5 SHIELDING EVALUATION

This section of the application identifies the principal radiation shielding design features of the packaging that are important to safety and provides the results of analysis that shows the packaging meets the shielding requirements of the regulations.

5.1 Description of Shielding Design

5.1.1 Design Features

The gamma shielding present in the Safkeg-HS 3977A package with the standard and split lid CV variants is shown in Figures 5-1, 5-2 and 5-3. The materials of construction and dimensions are fully specified in the drawings in Section 1.3.3. Gamma shielding is provided principally by the depleted uranium present in the containment vessel body and lid; the steel of the CV provides some additional shielding.

The depleted uranium is machined to specification and then positioned inside the stainless steel cladding of the body and the lid. Gaps of 0.75 mm exist between the CV cavity and the depleted uranium and between the depleted uranium and the CV outer wall. There is a 0.7 mm axial gap between the depleted uranium and the base of the CV cavity wall. The method of fitting the CV base leaves no gap between the base and depleted uranium. For the CV lid, a radial gap of 0.05 mm exists between the depleted uranium and the stainless steel cladding. There is no axial gap as the depleted uranium is machined such that fitting to the CV lid top leaves no gap. The containment vessel is designed so that the shielding in the lid and body are stepped to reduce radiation streaming. The upstanding ring on the lid also provides some additional steel shielding to reduce the radiation streaming from the gap between the CV Lid and CV Body.

The contents of the package are defined as everything that is carried within the CV cavity. Additional shielding is provided by inserts (where these are required) as shown in Figures 5-4, 5-5, 5-6, 5-7 and 5-8 – these are fully specified in Section 1.2.2.2. These inserts provide different amounts of shielding with either tungsten material for the 3982 and 3985 or stainless steel in the case of the 3987, 4081 and 4109 inserts. For the 4081 stainless steel insert a tungsten liner is also placed in the containment vessel to provide additional shielding. The inserts provide confinement for all contents under NCT and HAC.

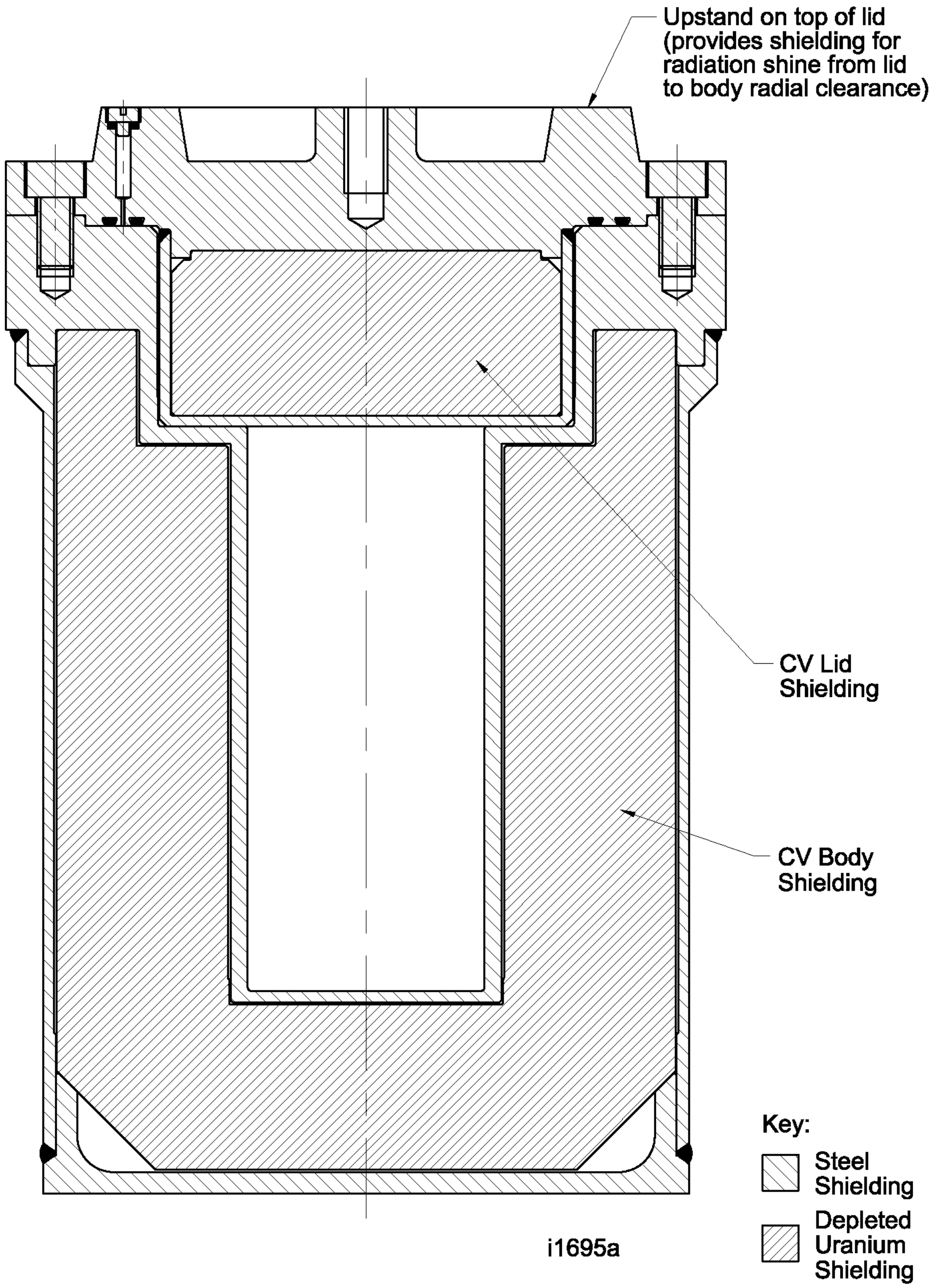


Figure 5-1 Gamma shielding present in the 3977A package with a standard CV lid

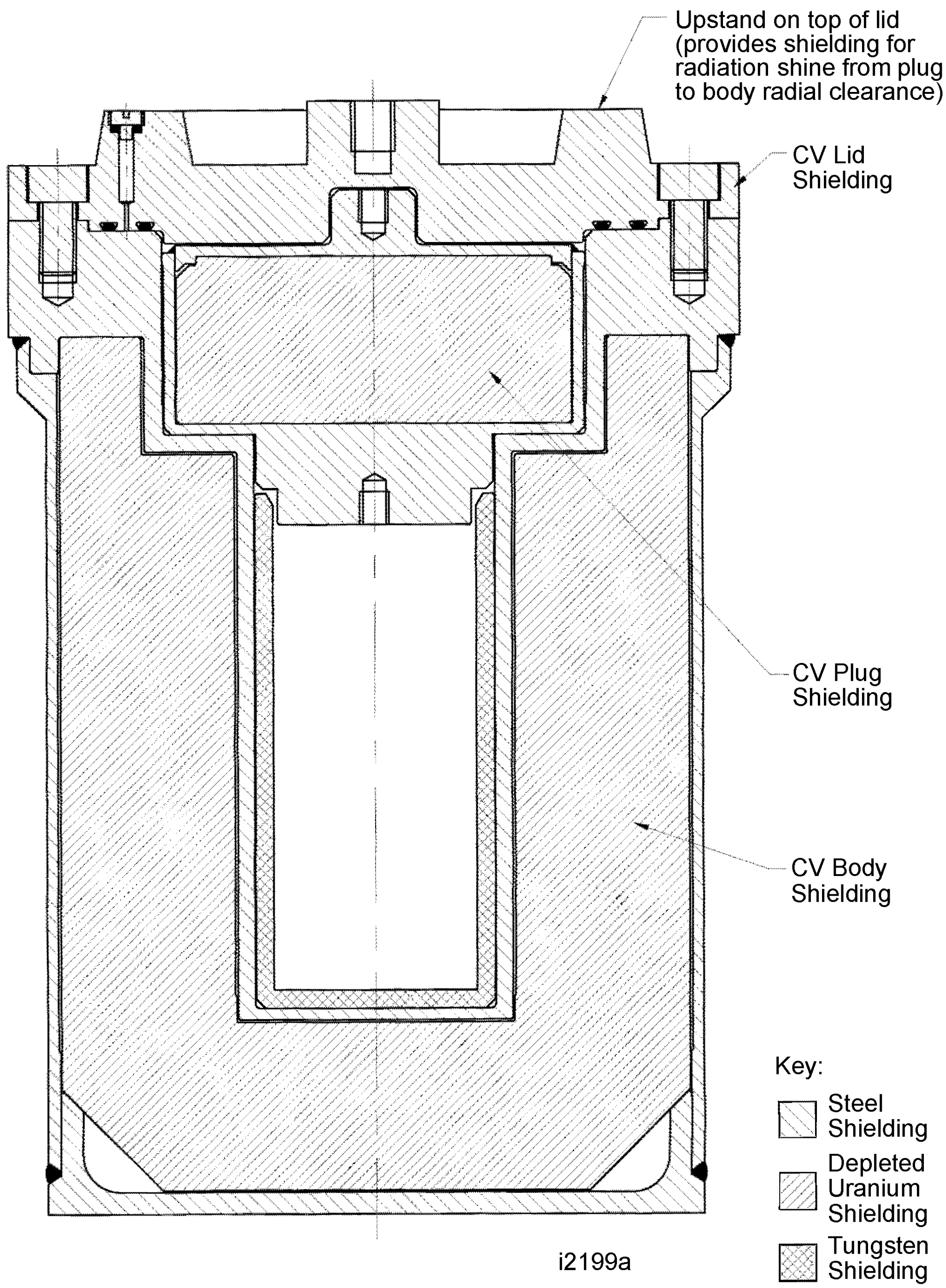


Figure 5-2 - Gamma shielding present in the 3977A package with a split CV lid and tungsten liner

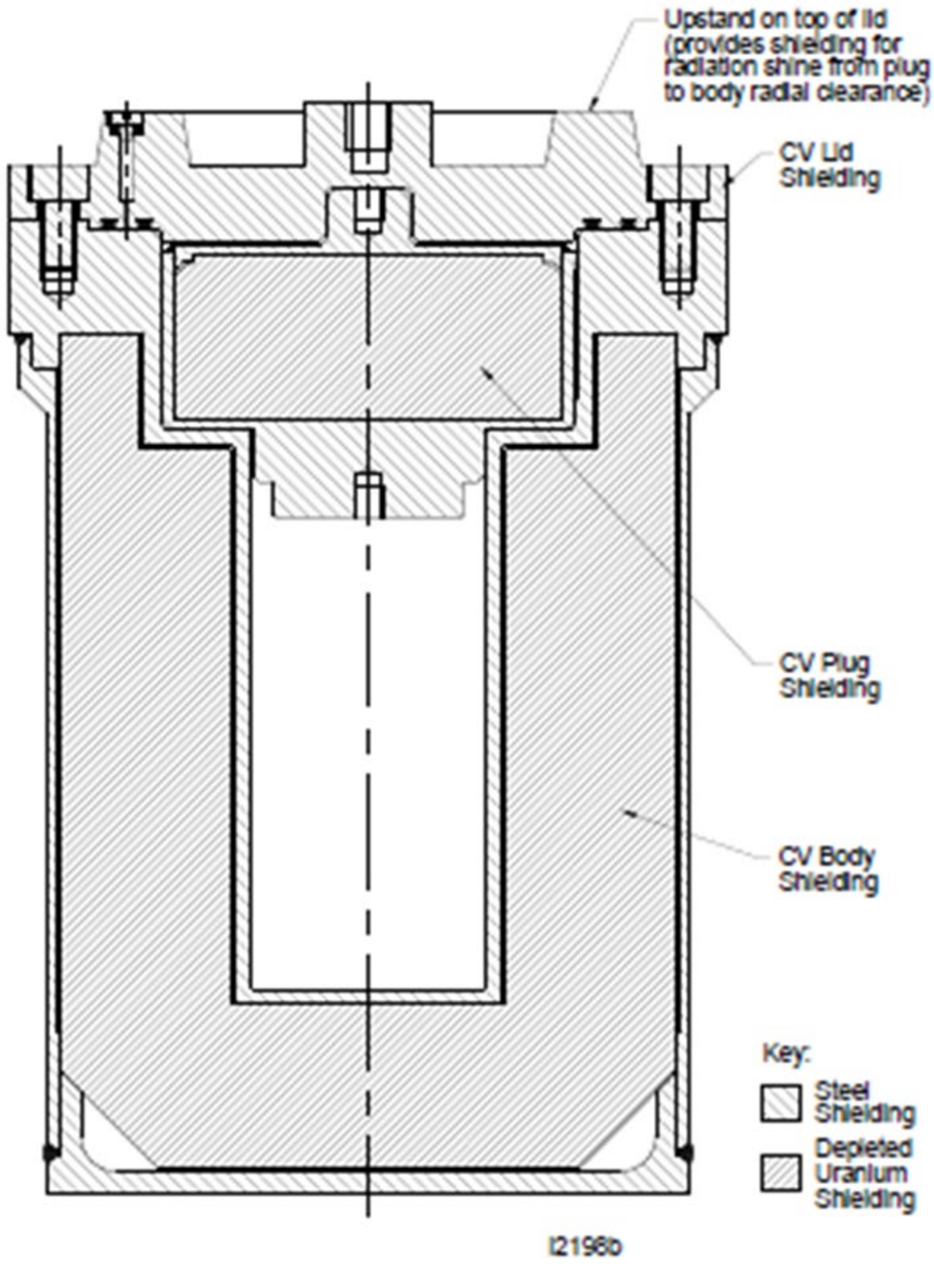


Figure 5-3 - Gamma shielding present in the 3977A package with a split CV lid and no liner

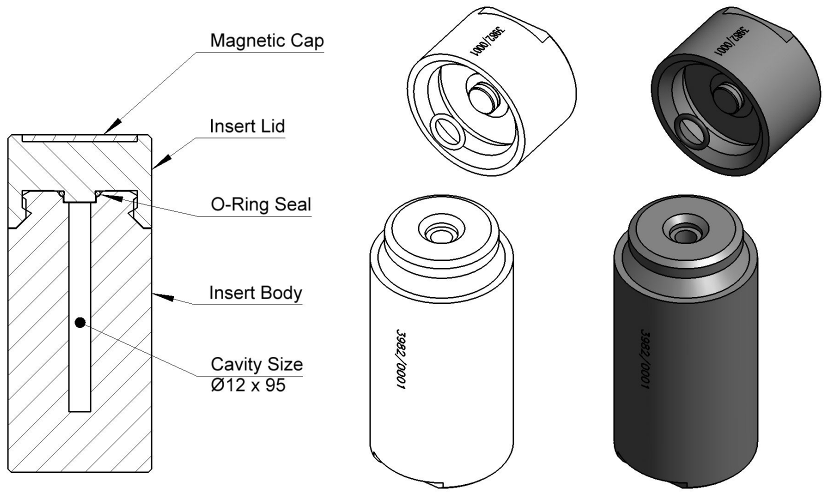


Figure 5-4 - Shielding insert HS-12x95-Tu insert Design # 3982

Figure 5-5 - Shielding insert HS-31x114-Tu insert Design # 3985

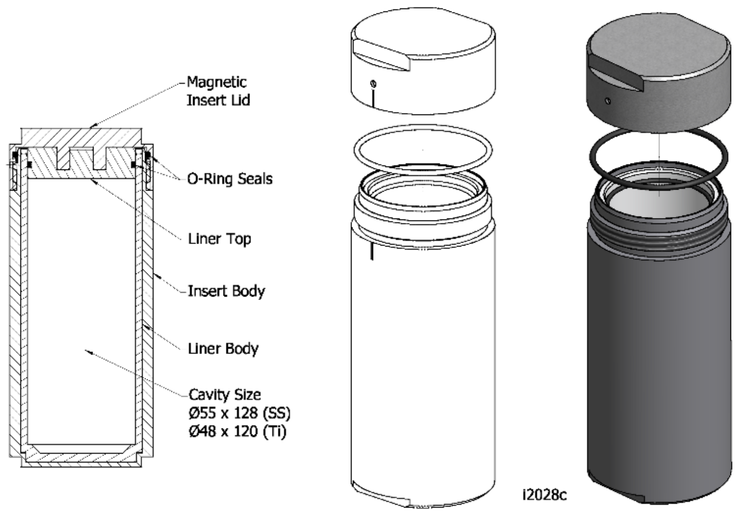


Figure 5-6 - Shielding insert HS-55x128-SS Insert Design # 3987

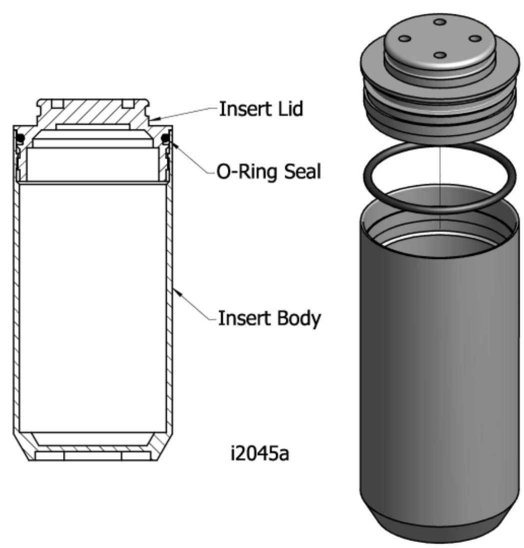


Figure 5-7 - Shielding insert HS-50x128-SS Insert Design # 4081

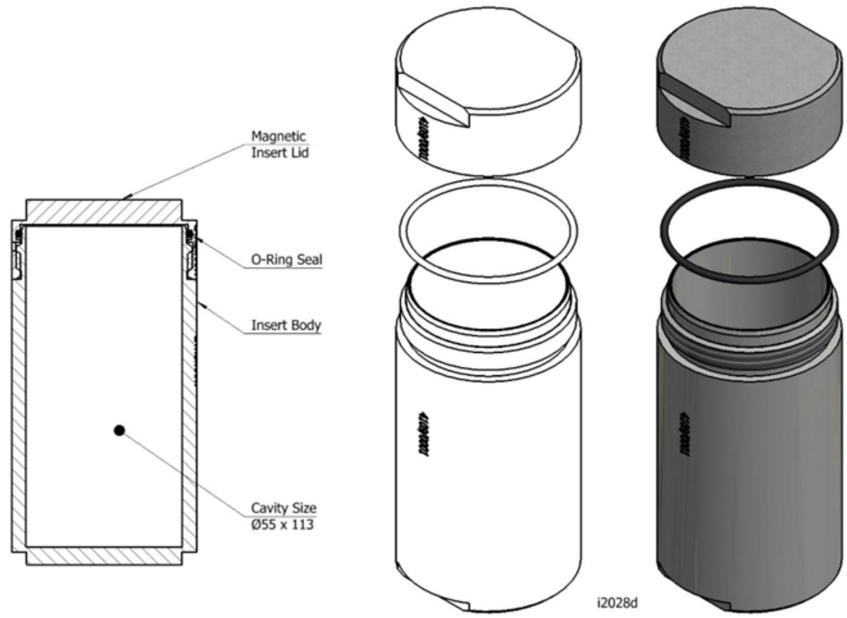


Figure 5-8 - Shielding insert HS-55x113-SS– Design No 4109

5.2 Summary Table of Maximum Radiation Levels

5.2.1 Normal Conditions of Transport

Table 5-1 shows the package maximum NCT dose rates for exclusive use. The maximum quantities of the allowable contents were derived assuming a surface dose rate of 2 mSv/hr. However due to analytical uncertainties, package tolerances and the method of calculation the surface dose rates required increasing in accordance with CTR 2013/09. Therefore the surface dose rates exceeded that of non exclusive use so they were assessed against those of Exclusive use.

Under 10 CFR 71.47(b) if a package exceeds the limits specified in 71.47(a) it shall be shipped under exclusive use and the radiation levels shall not exceed the following during shipment:

1) 2 mSv/h (200 mrem/h) on the external surface of the package, unless the following conditions are met, in which case the limit is 10 mSv/h (1000 mrem/h):

(i) The shipment is made in a closed transport vehicle;

(ii) The package is secured within the vehicle so that its position remains fixed during transportation using a pallet as specified in Section 7.4; and

(iii) There are no loading or unloading operations between the beginning and end of the transportation;

(2) 2 mSv/h (200 mrem/h) at any point on the outer surface of the vehicle, including the top and underside of the vehicle; or in the case of a flat-bed style vehicle, at any point on the vertical planes projected from the outer edges of the vehicle, on the upper surface of the load or enclosure, if used, and on the lower external surface of the vehicle; and

(3) 0.1 mSv/h (10 mrem/h) at any point 2 meters (80 in) from the outer lateral surfaces of the vehicle (excluding the top and underside of the vehicle); or in the case of a flat-bed style vehicle, at any point 2 meters (6.6 feet) from the vertical planes projected by the outer edges of the vehicle (excluding the top and underside of the vehicle); and

(4) 0.02 mSv/h (2 mrem/h) in any normally occupied space, except that this provision does not apply to private carriers, if exposed personnel under their control wear radiation dosimetry devices in conformance with 10 CFR 20.1502.

The Safkeg-HS package will be transported in a closed sided truck. The smallest truck that shall be used is an 18 foot (5.5 m) truck. The minimum internal dimensions of this truck are 7’4” (2.24 m) wide and 7’ (2.13 m) high. The package shall be secured in position using a transport pallet it shall secure the pallet so that it is at least 20 cm from the base, side and top of the truck.

Within Table 5-1 it has been assumed that the dose rate for each surface is the highest rate calculated. The surface dose rate of the truck has been calculated assuming that the package is

only 20 cm from the surface of the truck, therefore accounting for the worst case scenario. For CT-6 Thorium Target, it has been shown that the maximum dose rates are at the bottom of the package (Atkins report 5183326-HS-REP-001, Section 5.6.2).

Table 5-1 Summary Table of Maximum Radiation Levels Under Normal Conditions of Transport Under Exclusive Use

	Total Gamma + Neutron mSv/h (mrem/h)			10 CFR 71.47(b) Limit
Location	Top	Side	Bottom	
For CT-1 to CT-5				
Package Surface	7.97 (797)	7.97 (7.97)	7.97 (797)	10 (1000)
Outer Surface of the Truck	1.35 (135)	1.35 (135)	1.35 (135)	2 (200)
2m from Edge of the Truck	0.03 (3)	0.03 (3)	0.03 (3)	0.1 (10)
For CT-6 Thorium Target				
Package Surface			8.18 (818)	10 (1000)
Outer Surface of Conveyance			0.24 (24)	2 (200)
2 m from Edge of Conveyance			0.03 (3)	0.1 (10)
1 m from Package Surface			0.17 (17)	
1 m from Edge of Conveyance			0.06 (6)	

5.2.2 Hypothetical Accident Conditions

The tests discussed in section 2 demonstrated that during the HAC tests the only significant damage sustained was to the rims and skirts of the package. These items play no role in the shielding of the contents. However an 11 mm dent was suffered to the side of the package. This dent would cause a 5% increase in dose rate on the package. The only other damage that would affect the shielding is the loss of the cork material during a fire. The model used for the NCT conditions assumes air in place of cork. The dose rates for accident conditions are shown in Table 5-2.

Table 5-2 - Summary Table of Maximum Dose Rates for Hypothetical Accident Conditions			
Hypothetical Accident Conditions	1 Meter from Package Surface mSv/h (mrem/h)		
Radiation	Top	Side	Bottom
Total Gamma + Neutron	0.16 (16)	0.16 (16)	0.16 (16)
10 CFR 71.51(a) Limit	10 (1000)	10 (1000)	10 (1000)

5.3 Source Specification [71.33 (b)(1)]

5.3.1 Gamma Source

The shielding calculations for contents types CT-1 to CT-5 were carried out using two different shielding models, MCBEND discussed in the attached reports AMEC/SF6652/001, AMEC/CRM37327/TN_001, AMEC/CRM42622/TN_001 and Microshield discussed in the attached reports CTR2011/01 and CTR 2013/09. A MCBEND model was used to determine the location of the point source which caused the highest surface dose rate for the tungsten inserts, and to allow the Microshield model to be validated against the MCBEND reference case (AMEC/SF6652/001). The MCBEND model was also used to determine the maximum surface dose rate for 7.4 TBq of I-131 (AMEC/CRM37327/TN_001) and 1000 Ci of Mo-99 (AMEC/CRM42622/TN_001) in the required stainless steel insert.

The MCBEND tungsten insert calculations were carried out using a 3kCi Cs-137 source in equilibrium with the daughter nuclide Ba-137m, with a gamma energy of 0.662 MeV and line intensity of 0.852.

The Microshield calculations were carried out with a point source using a section through the base of the package for 1 Ci of each nuclide listed in the contents. The gamma decay source data within Microshield version 8.03 is the Grove Library or ICRP 38. The source library chosen for each nuclide was the one that led to the highest surface dose rate. The MCBEND tungsten inserts calculations, demonstrated that the point to use for the highest dose was the side of the package, therefore an adjustment factor was applied to the Microshield results as discussed in Croft Report CTR 2013/09 (section 5.6.2).

For all nuclides the time at which the highest surface dose rate occurred was determined. For the majority of the contents this was at time = 0 however due to daughter products some nuclides had a peak surface dose rate hours, days or years into their life due to the formation of daughter products. Once the point of the decay process which provided the highest dose rate was identified, the nuclide was decayed to this point and the dose rate on the surface of the package determined. Table 5-3 shows all the daughter products that were included in the shielding calculation for applicable nuclides.

The betas and alphas were neglected as shielding source terms as it was assumed they were 100% absorbed into the packaging shielding material and did not contribute to the dose rate on the surface of the package. However, Bremsstrahlung radiation was calculated for all the beta emitters.

Table 5-3 - Daughter Nuclides Included in Shielding Model	
Parent Nuclide	Daughter Nuclides
Ac-225	At-217, Bi-213, Fr-221, Pb-209, Po-213, Tl-209
Ac-227	Bi-211, Fr-223, Pb-211, Po-211, Po-215, Ra-223, Rn-219, Th-227, Tl-207
Am-241	Ac-225, At-217, Bi-213, Fr221, Np-237, Pa-233, Pb-209, Po-213, Ra-225, Th-229, Tl-209, U-233
As-77	Se-77m
Cs-137	Ba-137m
Mo-99	Tc-99m, Tc-99
Np-237	Ac-225, At-217, Bi-213, Fr-221, Pa-233, Pb-209, Po-213, Ra-225, Th-229, Tl-209, U-233
Pb-210	Bi-210, Po-210
Pu-238	Bi-210, Bi-214, Pb-210, Pb-214, Po-210, Po-214, Po-218, Pu-238, Ra-226, Rn-222, Th-230, U-234
Pu-239	Ac-227, Bi-211, Fr-223, Pa-231, Pb-211, Po-211, Po-215, Ra-223, Rn-219, Th-227, Th-231, Tl-207, U-235
Pu-240	Ac-228, Bi-212, Pb-212, Po-212, Po-216, Ra-224, Ra-228, Rn-220, Th-228, Th-232, Tl-208, U-236
Pu-241	Ac-225, Am-241, At-217, Bi-213, Fr-221, Np-237, Pa-233, Pb-209, Po-213, Pu-241, Ra-225, Th-229, Tl-209, U-233, U-237
Ra-223	Bi-211, Pb-211, Po-211, Po-215, Rn-219, Tl-207
Ra-224	Rn-220, Po-216, Pb-212, Bi-212, Po-212, Tl-208
Ra-226	Bi-210, Bi-214, Pb-210, Pb-214, Po-210, Po-214, Po-218, Rn-222, At-218
Th-227	Bi-211, Pb-211, Po-211, Po-215, Ra-223, Rn-219, Tl-207
Th-228	Bi-212, Pb212, Po-212, Po-216, Ra-224, Rn-220, Tl-208
U-235	Ac-227, Bi-211, Fr-223, Pa-231, Pb-211, Po-211, Po-215, Ra-223, Rn-219, Th-227, Th-231, Tl-207
W-188	Re-188

The shielding calculations for contents type CT-6 were carried out using the Monte Carlo code MCNP and are detailed in Atkins report 5183326-HS-REP-001. For contents type CT-6 the source is activated thorium target nominally dia 60 mm x 0.37 mm thick and located at nominally the mid height of the cavity of the CV having a sealed split CV lid (see Section 1.2.2.2, Fig 1-7). The activation of the thorium target calculated using the FLUKA code is given in BNL report C-A/BLIP/001 (ref SARP Section 5.6.2) which lists all individual radioisotopes (498 isotopes in total) determined by the code at 24 hours decay time following the target irradiation (otherwise known as 24 hours End of Beam (EOB)). The activity (Bq) for each isotope is also provided and this is used in the Monte Carlo calculations detailed in Atkins report 5183326-HS-REP-001.

The MCNP calculations showed that location of the highest dose rate on the outer surface of the package is at the base.

The MCNP calculations (see Atkins report 5183326-HS-REP-001) for CT-6 Thorium target were carried out using an energy bin method with a source representing the thorium target to determine the package external dose rates and dose rates for the O-rings within the CV.The gamma source data is taken from BNL report C-A/BLIP/001.. Dose rate contributions from beta emission (via bremsstrahlung radiation) were calculated using ORIGEN (based on interactions within UO2) and by modelling the bremsstrahlung radiation gamma spectra in MCNP.

5.3.2 Neutron Source

None of the radionuclides specified in the contests emit neutrons.

5.4 Shielding Model

5.4.1 Configuration of Source and Shielding

The MCBEND model detailed in the attached report AMEC/SF6652/001 was used to determine the location of a point source which provided the highest surface dose rate for the tungsten inserts HS-12x95-Tu and HS-31x114-Tu (see Section 1.2.2.2). The model was also used to determine the maximum package surface dose rates for I-131 and Mo-99, as discussed in reports AMEC/CRM37327/TN_001 and AMEC/CRM42622/TN_001 respectively.

The 3D model was generated using the calculation drawings in section 1.3.2. The small chamfers and rounding at corners were ignored, except in the vicinity of the containment vessel O-rings. Nuts and bolts were omitted, but the central hole at the top of the containment vessel was included. Very small (< 0.1 mm) air-gaps and voids were ignored, except for the regions where the containment vessel lid interfaces to the vessel body in these regions the tolerance gaps were modelled explicitly. Cork is omitted for conservatism and modelled as void instead. O-ring material is not modelled and is treated as void. The 20x20 mm square cross-section tubing at either end of the Safkeg HS container has no significant impact on the calculations and is not modelled. Nominal thicknesses for each item were used.

The MCBEND model was then run with several different source locations as given in Table 5-4 and illustrated in Figures 5-8 and 5-9 for the Cs-137 source in the tungsten inserts. Figure 5-10 illustrates the source location used for the I-131 point source in the 55x128 steel insert and Figures 5-11 to 5-13 demonstrate the location of the Mo-99 liquid in a 50x85 steel insert with the split lid CV. It must be noted that when the source was located at the top of the insert the insert was moved so that it touched the lid. When the source was located at the bottom the insert was moved so that it touched the liner.

For CT-6 The MCNP model detailed in Atkins report 5183326-HS-REP-001 was used to determine the the package external dose rates and dose rates for the O-rings within the CV. The configuration of the source is as given in Table 5-4 and as shown in Figure 5-14 (see Atkins report 5183326-HS-REP-001, Section 5.6.2, Figs 9-6 & 9-7).

Table 5-4 - Summary of Source Configurations used in the Monte Carlo calculations				
Source	**Form**	**Activity**	**Container Configuration**	**Source location**
Cs-137[1]	Solid	3000 Ci	With standard CV lid Without Tungsten insert	top, centered
				Bottom, centered
				mid-cavity, eccentered
				Top, eccentered
			With standard CV lid With Tungsten inserts HS-31x114-Tu HS-12x95 Tu	top, centered
				bottom, centered
				mid-cavity, eccentered
				Top, eccentered
I-131[2]	Point Source	200 Ci (7.4 TBq)	With standard CV lid With Stainless steel insert HS-55x128 SS	top, centered
				bottom, centered
				mid-cavity, eccentered
				top, eccentered
Mo-99[3]	Liquid	1000 Ci, Maximum specific activity 60 Ci/ml	With split CV lid, tungsten liner and Stainless steel insert HS-50x85 SS	liquid, at base
				liquid, on side
				liquid, on top
Thorium target[4]	Solid	1 photon of each nuclide	With sealed split CV lid and no insert	target centered at approximately the mid height of the CV cavity

[1] AMEC/SF6652/001
[2] AMEC/CRM37327/TN_001
[3] AMEC/CRM42622/TN_001
[4] Atkins 5183326-HS-REP-001, Section 5.6.2, Figs 9-6 & 9-7

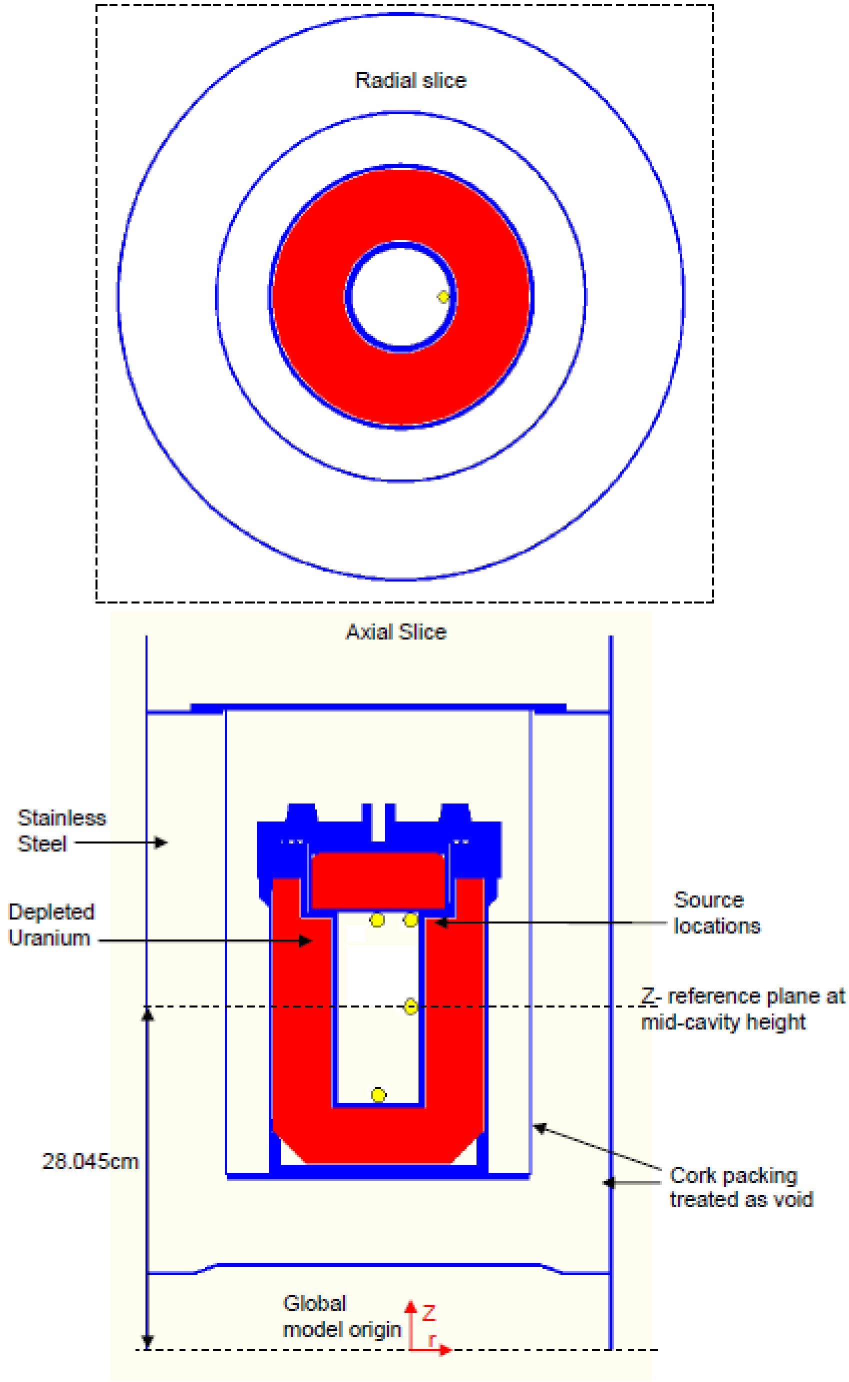


Figure 5-8 - Shielding Model and Source locations for HS package without an insert

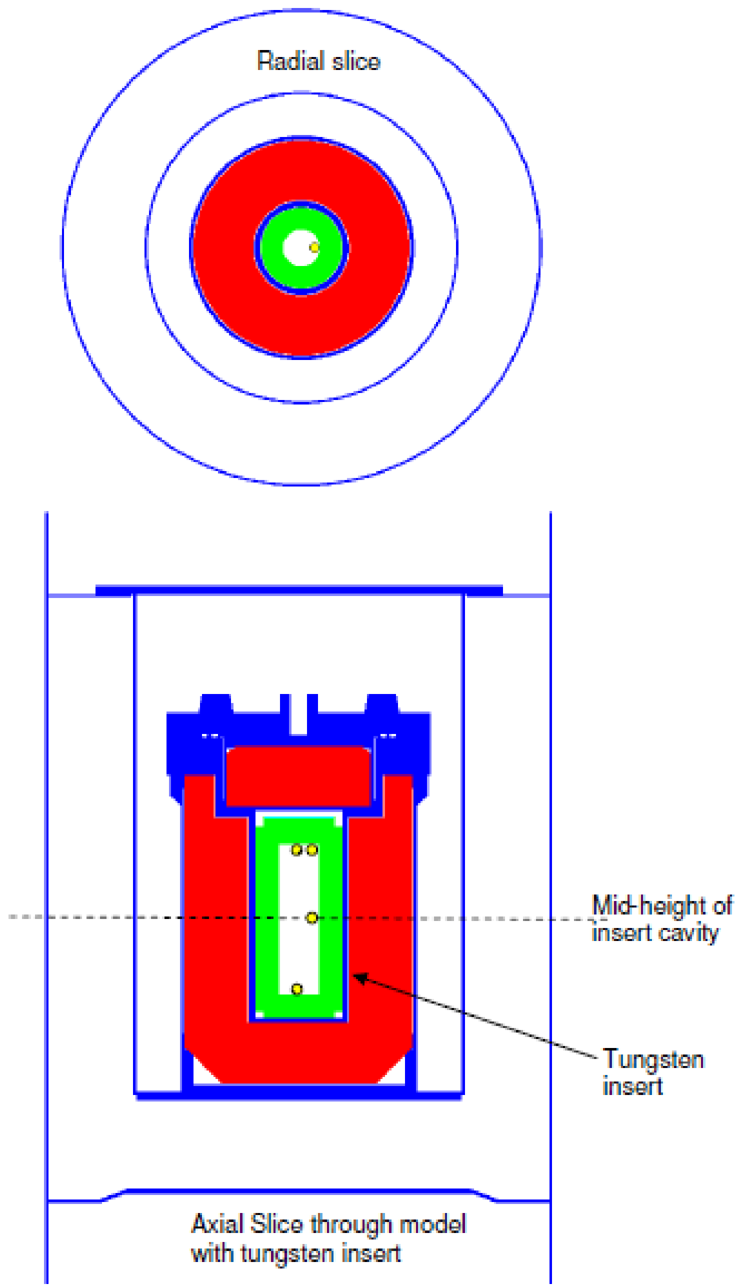


Figure 5-9 - Source Locations for MCBEND Model for HS package with Tungsten insert

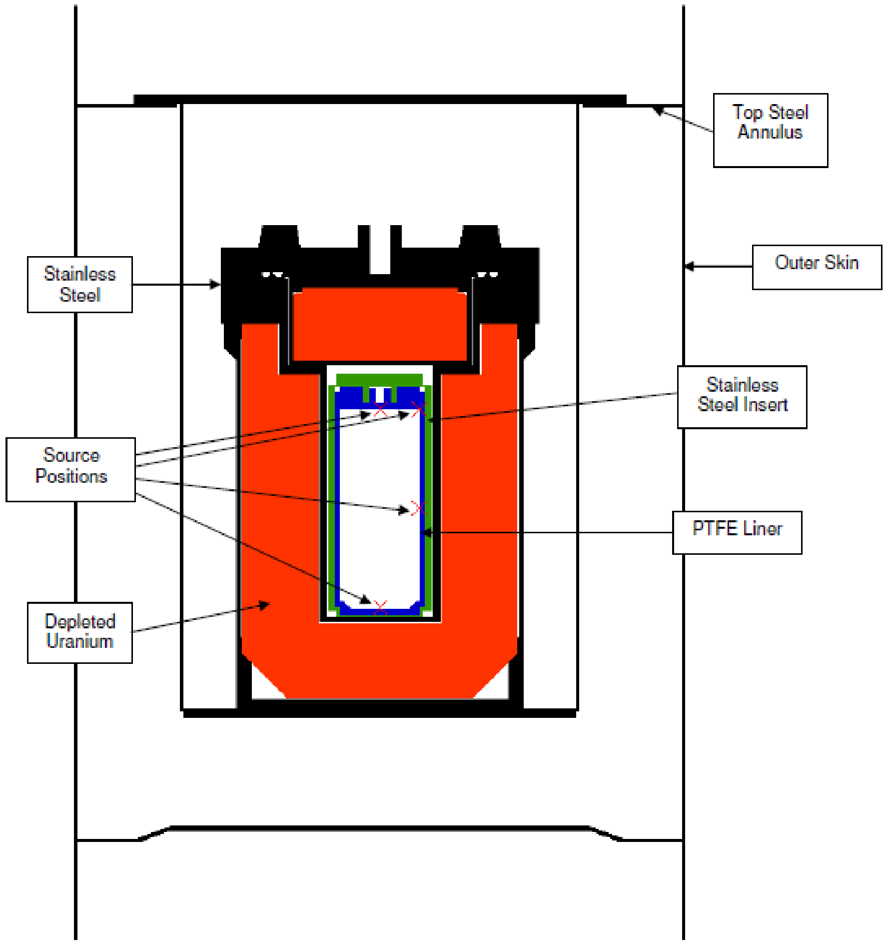


Figure 5-10 - I-131 Source Locations for MCBEND Model for HS Package with stainless Steel Insert

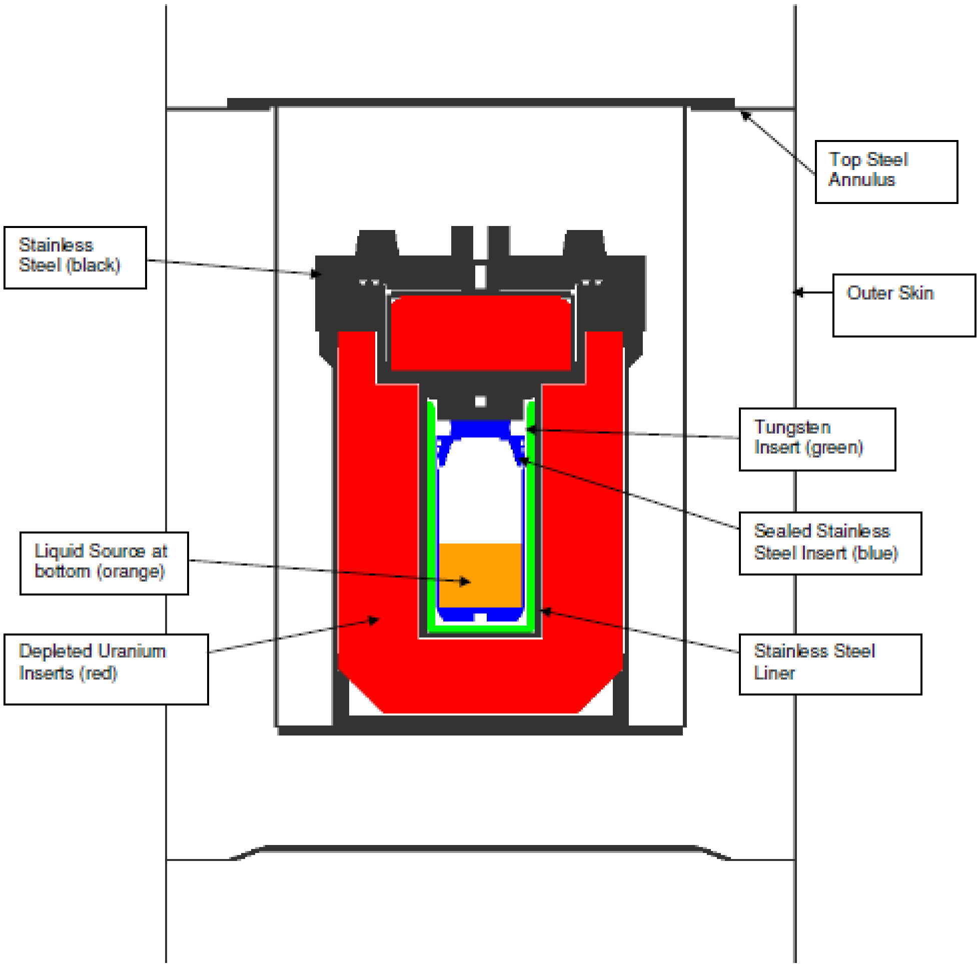


Figure 5-11 – Mo-99 Bottom Source Location for MCBEND Model for HS Package with stainless Steel Insert, Tungsten Liner and Split Containment Vessel Lid

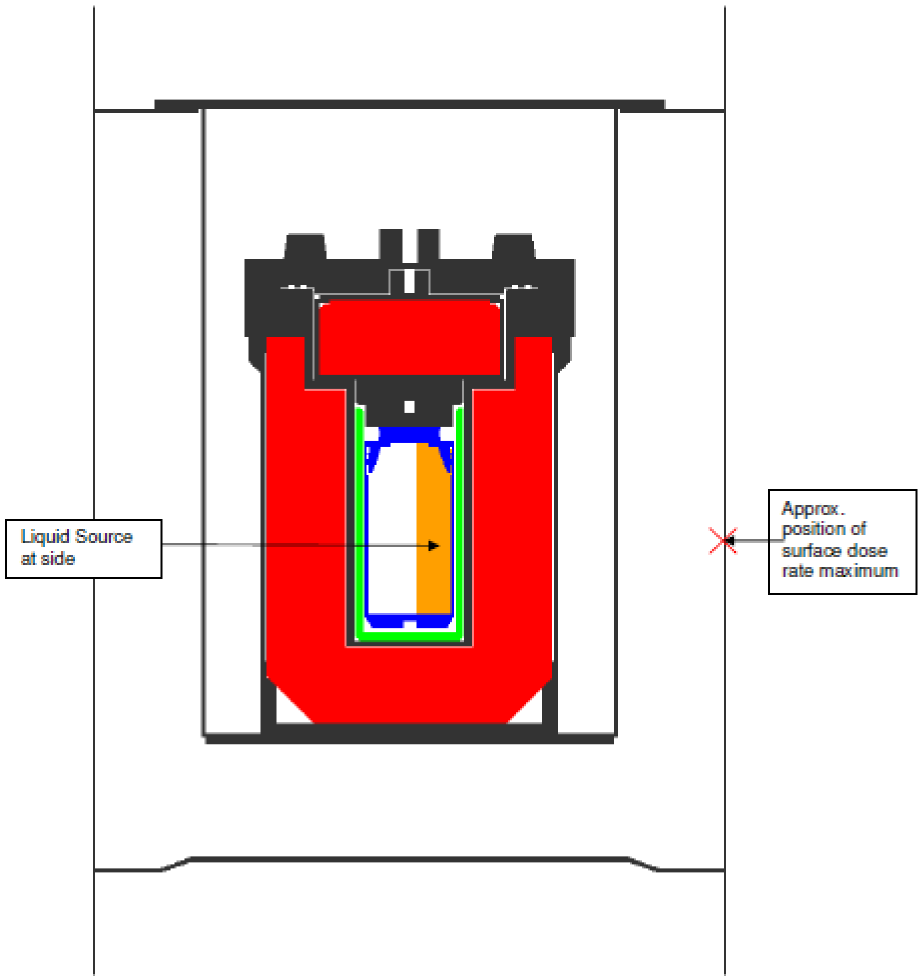


Figure 5-12 - Mo-99 Side Source Location for MCBEND Model for HS Package with stainless Steel Insert, Tungsten Liner and Split Containment Vessel Lid

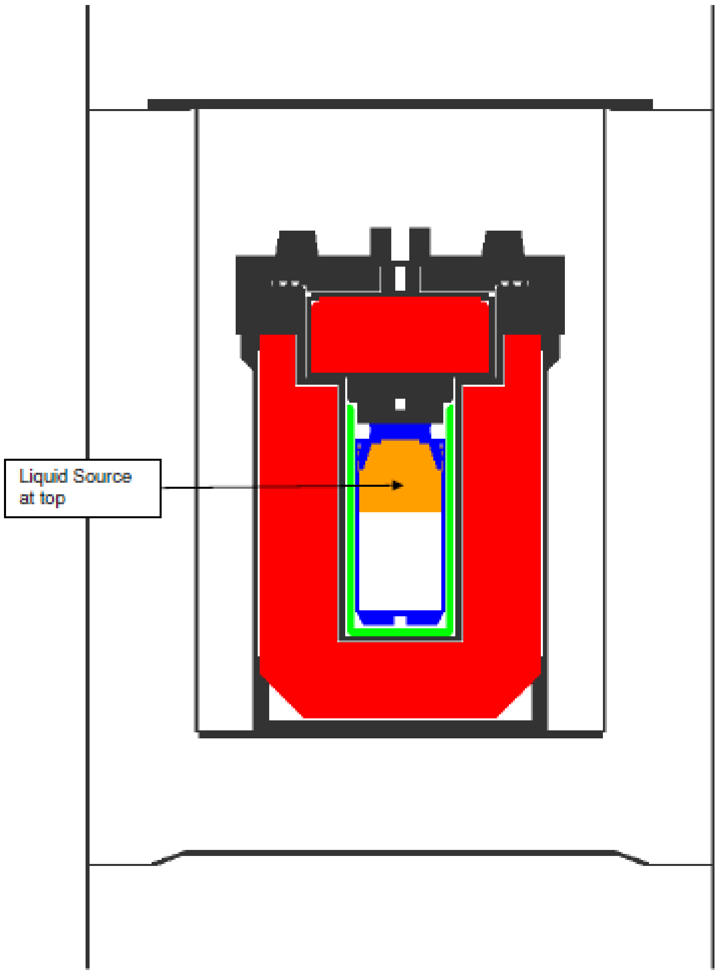
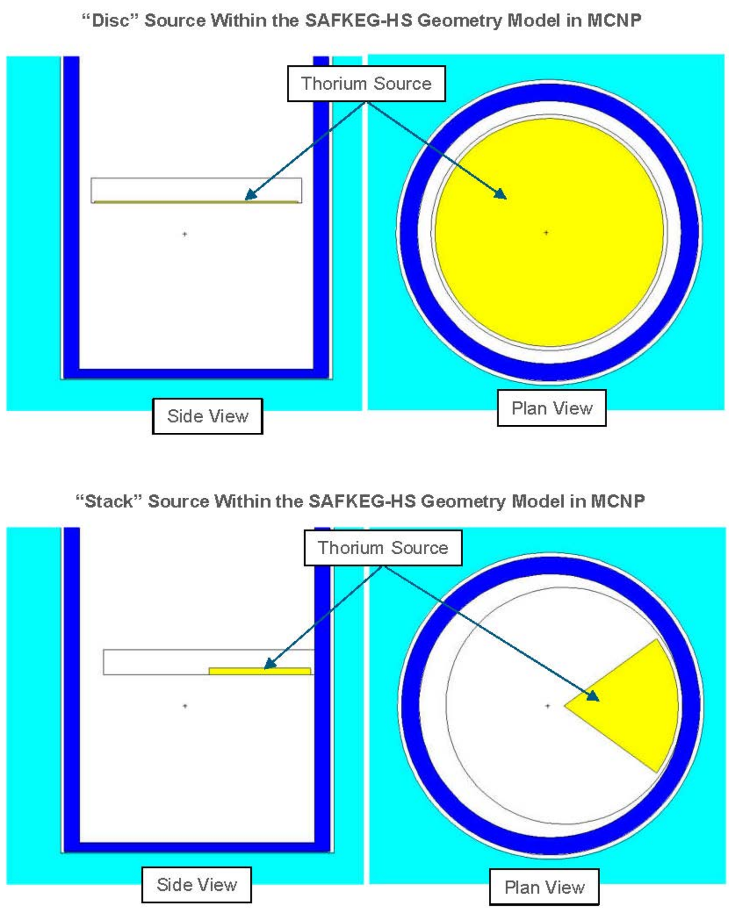


Figure 5-13 - Mo-99 Top Source Location for MCBEND Model for HS Package with stainless Steel Insert, Tungsten Liner and Split Containment Vessel Lid



The thorium target is the disc at approximately the axial mid height of the CV cavity (see report Atkins 5183326-HS-REP-001).

Figure 5-14 – Thorium target locations for MCNP Model for HS Package

For the tungsten inserts a Microshield model was built in order to determine the surface dose rate for all the nuclides to be carried. The Microshield calculations were carried out through the base of the package. In this model a point source was used with the shield dimensions taken from the nominal thicknesses, an illustration of the model is provided in Figure 5-15. The cork was modelled as an air gap whereas in reality the density of the cork is 250 kg/m^3. A different model was produced for each tungsten insert to determine the surface dose rates. The thicknesses used for each shield in the different insert models are provided in Table 5-5. The results from the MCBEND calculations showed that a point source located at the top corner of the insert provided the highest dose rate with the dose point taken at the side of the package, to account for this an adjustment factor was applied to the Microshield dose rates, as discussed in Croft report CTR 2013/09.

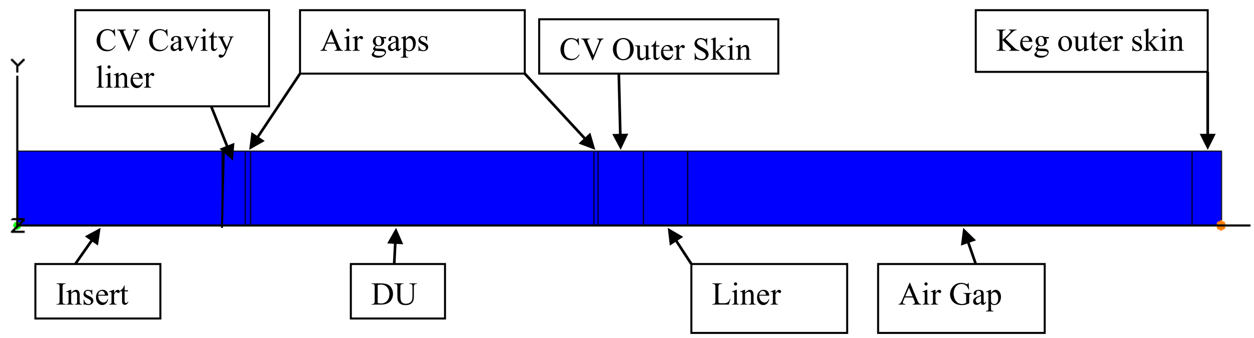


Figure 5-15 - Microshield model (3982 Insert)

Table 5-5 - Summary of Dimensions Used in Microshield Model

Feature	Thickness (cm)			Notes
	Insert 3982	Insert 3985	Insert 3987	
Insert	2.73	1.78	0.18	Tungsten was used for the insert material for 3982 and 3985. Iron was used as the insert material for 3987
CV cavity liner	0.31	0.31	0.31	Iron was used for this material in Microshield
Air gap	0.07	0.07	0.07	
CV shield	4.6	4.6	4.6	Depleted uranium
Air gap	0.06	0.06	0.06	
CV outer skin	0.6	0.6	0.6	Iron was used for this material in Microshield
3977 Cavity liner	0.6	0.6	0.6	Iron was used for this material in Microshield
Outer Cork liner	6.75	6.75	6.75	Cork was assumed to be air in the model
3977 outer skin	0.4	0.4	0.4	Iron was used for this material in Microshield

5.4.2 Material Properties

The material properties used for the MCBEND shielding evaluation are given in Table 5-6. The MCBEND model was used to determine the location of the point source that gave the highest dose rate and validate the Microshield model for the tungsten inserts and also determine the package surface dose for 200 Ci of I-131 and 1000Ci of Mo-99 in the stainless steel inserts.

The Microshield model was set up using the source locations in MCBEND and a runs were performed with 3000 Ci of Cs-137. The results obtained were compared to the MCBEND results. The Microshield results gave a higher dose rate than MCBEND. Therefore in order to match the results given in MCBEND the density of the uranium and tungsten were reduced to far below the actual density of the components.

For the Microshield model iron was used in place of stainless steel, iron has a lesser density than stainless steel. The densities used in the Microshield model are given in Table 5-7. The cork has been conservatively modelled as air in both MCBEND and Microshield.

Table 5-6 - Shielding Material Properties in MCBEND model

Material	Density (g/m³)	Elemental Composition	Mass Fraction
Stainless steel	8.027	Cr Mn Fe Ni	0.19 0.02 0.6975 0.0925
Depleted Uranium	18.65	U Mo	0.98 0.02
Tungsten	18	W Fe Ni	0.95 0.015 0.035
Stainless Steel 430 (magnetic cap)	7.75	C Cr Mn Si Fe	0.0012 0.17 0.01 0.01 0.8088

The material properties used for the MCNP shielding evaluation are given in Table 5-7

Table 5-7 - Shielding Material Properties in MCNP model

Material	Density (g/m³)	Elemental Composition and Mass Fraction
Stainless steel	8.0	See Atkins report 5183326-HS-REP-001
Depleted Uranium	18.0	
Tungsten	17.23	
Cork	0.23	
Air	0.0012	
Thorium metal	11.72	

5.5 Shielding Evaluation

5.5.1 Methods

The MCBEND model was used to determine the location of a point source that causes the highest dose rate on the surface of the package for the tungsten inserts. It was also used to calculate the maximum package surface dose for 1-131 and Mo-99 in the stainless steel inserts. The model also provided a reference case with which to validate the Microshield model. The Microshield model was then used to determine all the surface dose rates for the contents in the tungsten inserts.

MCBEND is a Monte Carlo radiation transport code. The calculations have been carried out using the latest version of MCBEND, version 10A_RU1. The code and data are maintained to a level of quality assurance consistent with the standards of the ANSWERS Software Service. This ensures that reference versions of the code, data libraries and test data are held, and that updating and archiving of the code and data are strictly controlled.

MCNP is a Monte Carlo radiation transport code. The calculations have been carried out using the latest version of MCNP.

Microshield is a photon/gamma shielding and dose assessment program. It was validated using the output from the MCBEND code for the 3000 Ci Cs-137 contents.

5.5.2 Input and Output Data

The input and output data for the MCBEND shielding calculations are reported in AMEC/SF6652/001, AMEC/CRM37327/TN_001 and AMEC/CRM42622/TN_001 (Section 5.5.6).

The input and output data for the MCNP shielding calculations are reported in Atkins 5183326-HS-REP-001 (Section 5.6.2).

The input and output data for the MicroShield shielding calculations is reported are CTR 2011/01 (Section 5.6.2). The Microshield model does contain several uncertainties which involved the application of several adjustment factors to the results. These uncertainties and the adjustment factors are discussed in CTR 2013/09 (Section 5.6.2).

5.5.3 Flux to Dose Rate Conversion

The dose rates from the MCBEND report AMEC/SF6652/001 are not used to calculate the dose rate for transport. The results are used to identify the location of the source that provides the highest dose and validate the Microshield result for 3000 Ci of Cs-137. Therefore the flux to dose rate conversion is not required. The ANSI/ANS-6.1.1 1977 dose conversion function was used in reports AMEC/CRM37327/TN_001 and AMEC/CRM42622/TN_001 to determine the surface dose for the stainless steel inserts.

The flux to dose rate conversion for MCNP is taken from ANSI/ANS 6.6.1-1977.

The flux to dose rate conversion for Microshield is taken from Table 2 in ICRP 51 (1987) as given in Table 5-8 below, the Anterior/Posterior values were taken as these gave the highest dose rate. ICRP 51 provides a lower surface dose rate than using the conversion factors in ANSI/ANS 6.6.1-1977. Therefore, a correction factor was applied to the results as detailed in CTR 2013/09.

Table 5-8 - Effective dose equivalent per unit fluence for photons

Photon Energy (MeV)	Conversion coefficient, 10^{-12} Sv cm^2				
	Anterior Posterior	Posterior Anterior	Lateral	Rotational	Isotropic
0.01	0.062	0	0.02	0.029	0.022
0.015	0.157	0.031	0.033	0.071	0.057
0.02	0.238	0.0868	0.0491	0.11	0.0912
0.03	0.329	0.161	0.0863	0.166	0.138
0.04	0.365	0.222	0.123	0.199	0.163
0.05	0.384	0.26	0.152	0.222	0.18
0.06	0.4	0.286	0.17	0.24	0.196
0.08	0.451	0.344	0.212	0.293	0.237
0.1	0.533	0.418	0.258	0.357	0.284
0.15	0.777	0.624	0.396	0.534	0.436
0.2	1.03	0.844	0.557	0.731	0.602
0.3	1.56	1.3	0.891	1.14	0.949
0.4	2.06	1.76	1.24	1.55	1.3
0.5	2.54	2.2	1.58	1.96	1.64
0.6	2.99	2.62	1.92	2.34	1.98
0.8	3.83	3.43	2.6	3.07	2.64
1	4.6	4.18	3.24	3.75	3.27
1.5	6.24	5.8	4.7	5.24	4.68
2	7.66	7.21	6.02	6.56	5.93
3	10.2	9.71	8.4	8.9	8.19
4	12.5	12	10.6	11	10.2
5	14.7	14.1	12.6	13	12.1
6	16.7	16.2	14.6	14.9	14
8	20.8	20.2	18.5	18.9	17.8
10	24.7	24.2	22.3	22.9	21.6

5.5.4 External Radiation Levels

5.5.4.1 Monte Carlo calculations

5.5.4.1.1 Monte Carlo calculations for reference case (Cs-137)

The results of the Monte Carlo shielding calculations are reported in AMEC/SF6652/001 (Section 5.5.2) for the reference case of 3kCi Cs-137 point source, with the source positioned all around the surface of the CV. The results from this report are summarised in Table 5-9 (surface radiation levels) and Table 5-10 (Radiation Levels at 1m from the Surface).

The calculations also provide the dose rate at the seal O-ring position – see Table 5-9.

Table 5-9 - Summary Table of External Surface Radiation Levels and Maximum O-ring Dose Rate - Monte Carlo calculations for reference case (Cs-137)

Source position in CV cavity or Insert	External Surface Radiation Levels (mSv/h)		
	No insert	HS-31x114-Tu Design No 3982	HS-12x95-Tu Design No 3985
	(least shielding)	(median shielding)	(most shielding)
Centre at the top of the cavity	9.75E+00	5.21E-01	1.34E-01
Centre at the bottom of the cavity	1.45E+01	8.17E-01	1.66E-01
Centre at side of the cavity	1.38E+01	7.49E-01	1.57E-01
Eccentered at the top of cavity	6.61E+02	3.06E+00	2.84E-01
CV O-ring	2.89E+03	4.01E+00	1.61E+00

The highest dose rate at the surface of the package for a point source in all positions within an insert is seen on the side surface when the point source is eccentered at the side of the CV cavity or insert.

Table 5-10 - Summary Table of External Radiation Levels at 1m from the Surface - Monte Carlo calculations for reference case (Cs-137)

Source position in CV cavity or Insert	External Radiation Levels at 1m from package surface (mSv/h)		
	No insert	HS-31x114-Tu Design No 3982	HS-12x95-Tu Design No 3985
	(least shielding)	(median shielding)	(most shielding)
Centre at the top of the cavity	2.52E-01	1.33E-02	3.46E-03
Centre at the bottom of the cavity	1.96E-01	1.27E-02	2.91E-03
Centre at side of the cavity	2.19E-01	1.55E-02	3.48E-03
Eccentered at the top of the cavity	1.25E+00	5.11E-02	5.83E-03

The highest dose rate at 1m from the surface of the package for a point source in all positions within the insert and empty containment vessel is seen to be with the source eccentered at the top of the cavity.

5.5.4.1.2 Monte Carlo calculations for I-131 in a Stainless Steel Insert

The results of the Monte Carlo shielding calculations are reported in AMEC/SF6652/001 (Section 5.5.2) for a 200 Ci (7.4 TBq) I-131 point source, with the source positioned all at several points inside the stainless steel insert. The results from this report are summarised in Table 5-11 (surface radiation levels for NCT) and Table 5-12 (surface radiation levels for HAC). The model assumed a PTFE liner of the insert however for the approved design a titanium liner is used. The thickness and geometry of the liner is unchanged from the PTFE to the titanium. The density of titanium is 4.506 g/cm^3 in comparison to a density of 2.2 g/cm^3 for PTFE therefore titanium will provide greater shielding than the PTFE in the model. I-131 is a beta emitter so there is the possibility that the bremsstrahlung radiation may increase with titanium as opposed to the PTFE. The fraction of incident beta energy converted into photons is:

$$f_\beta = 3.5 \times 10^{-4} Z E_m$$

Z = atomic number of the absorber

E_m = maximum energy of the beta particle, MeV

Therefore, the fraction of beta energy converted in photons is 2.34 x 10^{-3} for PTFE and 6.21 x 10^{-3} for titanium. So, the titanium generates 2.7 times more bremsstrahlung than PTFE. The calculated brem dose in the report AMEC/CRM37327/TN-001 was 0.4 microSv/hr for the PTFE if it is increased by 2.7 times this gives a dose of 1 microSv/hr with a titanium liner. As with the PTFE model we would ignore this contribution as it remains insignificant compared to the gamma ray source. Therefore, the dose on the surface of the package with the titanium liner would be at least the same if not less than the existing model predicts.

Table 5-11 - Summary Table of Maximum Surface Dose Rates for I-131 in the stainless steel Insert under Normal Conditions of Transport

Source Position in insert HS 55x128 No 3987 cavity	Maximum Surface Dose Rate (μSv/hr)
Bottom of cavity, centered	72
Side of cavity, halfway up cavity	49
Top of cavity, centered	173
Top corner of cavity	205.4

Table 5-12 - Maximum Package Surface Dose Rate for I-131 in a Steel insert under Hypothetical Accident Conditions

Source Position in insert HS 55x128 No 3987 cavity	Maximum Surface Dose Rate (μSv/hr)
Top Corner of Cavity	218

5.5.4.2 Monte Carlo calculations for Mo-99 in a Stainless Steel Insert

The results of the Monte Carlo shielding calculations are reported in AMEC/CRM37327/TN_001 (Section 5.5.2) for a 1000 Ci (37 TBq) Mo-99 liquid source with its significant daughters, contained in a natrium molybdenate solution.

The maximum source volume for the solution is 75 ml. The maximum specific activity of the solution that may be shipped is 60 Ci/ml. Therefore, calculations were carried out with a maximum source volume of 75 ml with a corresponding specific activity of 13.333 Ci/ml and minimum source volume with a corresponding maximum specific activity of 60 Ci/ml. The maximum surface dose rate was then calculated with the package upright, on its side and upside down on its lid. The results from this report are summarised in Table 5-13 (surface radiation levels for NCT) and Table 5- 14 (surface radiation levels for HAC).

Table 5-13 - Summary Table of Maximum Surface Dose Rates for Mo-99 in the stainless steel Insert under Normal Conditions of Transport

Source Volume Position in insert HS 50x128 No 4081 cavity	Location of dose rate measurement	16.6667 ml Source Maximum Surface Dose Rate (μSv/hr)	75 ml Source Maximum Surface Dose Rate (μSv/hr)
Bottom of insert cavity	Bottom surface	1143	905
Top of insert cavity	Side surface	819	880
	Top surface	581	346
Side of insert cavity	Side surface	1214	947
	Top surface	246	219

Table 5-14 - Maximum Package Surface Dose Rate for Mo-99 in a Steel insert under Hypothetical Accident Conditions	
Source Position in insert HS 50x128 No 4081 cavity	16.6667 ml Source Maximum Surface Maximum Surface Dose Rate (μSv/hr)
Side of insert cavity	1214

5.5.4.3 MCNP calculations for thorium target

The radioactive content of the thorium target arises from proton irradiation at 191 MeV at 165 uA to produce nominally 0.2 Ci Ac-225 at EOB [End Of Beam - removal from the proton beam] (BNL report C-A/BLIP/001, Section 5.6.2). The target is allowed to decay for at least 24hour after EOB to allow short halflife radionuclide to decay and reduce the radiation dose from the target. The radionuclide content present in the thorium target has been calculated by BNL (report C-A/BLIP/001, Section 5.6.2) with 498 radionuclides produced with activity greater than 1.E-09 of the total activity.

The results of the Monte Carlo shielding calculations for the thorium target are reported in Atkins report 5183326-HS-REP-001 (Section 5.6.2). The calculations determine the package external dose rates and dose rates for the O-rings within the CV for all the 498 radionuclides and activities given in the BNL report referenced in Table 5-15.

Table 5-15 - Summary Table of package external dose rates from MCNP calculations for CT-6 Thorium Target
See Atkins report 5183326-HS-REP-001 (Section 5.6.2)

Note that the dose rate calculations (see Atkins document 5183326, SARP Section 5.6.2) were carried out for the contents carried in the CV without an insert. As the packing is similar with the required insert (HS-55x113-SS), the dose rates with the insert would be slightly lower than without the insert.

Under NCT and HAC, it is assumed that the contents (thoriuim target) are contained in the CV cavity by the form of the thorium metal and by the seal system provided by the CV and sealed split CV lid with the target being restrained to sit in the axial centre of the CV cavity.

The dose rate at the base of the package, as given in Section 5.2.1, Table 5-1, for the thorium target (thorium metal disc) has been calculated (see Atkins report 5183326-HS-REP-001, Section 5.6.2) for the radioactive content of the thorium target given in BNL report C-A/BLIP/001 (Section 5.6.2).

The calculated dose rates for each of the 498 radionuclides are given in Table A-1 in BNL report C-A/BLIP/001 (Section 5.6.2). On sorting this data on Total dose rate for each radionuclide, it is seen that there are only 17 that individually contribute >1% to the total dose rate and 56 that contribute towards 99% of the total dose rate. It is noted that the activity of these radionuclides is reducing by radioactive decay as shown in Figure 5-16 which is for the 17 dominant radionuclides + Ac-225. The data in Figure 5-16 does not include any contribution from build up of daughters but it is indicative of the reduction of the activity of the contents also of the reduction of the package external dose rates.

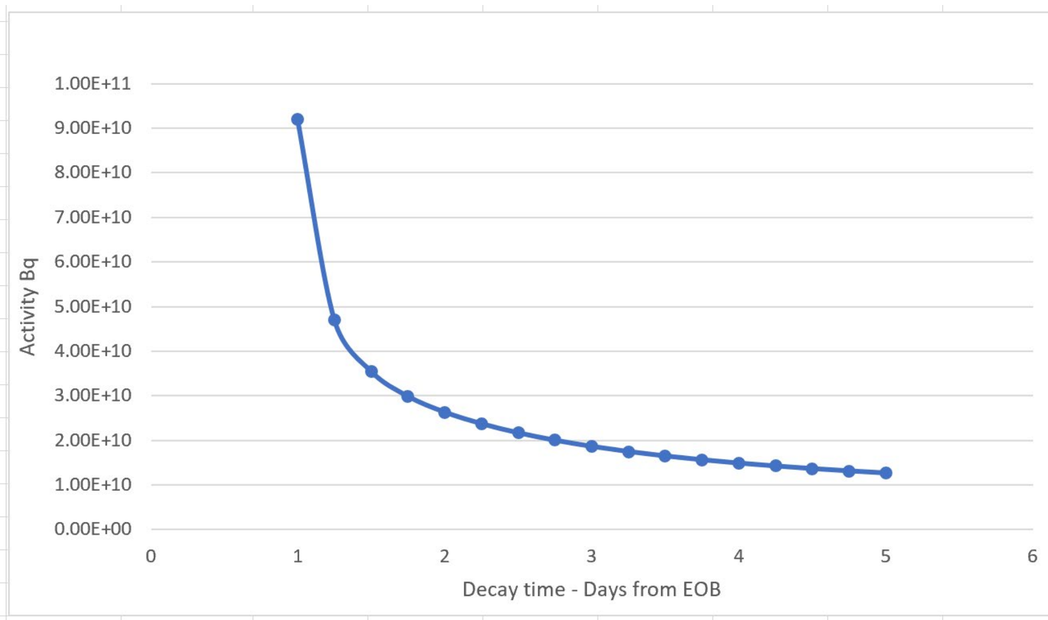


Figure 5-16 – Decay of dominant radionuclides

5.5.4.4 MicroShield calculations

The results of the MicroShield shielding calculations (reported in CTR 2011/01 (Section 5.5.2), considering all of the nuclides to be represented as a point source positioned at the centre of the bottom of each insert, are given in Table 5-16.

Under NCT and HAC, it is assumed that both liquids and gaseous contents are contained in sealed product containers within the applicable insert and that the liquids and gaseous contents do not leak from the insert. Therefore the shielding calculations for liquid and gaseous contents are represented by the calculations for a point source positioned at the centre of the bottom of each insert. These results had further adjustments made due to any uncertainties in the shielding calculations and the results were altered as indicated in CTR 2013/09 (Section 5.6.2). The shielding limits were taken from this document and are those given in Table 5-16.

The activities given in Table 5-16 are used to determine the package limit, taking into account mass limit, heat limit, gas limit and shielding limit – see report PCS 038 (see Section 1.3.4).

Table 5-16 - Summary Table of Nuclide Activities required to give a surface dose rate of 8 mSv/h - MicroShield calculations

Nuclide	Insert	
	HS-12x95 -Tu Design #3982	HS-31x114-Tu Design #3985
Ac-225	2.51E+12	1.09E+12
Ac-227	7.24E+11	3.26E+11
Ac-228	4.28E+11	1.86E+11
Am-241	3.58E+12	1.58E+12
As-77	9.43E+19	1.14E+19
Au-198	6.99E+14	2.43E+14
Ba-131	1.88E+14	6.12E+13
C-14	6.92E+27	6.13E+27
Co-60	2.38E+11	9.37E+10
Cs-131	8.39E+35	7.43E+35
Cs-134	7.05E+12	2.63E+12
Cs-137	1.58E+15	3.16E+14
Cu-67	6.50E+25	2.84E+24
Hg-203	3.57E+13	5.32E+34
Ho-166	2.04E+12	9.20E+11
I-125	4.49E+35	3.98E+35
I-129	3.31E+26	2.93E+26
I-131	4.11E+15	9.94E+14
In-111	1.45E+28	1.29E+28
Ir-192	2.71E+15	7.19E+14
Ir-194	3.87E+13	1.47E+13

Table 5-16 - Summary Table of Nuclide Activities required to give a surface dose rate of 8 mSv/h - MicroShield calculations		
Nuclide	Insert	
	HS-12x95 -Tu Design #3982	HS-31x114-Tu Design #3985
Kr-79	6.00E+13	2.30E+13
Lu-177	1.56E+24	1.38E+24
Mo-99	5.27E+13	1.91E+13
Na-24	2.63E+10	1.28E+10
Np-237	3.58E+12	1.58E+12
P-32	5.58E+12	2.49E+12
P-33	5.10E+37	3.61E+37
Pb-203	1.18E+17	2.45E+16
Pb-210	8.04E+12	3.31E+12
Pd-109	2.96E+14	9.61E+13
Pu-238	1.16E+20	5.30E+19
Pu-239	2.33E+25	6.04E+24
Pu-240	1.15E+25	5.62E+24
Pu-241	7.21E+20	1.90E+20
Ra-223	1.02E+13	4.14E+12
Ra-224	8.86E+10	4.37E+10
Ra-226	1.02E+11	4.80E+10
Re-186	1.56E+14	5.31E+13
Re-188	1.22E+12	5.67E+11
Rh-105	1.05E+31	1.17E+29
Se-75	8.89E+18	7.87E+18
Sm-153	6.12E+11	1.91E+15
Sr-89	1.22E+13	5.17E+12
Sr-90	1.73E+12	8.30E+11
Tb-161	1.61E+13	7.39E+12
Th-227	1.01E+13	4.17E+12
Th-228	6.79E+10	3.35E+10
Tl-201	1.59E+22	1.41E+22
U-235	9.17E+17	2.38E+17
W-187	2.24E+13	8.56E+12
W-188	1.23E+12	5.68E+11
Xe-133	2.25E+33	1.99E+33
Y-90	1.73E+12	8.30E+11
Yb-169	1.88E+19	1.66E+19
Yb-175	6.04E+23	6.09E+22

5.6 Appendix

5.6.1 References

[3.1] Title 10, Code of Federal Regulations, Part 71, Office of the Federal Register, Washington D.C.

[3.2] ICRP Publication 74, "Conversion Coefficients for use in Radiological Protection against External Radiation", Annals of the ICRP 26 3/4, 1996

[3.3] ICRP Publication 51, "Data for Use in Protection against External Radiation", Annals of the ICRP, 1984

5.6.2 Supporting Documents

Document Reference	Title
CTR 2011/01	SAFKEG HS 3977A: Package Activity Limits Based on Shielding
CTR 2013/09	Uncertainties Associated with the Proposed Shielding Calculation Method for the SAFKEG-HS 3977A Package
AMEC/SF6652/001	Monte Carlo Modelling of Safkeg HS Container
AMEC/CRM37327/TN_001	HS Container Shielding Assessment with I-131
AMEC/CRM42622/TN_001	HS Container Shielding Assessment with Mo-99
Atkins report: 5183326-HS-REP-001	Shielding Assessment of the 3977A SAFKEG Transport Package Type B(U) with Thorium Target
LANL Report 2018-01-05	Radionuclide content present in a typical thorium target activated to produce 0.2 Ci Ac-225 at EOB.