021 Containment System

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1. PURPOSE AND SCOPE

The R7021 is a Type B transport package designed to transport both Special Form and non-SF solid radioactive material. The purpose of this document is to describe the containment system and demonstrate that it meets all its design and regulatory requirements and guidelines. It will also detail the criteria for routine and periodic testing.

2. DESCRIPTION

The R7021 consists of a lead shielded, stainless steel flask mounted on a pallet and protected from heat and impact by a pallet, jacket and top shield. The flask is an upright, cylindrical fabrication with a removable shield plug, the closure, at the top. The cavity is equipped with a drain tube at its base and a venting hole through the closure. The closure, vent and drain plugs are each sealed with an elastomer O-ring. In each case a second O-ring and an interseal test point is provided which enable the inner O-ring to be leak tested. The flask and closure are also equipped with connection points in order the containment boundary (the flask and closure internal surfaces) may be routinely leak tested. As the drain tube is enclosed by an outer sleeve the flask has two test points; one directly into the shielding space and one into the space between the drain tube and sleeve. These allow the entire containment boundary to be tested.

3. CRITERIA

1. The containment system O-ring material shall be suitable for the physical environment (DTLR guide).
2. The containment system O-ring material shall be suitable for the radiation environment (DTLR guide).
3. The containment system O-ring material shall be suitable for use at -40°C (para 637, TS-R-1) and +55°C (para 618, TS-R-1).
4. Containment system O-ring temperatures under normal conditions of transport shall not exceed 204°C (the long term limit for fluorocarbon (FKM) O-ring materials (Precision O-ring Handbook)).
5. Containment system O-ring temperatures under accident conditions of transport shall not exceed 270°C and shall not exceed 250°C for longer than 2hrs (the high temperature test results used for the FKM type V1289 seal material are 70 hrs at 250°C (Parker report ORD 5743) and 2 hrs at 270°C (Ceetak report 22550C)).
6. Containment system O-ring compression shall not be less than 10% after one year in a fully loaded flask in a mean ambient of 20°C.
7. Containment system O-ring compression shall not exceed 30% under normal conditions of transport.
8. Containment system O-ring groove fill shall not exceed 90% during accident conditions of transport.
9. The containment system shall remain leaktight after accident conditions mechanical tests.
10. Source capsule temperatures shall not exceed 800°C during the thermal test, with or without damage from the drop tests, (Special Form material may be used as the containment system and performance testing is conducted at 800°C).
11. Routine and periodic leak testing shall comply with the DfT and ANSI N15.5 requirements and recommendations.
12. Closure O-ring compression shall not be reduced by more than 1% as a result of thermal distortion during the thermal test.

4. ASSESSMENT

4.1 DATA

4.1.1 O-Ring details

Position	Material	Dimensions (mm)		
		Inside Diameter	Cross-Section	C/S Tolerance (±)
Closure	FKM V1289	279	5.33	0.13
Vent Plug	FKM V1289	20.3	2.62	0.09
Drain Plug	FKM V1289	9.19	2.62	0.09

Note: Tolerances are taken from the Precision O-Ring Handbook.

4.1.2 Coefficients of thermal expansion

Material	Coefficient, α (x 10^{-6})
FKM	160
300 series stainless steel	16

Note: The FKM coefficient is taken from the Precision O-Ring Handbook, the stainless steel from ASME II.

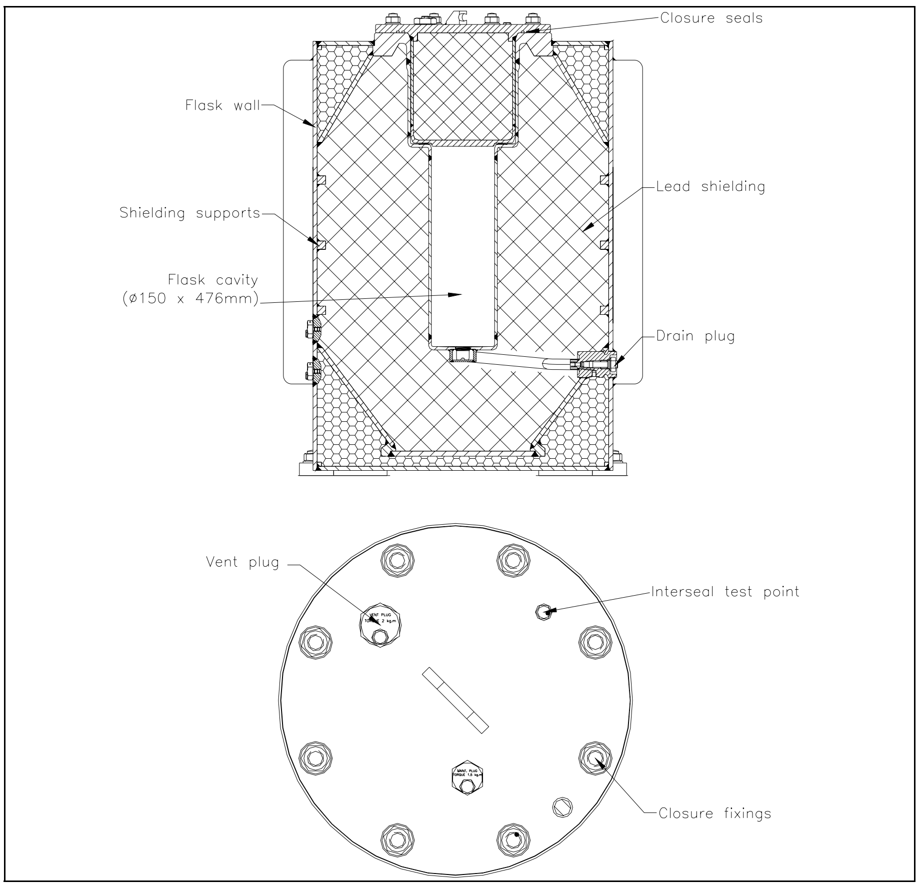

Figure 1: R7021 Flask Section

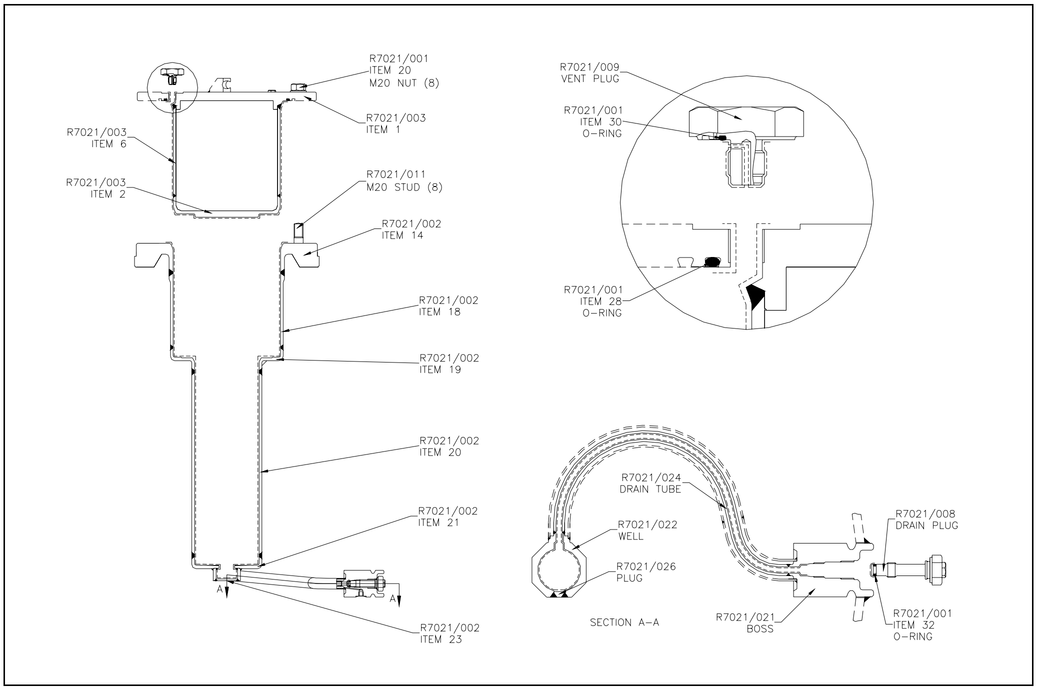

Figure 2: R7021 Containment Boundary (shown in small chain dot)

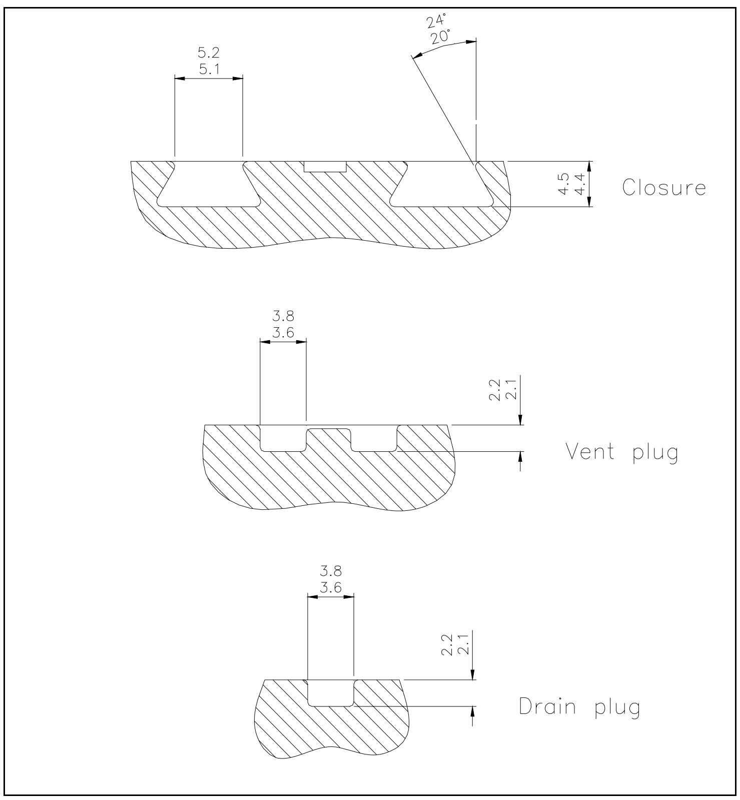

Figure 3: O-Ring Groove Details

Note: Drain plug groove depth is measured from the bottom of the groove to the internal diameter of the cylinder as it is a piston seal.

4.1.3 Physical environment

The physical environment is inside stainless steel housings where the seals will be containing an inert noble gas such as helium or neon (see OP 381). Although the flask is dried thoroughly after pond operations (see OP 381) the seals could be exposed to water vapour from any residue.

4.1.4 Long term heat load

The ^{60}Co contents generate an internal heat load. The nuclide has a half life of 5.271 years (TS-G-1.1). After one year the contents activity will have reduced to 87.7% (the mean activity over the year being 93.9%) and flask and seal temperatures will be reduced proportionally.

4.1.5 Operating temperatures

Environment	Seal Temperature (°C)
Normal Conditions of Transport	144
Accident Conditions of Transport	262
20°C Ambient and 93.9% Content Activity	120
-40°C Ambient and 87.7% Content Activity	46
55°C Ambient	75

Notes:

- Normal (144°C) and accident conditions (262°C) O-ring temperatures are taken from the R7021 thermal analysis report, RTM 120.
- The O-ring temperature in a 20°C ambient is derived from the normal conditions temperature by deducting the effect of insolation together with the 18°C temperature difference i.e. 144 - 18 - 6 = 120°C
- The O-ring temperature in a -40°C ambient, when the flask contains an 87.7% heat load from the contents (the heat load after one year of decay), is derived as follows: The effect of insolation and the 38°C ambient are deducted from the normal conditions O-ring temperature to give the temperature difference caused by the contents heat load alone, i.e. (144 - 8 - 38 = 98°C). Multiplying by 0.877 allows for decay of the cobalt contents and adding the resulting temperature difference to the -40°C ambient gives the seal temperature, i.e. (98 x 0.877) - 40 = 46°C.
- The O-ring temperature at 55°C ambient is only important for air shipments, when the content activity will be limited to 32.4 kCi (3000 x the A_2 limit for ^{60}Co (para 433 and Table 2, TS-R-1). It is derived as follows: The effect of insolation and the 38°C ambient are deducted from the normal conditions O-ring temperature to give the temperature difference caused by the contents heat load alone, i.e. (144 - 8 - 38 = 98°C). Multiplying by the air shipment limit and dividing by the license limit reduces this temperature in proportion to the content activity, i.e. (98 x 32.4) / 160 = 20°C. Adding the new ambient gives the seal temperature, i.e. 20 + 55 = 75°C. This value is lower than the seal temperature under normal conditions of transport, hence any subsequent calculations for normal conditions will always present a worst case.

4.2 ASSESSMENT AGAINST CRITERIA

4.2.1 O-Ring suitability for physical environment

FKM seals are compatible with air to 204°C (Precision O-Ring Handbook). They are susceptible to acids, alkalis, mineral oils and hydrocarbons. The R7021 Operating and Maintenance Instructions, OP 381, alert the operator to this issue.

4.2.2 O-Ring suitability for radiation environment

FKM is unaffected by exposures of up to about 10^6 Rads (Precision O-Ring Handbook). The containment system O-rings are all outside the flask shielding are so are exposed to the minimum dose. A maximum radiation level of 4.53 mSv/hr will occur at the drain O-ring when fully loaded (RTM 124). This will give rise to a cumulative dose over a period of one year of $4.53 \times 10^{-3} \times 24 \times 365 = 40$ Sv. This is broadly equivalent to 40 x 100 = 4,000 Rad.

4.2.3 O-Ring suitability for low temperature

FKM V1289 has a low temperature limit of -50°C for static seals (Ceetak report RC 19356A). This exceeds the normal conditions low temperature limit of -40°C and agrees with the manufacturers recommendations (ORD5743).

4.2.4 O-Ring suitability for long term normal conditions temperature

FKM has a long term temperature limit of 204°C (DTLR/RMTD/0004). This comfortably exceeds the normal conditions temperature of 144°C. Note: There is an additional 18°C margin of safety as the maximum long term mean ambient temperature may reasonably be assumed to be 20°C rather than 38°C.

RTM 120 gives the temperature of the drain plug seal, the hottest of the three seals, as 144°C. The margin of safety to the maximum allowable design value is 204 - 144 = 60°C. The temperature difference from ambient is 144 - 38 = 106°C. This affords a safety margin of 57%, which is sufficient to compensate for any calculational inaccuracy.

4.2.5 O-Ring suitability for short term accident conditions temperature

R7110/1.1 provides the following time/temperature data for the seals:

Peak Seal Temperature and Duration over 250°C			
Package Orientation	Condition	Closure and Vent Plug	Drain Plug
Upright	Undamaged	259°C, 67 mins	236°C, 0
Inverted		251°C, 25 mins	262°C, 83 mins
Angled Side		252°C, 33 mins	257°C, 80 mins
Upright	With damage	253°C, 33 mins	228°C, 0
Inverted		253°C, 33 mins	261°C, 80 mins
Angled Side		253°C, 42 mins	256°C, 70 mins
Maximum		262°C, 83 mins	

Peak temperature: The peak seal temperature is 262°C. The minimum margin of safety to the design limit is 270 - 262 = 8°C. The temperature increase over normal conditions is 262 - 144 = 118°C. This affords a safety margin of 7%, which is sufficient to compensate for any calculational inaccuracy.
Duration over 250°C: The maximum temperature duration over 250°C is 83 minutes. This affords a safety margin of 45%, which is sufficient to compensate for any calculational inaccuracy.

4.2.6 Minimum O-ring compression

Containment system O-ring compression shall not be less than 10%:

- After one year with the flask fully loaded in an ambient temperature of 20°C and subsequently in an ambient of -40°C or:

- The minimum flask loading (empty) in an ambient of -40°C.

In both instances the manufacturing tolerances shall be worst case, i.e. O-rings at minimum diameter and housings at maximum depth.

The minimum O-ring compression will occur at -40°C (the elastomer will shrink more than the groove due to its much higher coefficient of expansion) either with the seal having the maximum compression set (after a year, fully loaded in an ambient of 20°C) or with the minimum contents heat load and no compression set.

In the first case the seal/groove temperature in an ambient of -40°C with maximum contents after a year's decay is 46°C. Thus:

- Maximum Groove Depth:

The formula used is $D_{max46} = (D + tol) \times (1 + \alpha(46 - 20))$

Position	Maximum Depth (mm)	
	@ 20°C	@ 46°C
Closure	4.50	4.50
Vent Plug	2.20	2.20
Drain Plug	2.22	2.22

- Minimum Seal Diameter:

The formula used is $XS_{min46} = (XS - tol) \times (1 + \alpha(46 - 20))$

Position	Minimum Cross-Section Diameter (mm)	
	@ 20°C	@ 46°C
Closure	5.20	5.22
Vent Plug	2.53	2.54
Drain Plug	2.53	2.54

- Effect of Compression Set:

The Precision O-Ring Handbook gives the compression set, CS, for FKM (FKM) at 134°C after 70 hrs (at which time the set has stabilised) as 10%. The formula for calculating the effect of compression set on seal compression is:

$$CS = \frac{h_0 - h_2}{h_0 - h_1}$$

where

h_0 = original seal cross-section = XS_{min46}

h_1 = height of deformed seal = maximum groove depth at 46°C = D_{max46}

h_2 = height of released seal

re-arranging

$h_2 = h_0 - CS(h_0 - h_1) = XS_{min46} - CS(XS_{min46} - D_{max46})$

and the minimum compression at 46°C, $C_{min46} = 1 - \frac{h_1}{h_2}$

Position	XS_{min46} (h_0)	D_{max46} (h_1)	h_2	C_{min46} (%)
Closure	5.22	4.50	5.15	12.6
Vent Plug	2.54	2.20	2.51	12.2
Drain Plug	2.54	2.22	2.51	11.5

In the second case the seal/groove temperature in an ambient of -40°C with minimum contents is -40°C. Thus:

- Maximum Groove Depth:

$D_{max-40} = (D + tol) \times (1 + \alpha(-40 - 20))$

Position	Maximum Depth (mm)	
	@ 20°C	@ -40°C
Closure	4.50	4.50
Vent Plug	2.20	2.20
Drain Plug	2.22	2.22

- Minimum Seal Diameter:

$XS_{min-40} = (XS - tol) \times (1 + \alpha(-40 - 20))$

Position	Minimum Cross-Section Diameter (mm)	
	@ 20°C	@ -40°C
Closure	5.20	5.15
Vent Plug	2.53	2.51
Drain Plug	2.53	2.51

- Effect of Compression Set:

Compression set will not exceed 10% for FKM at temperatures below 100°C (Fig 6.5, Precision O-Ring Handbook).

Position	XS_{min-40} (h_0)	D_{max-40} (h_1)	h_2	C_{min-40} (%)
Closure	5.15	4.50	5.09	11.6
Vent Plug	2.51	2.20	2.48	11.2
Drain Plug	2.51	2.22	2.48	10.4

4.2.7 Maximum O-ring compression

Containment system O-ring compression shall not exceed 30% under normal conditions of transport (manufacturing tolerances at worst case):

The maximum O-ring compression will occur in the maximum ambient (the elastomer will expand more than the groove due to its much higher coefficient of expansion) with the flask fully loaded, the minimum groove depth and no compression set.

The seal/groove temperature in an ambient of 38°C with maximum contents and insolation is 144°C. Thus:

- Minimum Groove Depth:

The formula used is $D_{min144} = (D - tol) \times (1 + \alpha(144 - 20))$

Position	Minimum Depth (mm)	
	@ 20°C	@ 144°C
Closure	4.40	4.41
Vent Plug	2.10	2.10
Drain Plug	2.10	2.10

- Maximum Seal Diameter:

The formula used is $XS_{max144} = (XS + tol) \times (1 + \alpha(144 - 20))$

Position	Maximum Cross-Section Diameter (mm)	
	@ 20°C	@ 144°C
Closure	5.46	5.57
Vent Plug	2.71	2.76
Drain Plug	2.71	2.76

- Maximum Compression:

$$C_{max204} = 1 - \frac{D_{min144}}{XS_{max144}}$$

Position	D_{min144}	XS_{max144}	C_{max144} (%)
Closure	4.41	5.57	20.8
Vent Plug	2.10	2.76	23.9
Drain Plug	2.10	2.76	23.9

4.2.8 Maximum groove fill

Containment system O-ring groove fill shall not exceed 90% under accident conditions of transport thermal test (manufacturing tolerances worst case, i.e. O-rings at maximum diameter and housings at minimum depth and width).

The maximum groove fill will occur at the maximum temperature (accident conditions) with the minimum groove width, depth and side angle.

The maximum seal/groove temperature in accident conditions is 262°C with maximum contents and insolation. Thus:

- Minimum Groove Depth:

The formula used is $D_{min262} = (D - tol) \times (1 + \alpha(262 - 20))$

Position	Minimum Depth (mm)	
	@ 20°C	@ 262°C
Closure	4.40	4.42
Vent Plug	2.10	2.11
Drain Plug	2.10	2.11

- Minimum Groove Width:

The formula used is $W_{min265} = (W - tol) \times (1 + \alpha(262 - 20))$

Position	Minimum Width (mm)	
	@ 20°C	@ 262°C
Closure	5.10	5.02
Vent Plug	3.60	3.61
Drain Plug	3.60	3.61

- Minimum Groove Area:

The cross-sectional area of the trapezoidal groove is taken as the rectangular area in the centre plus the two triangular fillets to each side. Thus:

$GA_{min262} = D_{min262}(W_{min262} + D_{min262}\tan\theta)$

Position	D_{min262}	W_{min262}	θ (Groove Angle)	GA_{min262} (mm^2)
Closure	4.42	5.02	20°	29.3
Vent Plug	2.11	3.61	0°	7.62
Drain Plug	2.11	3.61	0°	7.62

- Maximum Seal XS Area:

$SA_{max262} = 0.25\pi((XS + tol) \times (1 + \alpha(262 - 20)))^2$

Position	Maximum Diameter (mm^2)		Maximum Cross-Section Area (mm^2)
	@ 20°C	@ 262°C	@ 262°C
Closure	5.46	5.67	25.3
Vent Plug	2.71	2.82	6.23
Drain Plug	2.71	2.82	6.23

- Maximum Groove Fill:

$$GF_{max262} = \frac{SA_{max262}}{GA_{min262}}$$

Position	GA_{min262} (mm^2)	SA_{max262} (mm^2)	GF_{max262} (%)
Closure	29.3	25.3	86.4
Vent Plug	7.62	6.23	81.7
Drain Plug	7.62	6.23	81.7

4.2.9 Accident conditions mechanical tests

- The length of the eight M20 closure studs was measured before and after drop testing (see IR 0671 & 0676). The results show only normal measurement variation. The calculated mean lengths were respectively 87.04 mm and 87.01mm. The pass criteria was no permanent elongation exceeding 0.2mm (RTM 118). There was no permanent elongation.
- Helium leak test measurements on the seals were taken after drop testing (see RTR 263). The results were:

Position	Leakrate after testing (mbar.l/s)
Closure	1×10^{-8}
Drain Plug	6×10^{-8}
Vent Plug	1×10^{-7}

The pass criteria was that flask seals remained leaktight to 2.65×10^{-7} mbar.l/s (RTM 118).

4.2.10 Containment boundary

Accident conditions mechanical testing caused no physical damage to the closure or the vent and drain plugs (see inspection report, IR 0675). However, failure of the outer drain tube weld caused the containment boundary to fail its leak test (RTR 263). Computer modelling identified the cause as movement of the lead shielding (AMEC report C15578/TR/0001). The drain tube was subsequently fitted with an outer sleeve to isolate it from lead movement. At the same time a number of minor modifications were made to the impact limiters to improve their performance in the mechanical tests. The modified design was then modelled in seven different drop test orientations. The results demonstrate that all significant stresses in the drain and its welds have been eliminated. It also demonstrates that strains in the rest of the containment boundary, including the closure fixings, are within acceptable limits.

4.2.11 Capsule temperature (accident conditions)

RTM 120 gives the peak mean capsule temperature under accident conditions as 471°C. The margin of safety to the maximum allowable design value is 800 – 471 = 329°C. This is sufficient to compensate for any calculational inaccuracy.

4.2.12 Thermal distortion of closure flange

The normal flow of heat through the closure flange is outwards, i.e. the temperature of its upper face will be lower than the underside. During the thermal test when the heat flow is inwards this is reversed which could lead to an upwards distortion (hogging), resulting in a reduction of O-ring compression.

The environment enclosing closure flange is primarily the disc on the underside of the top shield. Heat from the thermal test has to pass through the top shield and then a layer of insulation of uniform thickness to reach the disk. The conductivity of the steel disk and presence of an air gap beneath it ensure that any variations in temperature distribution outside the insulation are not able to manifest themselves in the disc. This will therefore present a surface of essentially uniform temperature to the closure flange.

The closure flange is a disc of more or less constant thickness retained by a ring of fixings set inside its diameter. It may therefore best be considered a disc of the same diameter as the PCD of its fixings with its outer edge fixed. Roark (Table 11.2, Case No 15b) states that when such a plate is subjected to a uniform temperature gradient bending moments are the same throughout and the plate will not distort. Therefore there will be no reduction in O-ring compression.

RTM 120 shows that the maximum reverse temperature gradient is 3°C, hence even if the temperature distribution across the closure flange were not to be completely uniform it would not be conceivable for it to have any significant effect.

5. LEAKTESTING

5.1 ROUTINE ASSEMBLY AND LEAKTESTING

The operating instructions, OP 381, require checklists to be used for all operations. Turnround inspection, Section 10, requires each package to be inspected before loading to ensure all components are present, correct and in a serviceable condition. The assembly procedure, Section 5.4, requires all components to be correctly positioned and secured and includes leaktesting each of the three O-ring seals to verify a maximum helium leak rate of 5.0×10^{-4} mbar.l/s at 1 bar differential, the value accepted by the DfT for solids and particulates. This also complies with ANSI N14.5.

5.2 PERIODIC LEAKTESTING

Scheduled inspection, Section 11, requires each of the three O-ring seals and the containment boundary to be leaktested annually to verify a maximum helium leak rate of 1×10^{-6} mbar.l/s at 1 bar differential, the value recommended in TS-G-1.1 para. 657.13 as representing leaktightness for solid particulate material.

6. CONCLUSIONS

Design Aspect	Performance	Criteria
Material Compatibility	Suitable	Compatible with water, water vapour, air and noble gases
Radiation Resistance	4,000 Rads	$\leq 10^6$ Rads
Long Term Temperature	144°C	≤204°C
Peak Temperature	262°C	≤270°C
Temperature Duration Over 250°C	83 mins	≤120mins
Minimum Compression	10.4%	≥10%
Maximum Compression	23.9%	≤30%
Maximum Groove Fill	86.4%	≤90%
Accident Conditions	Unaffected	Unaffected by mechanical tests
Capsule Temperature	471°C	≤800°C
Thermal Compression Reduction	0	<1%

- The table above demonstrates that the R7021, O-ring material and the design of the seal housings meets all relevant Type B(U) regulatory containment criteria and guidelines for transporting up to 160 kCi of ^{60}Co as normal form material.
- Routine and periodic leaktesting comply with the DfT requirements and ANSI N14.5.

7. References

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