REVISS Services
Quality and Regulatory Group

Technical Memorandum

Shielding Performance of the R7021 Transport Container

Author:		**Reviewer:**	
Name	P J G Robbins	Name	D W Rogers
Signature	[signature]	Signature	[signature]
Date	13/05/11	Date	13/05/2011

1. PURPOSE AND SCOPE

The purpose of this document is to characterise the shielding performance of the R7021 transport container and to assess its performance under TS-R-1 normal and accident conditions tests for Type B package designs.

2. DESCRIPTION

The design consists of a lead shielded, stainless steel flask mounted on a pallet and protected from heat and impact by a jacket and top shield (Figure 1).

3. CRITERIA

1. The maximum dose level at the surface of the package shall not exceed 2.0 mSv/h (para. 531, TS-R-1).
2. The maximum dose level at 1m from the surface of the package shall not exceed 100 μSv/h (para. 530, TS-R-1).
3. The maximum dose level at the surface of the package shall not increase by more than 20% after normal conditions tests (para. 646(b), TS-R-1).
4. The maximum dose level at 1m from the package after accident conditions tests shall not exceed 10 mSv/h (para 657(b)(ii)(i), TS-R-1)).
5. The maximum lead temperature during accident conditions of transport shall not exceed its melting point of 327°C (Metals Handbook). Note that the latent heat of fusion of lead, 23.0 J/kg, compared to its heat capacity, 0.129 J/kg.°C (Handbook of Chemistry and Physics), means that the heat required to melt lead is equivalent to an additional temperature increase of 178°C.
6. The drain filter and spring gasket shall not allow particles greater than 100μm in diameter to pass through after either normal or accident conditions of transport.
7. Stresses in the spring gasket shall not exceed the design strength (yield) at maximum accident conditions temperature.
8. The spring gasket load on the underside of the closure shall not exceed 16kg (10% of the closure weight), i.e. it shall not affect closure retention in either normal or accident conditions of transport.

4. DESIGN

4.1 MAXIMUM CONTENTS

The R7021 is designed to transport a maximum of 7.40 PBq (200 kCi) of Special Form ^{60}Co and a maximum of 5.92 PBq (160 kCi) of normal form ^{60}Co.

4.2 SHIELDING

The shielding is primarily lead with a small contribution from the carbon and stainless steel structures. The design of the R7021 was modified slightly after prototype testing. Differences in lead and steel thickness are shown in the table below:

Direction	Shielding Thicknesses (mm)					
	Prototype		Modified Design		Difference	
	Lead	Steel	Lead	Steel	Lead	Steel
Radial	265	28	265	28	0	0
Up	247	53	255	59	8	6
Down	244	42	241	42	-3	0

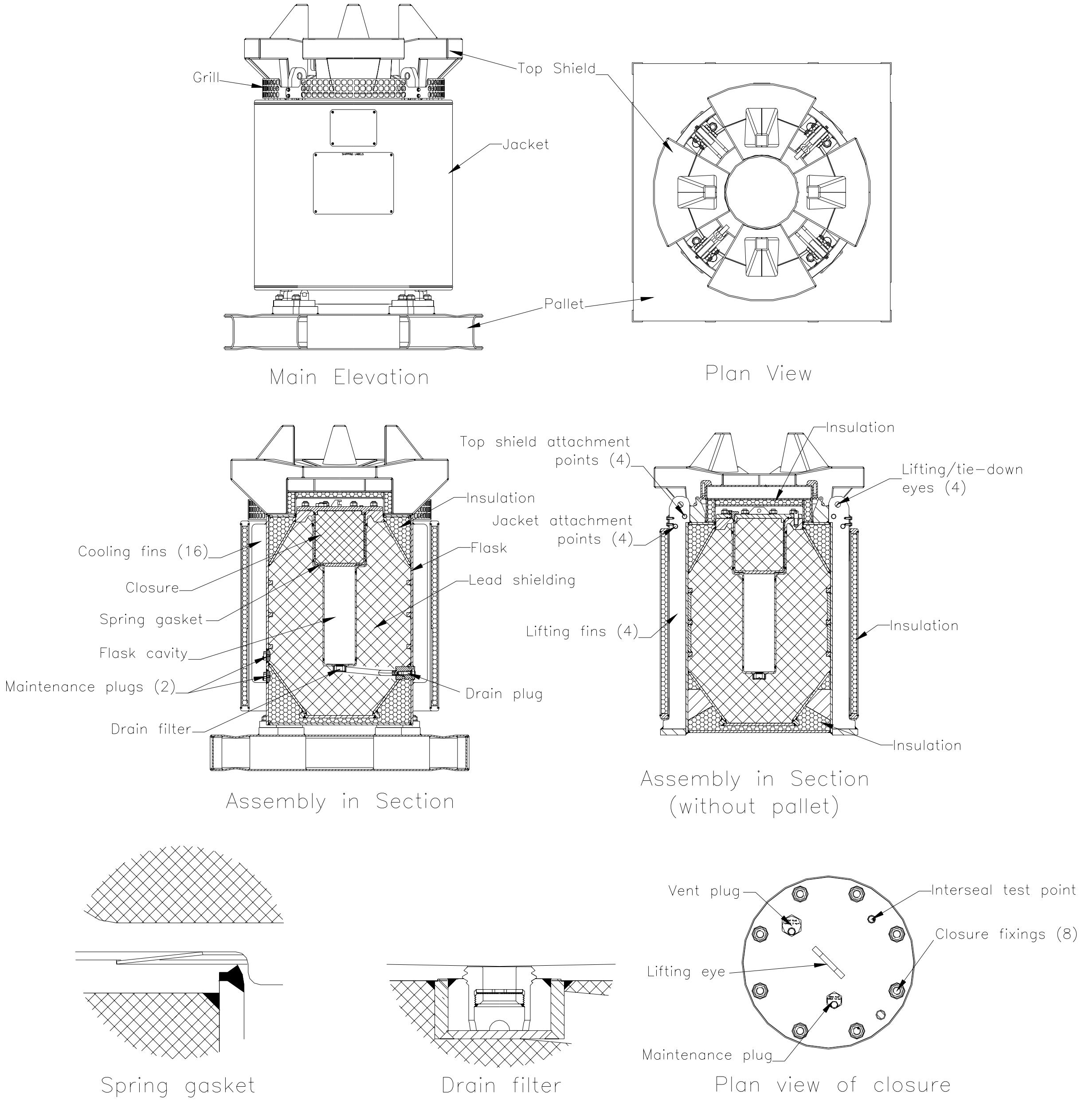

Figure 1: R7021 Constructional Details

Dose rates are calculated in the three principal directions (radially, upwards and downwards), based on the design specification at issue 5 of the drawings list, QS7021. Subsequent improvements were made to the shielding on the lower portion of the flask. More information on the modifications may be found in the Appendix.

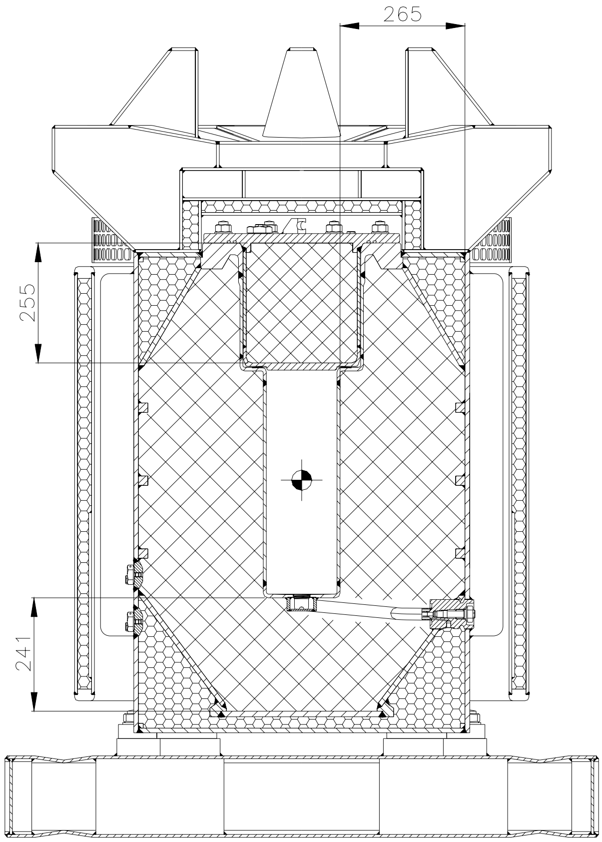

Figure 2: Package cross-section

5. CALCULATIONS

The following calculations estimate the maximum surface dose and Transport Index (TI) when the R7021 is carrying the maximum activity contents. This is achieved by adjusting measurements made on the prototype to take account of differences in contents, shielding and distance. Radiation levels at the drain, vent and closure seals are included for information only and are not subject to the criteria in Section 3.

5.1 MEASUREMENTS

The prototype was surveyed for shielding efficiency after accident conditions drop testing (RTR 264) without its top shield, jacket and pallet. The results were as follows:

Direction/Location	Maximum Dose Rate* with 2.11 PBq Co^{60}	
	Package Surface	1m from Flask Surface
Radial	975 µSv/h	37 µSv/h
Up	1825 µSv/h	100 µSv/h
Down	615 µSv/h	23 µSv/h
Drain Seal	775 µSv/h	-
Vent Seal	1825 µSv/h	-
Closure Seal	1825 µSv/h	-

* The 5µSv/h background dose rate has been subtracted from all readings.

5.2 RADIATION LEVEL

The radiation level, E, from BS 4094:

$$E = \frac{\Gamma QT}{d^2} \quad R/h$$

where,

Γ = specific gamma ray constant = 1.32 R/Ci.h at 1m
Q = source activity in curies
T = transmission factor for shielding material.
d = distance of exposure point from point activity.

5.3 CONTENTS

The prototype shielding surveys were conducted with 2.11 PBq Co^{60} in the bare flask. The equation above shows that the results require adjusting in direct proportion to the contents, i.e. by a factor of 3.51 (based on the maximum content limit; that for Special Form material).

5.4 SHIELDING

The prototype shielding surveys were conducted on the bare flask so there was no supplementary shielding from the carbon steel in the pallet, jacket and top shield. The effect of this when combined with the design changes above results in the following total variations:

Direction/ Location	Shielding Thicknesses (mm)					
	Prototype		Modified Design		Difference	
	Lead	Steel	Lead	Steel	Lead	Steel
Radial	265	16	265	28	0	12
Up	247	36	255	59	8	23
Down	244	30	241	42	-3	12
Drain Seal	265	16	265	16	0	0
Vent Seal	247	36	255	35	8	1
Closure Seal	247	36	255	35	8	1

The differences in attenuation may then be calculated using Fig 2b(i), BS 4094:

Direction/ Location	Attenuation				
	Lead		Steel		Total
	Thickness (mm)	Attenuation	Thickness (mm)	Attenuation	
Radial	0	1.00	12	0.674	0.674
Up	8	0.642	23	0.469	0.301
Down	-3	1.18	12	0.674	0.795
Drain Seal	0	1.00	0	1.00	1.00
Vent Seal	8	0.642	1	0.968	0.621
Closure Seal	8	0.642	1	0.968	0.621

5.5 DISTANCE

Radiation levels are inversely proportional to the square of the measurement distance. The difference in the source-to-surface measurements along each principal axis and the corresponding correction factor, the centre of activity being taken as the geometrical centre of the cavity, are as follows:

Direction/ Location	Measurement Distance (m)					
	Prototype		Modified Design		Ratio of squared values	
	Surface	At 1m	Surface	At 1m	Surface	At 1m
Radial	0.357	1.357	0.482	1.482	1.82	1.19
Up	0.526	1.526	0.724	1.724	1.89	1.28
Down	0.535	1.535	0.756	1.756	2.00	1.31
Drain Seal	0.357	-	0.277	-	0.60	-
Vent Seal	0.526	-	0.526	-	1.00	-
Closure Seal	0.526	-	0.526	-	1.00	-

* Dimensions derived from manufacturing drawings, QS 7021.

5.6 MAXIMUM DESIGN RADIATION LEVELS

When the correction factors calculated above are applied the dose rates at the surface and at 1m become:

Surface Radiation Levels, E					
Direction/ Location	Measurement (µSv/h)	Attenuation	Ratio of activities	Ratio of squared distances	Dose Rate (mSv/h)
Radial	975	0.674	3.51	1.82	1.27
Up	1825	0.301	3.51	1.89	1.02
Down	615	0.795	3.51	2.00	0.858

These are within the maximum allowable surface dose rate, 2.0 mSv/h (Section 3.1) for normal conditions of transport.

Radiation Levels at 1m from Surface, E					
Direction/ Location	Measurement (µSv/h)	Attenuation	Ratio of activities	Ratio of squared distances	Dose Rate (µSv/h)
Radial	37	0.674	3.51	1.19	73.6
Up	100	0.301	3.51	1.28	82.5
Down	23	0.795	3.51	1.31	49.0

These are within the maximum allowable dose rate at 1m, 100 µSv/h (Section 3.2) for normal conditions of transport.

Radiation Levels at Seals, E					
Direction/ Location	Measurement (μSv/h)	Attenuation	Ratio of activities	Ratio of squared distances	Dose Rate (mSv/h)
Drain Seal	775	1.00	3.51	0.60	4.53
Vent Seal	1825	0.621	3.51	1.00	3.98
Closure Seal	1825	0.621	3.51	1.00	3.98

6. EFFECT OF IAEA TESTING ON RADIATION LEVELS

6.1 NORMAL CONDITIONS DROP TESTING

The prototype was subjected to three normal conditions drop tests and one penetration test which caused no significant damage to the specimen (see IR 0674). The design was subsequently modified to improve accident conditions performance (see RTM 151). None of the design changes have any adverse effect on normal conditions performance and therefore there will be no change to the dose rates calculated above.

6.2 ACCIDENT CONDITIONS DROP TESTING

The prototype was subjected to nine puncture tests and four drop tests which caused no significant change to the shielding performance. The modified design has been computer modelled in the seven most damaging drop test orientations (see AMEC report C15788/TR/0001). In order for the surface dose rate to increase significantly one or more of the following would have to occur:

- Loss of the pallet, jacket or top shield.
- Failure of the closure retention system.
- Gross distortion of the flask.
- Migration of radioactive particulates past the shielding (normal form contents only).

6.2.1 Loss of the pallet, jacket or top shield

The pallet, jacket and top shield remained securely attached during drop testing (IR 0675). Computer modelling (C15788/TR/0001) demonstrated the modified design performed equally well. The 9m upright drop did however reduce the distance from the underside of the pallet. The effect of this is shown below:

Location	Dose Rate (μSv/h)	Measurement distance (m)		Ratio of squared distances	Dose Rate
		Damaged	Undamaged		
At surface	643	0.619	0.756	0.670	0.96 mSv/h
At 1m	36.7	1.619	1.756	0.850	43.2 μSv/h

As these are less than the values in other directions there will be no increase in the maximum dose rate, either on the surface or at 1m.

6.2.2 Failure of the closure retention system

The closure remained securely attached and there was no change in length of the closure fixings outside of normal measurement variation (IR 0671 & IR 0676) indicating all strains remained in the elastic region. Computer modelling of the modified design (C15788/TR/0001) demonstrated the closure fixings remained within their yield stress at all times.

6.2.3 Gross distortion of the flask

The only damage to the flask was superficial marking and bruising of external surfaces (see IR 0675) which was corroborated by the post drop test shielding survey. Computer modelling of the modified design (C15788/TR/0001) demonstrated the shielding remained securely supported and retained by the flask at all times.

6.2.4 Migration of radioactive particulates past the shielding (normal form contents only)

Although all normal form material must be encapsulated the possibility of a capsule rupturing under accident conditions must be considered. The smallest normal form material transported is Ø1mm x 1mm cobalt pellets (see OP 381). The flask is therefore equipped with a drain filter with a 0.1 mm mesh at its inner end, whilst the gap between the underside of the closure and the flask is closed by a spring gasket. Both of these were completely undamaged and secure after accident conditions tests so there is no possibility of such material migrating past the shielding.

The possibility exists however that such material could include particulate matter generated by vibration encountered in normal transport. Such particles, if small enough, could, if the capsule was ruptured, migrate along the drain tube or the side of the closure and cause a local increase in dose rate.

A test was conducted therefore in which 76.7g of Ø1mm x 1mm, nickel plated, cobalt pellets (the maximum quantity that would fit), was sealed in a typical capsule and subjected to a vibration and shock regime (to Def Stan 00-35) simulating 5,000 km road transport (see report 2209). The capsule was orientated vertically, as in normal conditions of transport.

After the test the capsule was cut open and the contents presented to a 106 µm filter (see PS/W000339RL001). Chemical analysis revealed a total quantity of 129 µg of particulate material had passed the filter (see INORG/W000925RL001). This represents, by proportion of the maximum contents, an activity of 9.96 GBq. This, if it were behind the drain plug, could, using the equation in 5.2, give a dose rate at 1m of:

Radiation Levels, E, at 1m				
Location	Steel thickness (mm)	Attenuation	Distance to measurement point (m)	Dose Rate (mSv/h)
Drain Plug	26	0.425	1.126	1.19

This is comfortably less than 10mSv/h, the maximum permitted radiation level at 1m after accident conditions of transport (see 3.4).

6.2.5 Spring gasket stress

The spring gasket is a bevelled stainless steel ring designed to keep particulate material from passing into the gap between the closure and the flask body and hence circumnavigating the shielding. Its outer diameter sits in a recess in the flask body, while its inner diameter is in contact with the base of the closure. All contact surfaces are machined. The height of the gap between the flask and the closure is 3.1 - 3.1 mm while the height of the spring gasket is 5.2 - 5.4 mm. This ensures that there is always positive contact with both surfaces.

The spring gasket is deformed when the closure is in place, which generates a bending stress. The load case is a circular plate with the outer edge simply supported and the inner edge free (Case 1a, Table 24, Roark).

Max. stress, $\sigma = \dfrac{6M}{t^2}$

where:

M = maximum moment = awK_{Mtb}

t = plate thickness

and:

a = outside radius

w = unit line load

K_{Mtb} is related to $\dfrac{b}{a}$ through interpolation of special case values in Case 1a.

b = inside radius

Max. deflection, $y = h_1 - h_2 = \dfrac{K_y w a^3}{D}$ = -2.3 mm

where:

h_1 = min. height of flask/closure gap = 3.1 mm

h_2 = max. height of gasket = 5.4 mm

K_y is related to $\dfrac{b}{a}$ through interpolation of special case values in Case 1a.

D = plate constant = $\dfrac{Et^3}{12(1-\nu^2)}$

and:

E = modulus of elasticity = 200,000 N/mm^2

ν = Poisson's ratio = 0.285

thus:

$$\sigma = \frac{6aK_{Mtb}w}{t^2} = \frac{6aK_{Mtb}\left(\dfrac{yD}{K_y a^3}\right)}{t^2} = \frac{6aK_{Mtb}y\left(\dfrac{Et^3}{12(1-\nu^2)}\right)}{K_y a^3 t^2} = \frac{6aK_{Mtb}yEt^3}{12(1-\nu^2)K_y a^3 t^2}$$

therefore:

$$\sigma = \frac{6K_{Mtb}yEt}{12(1-\nu^2)K_y a^2}$$

The highest stress in the gasket occurs when the thickness, t, and K_{Mtb} are at a maximum and the outside radius, a, and K_y at a minimum.

therefore:
t = 1.15 mm
a = 114.75 mm

K_{Mtb} is at a maximum and K_y a minimum for higher values of $\frac{b}{a}$, i.e. when b is at a maximum.

therefore:
b = 85.25 mm

thus:
$\frac{b}{a}$ = 0.806

K_{Mtb} = 0.8814 (for $\frac{b}{a}$ = 0.7 (through interpolation of special case values in Case 1a))

K_y = -0.1927 (for $\frac{b}{a}$ = 0.7 (through interpolation of special case values in Case 1a))

therefore:
σ = 100 N/mm^2

This is below the design strength, 116 N/mm^2, based on the maximum cavity wall temperature at accident conditions of 316ºC (RTM120). Taken from PD 5500, Annex K, Table K.1-4, for 304S11 as 1.35 x f_N, where f_N = nominal design strength and 1.35 is the factor that gives the point of transition between linear elastic and linear plastic behaviour (para. K.1.4.1.3).

6.2.6 Spring gasket load

Deformation of the gasket creates a load on the closure fixings as follows:

Total load, $W = \frac{cw}{g}$

where:
c = circumference of inside edge = 2πb
g = gravitational acceleration = 9.81 m/s^2

therefore:
W = 12.3 kg

6.3 Accident Conditions Thermal Testing

RTM 120 details the thermal performance of the R7021. Peak accident conditions lead temperature is 302°C.

7. Conclusions

1. The maximum surface dose rate, when loaded with 7.40 PBq ^{60}Co, is 1.27 mSv/h.
2. The maximum dose rate at 1m, when loaded with 7.40 PBq ^{60}Co, is 82.5 µSv/h.
3. Radiation levels are unaffected by normal conditions of transport.

4. Maximum radiation levels after accident conditions of transport.
    - Special Form contents: Are unaffected.
    - Normal form contents: Could rise to 1.19 mSv/h at 1m should all encapsulation be ruptured and all possible particulate matter less than 0.1 mm in diameter make its way to the outer end of the drain tube.
5. Lead temperature: The margin of safety to the maximum allowable design value is 25°C. This represents 23% of the temperature rise during the thermal test. This is sufficient to compensate for any calculational inaccuracy.
6. The drain filter and spring gasket will not allow particles greater than 100 µm in diameter to pass through in either normal or accident conditions of transport.
7. Stress in the spring gasket does not exceed the design strength (yield) at maximum accident conditions temperature.
8. Closure load from the spring gasket is less than 10% of the closure weight and will have no significant affect on normal or accident conditions performance.

8. REFERENCES

- 2209: Test Report (Vibration and Shock Testing), Product Assessment and Reliability Centre (PARC).
- BS 4094: Part 1, 1966. Data on shielding from ionising radiation. British Standards Institution.
- C15788/TR/0001 issue 2: Impact assessment of the Reviss R7021 package, AMEC Ltd.
- Def Stan 00-35: Environmental Handbook for Defence Materiel, Part 5, Induced Mechanical Environments, MoD.
- Handbook of Chemistry and Physics: 76th Edition, 1995/6, CRC Press.
- INORG/W000925RL001: Determination of Cobalt and Nickel contents on filter papers by ICP-OES, Intertek MSG.
- IR 0673: Inspection Report on 3981/01 after normal conditions drop testing, REVISS Services (UK) Ltd.
- IR 0675: Inspection Report on 3981/01 after accident conditions drop testing, REVISS Services (UK) Ltd.
- Metals Handbook: Desk Edition, 1995, American Society for Metals.
- PD 5500: 2009: Specification for unfired fusion welded pressure vessels. British Standards Institution.
- PS/W000339RL001: Isolation and chemical analysis of fragments of metal particles produced during the vibration testing of cobalt pellets, Intertek MSG.
- OP 214 issue 7: Transport container shielding test procedure, REVISS Services (UK) Ltd.
- OP 381 issue 2: R7021 Operating and maintenance instructions, REVISS Services (UK) Ltd.
- QS 7021 issue 5: Drawings List R7021 Transport Container, REVISS Services (UK) Ltd.
- QS 7021 issue 6: Drawings List R7021 Transport Container, REVISS Services (UK) Ltd.
- Roark's Formulas for stress and strain, 7th Edition, WC Young, McGraw-Hill, 2002.
- RTM 118: Test plan for R7021, REVISS Services (UK) Ltd.
- RTM 120: Thermal performance of R7021, REVISS Services (UK) Ltd.
- RTM 151: R7021 Transport Container Design Justification, REVISS Services (UK) Ltd.
- RTM 168: Performance of the Shielding Modifications to the R7021 Flask in IAEA Drop Testing, REVISS Services (UK) Ltd.
- RTR 264: 3981/01 Shielding Survey Report, REVISS Services (UK) Ltd.
- TS-R-1: Regulations for the Safe Transport of Radioactive Material, 2005 Edition, IAEA, Vienna.

APPENDIX

SHIELDING MODIFICATIONS MADE AT QS7021 ISSUE 6

Shielding surveys on the first batch of production units revealed higher than expected radiation levels towards the base of the assembly. To optimise the dose field therefore additional shielding components were added (Figure 3). Four stainless steel plates were added around the flask lower cone. One of the plates has a lead plate set into a cut-out and covered with a capping sheet. In addition, a stainless steel disc is welded under the flask base.

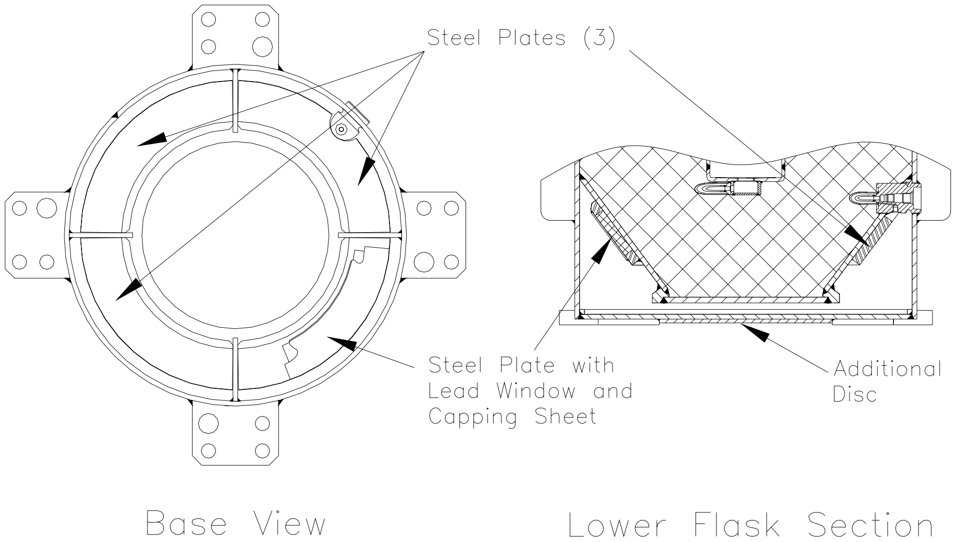

Figure 3: Shielding Modifications

The addition of these plates reduces peak dose rates, which reduces dose uptake to operators and optimises shipping efficiency. The modifications have no effect on the drop test performance of the assembly and the added components will remain securely attached under normal and accident conditions of transport (see RTM 168). The modifications have no effect on the thermal performance of the assembly (see RTM 120).