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CRITICALITY AND DOSE UPTAKE BENEFITS FROM NEW PACKAGE DESIGN

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ABSTRACT

Packages used by Sellafield Ltd for the on-site and off-site transport of cans of fissile materials have been in service for a number of years. These were designed against the relevant regulations and requirements at the time for the anticipated materials to be transported, using extant technology.

An increased range of Pu and U compounds need to be transported including those from reprocessing operations and residues from experimental and decommissioning operations. Some of these will be of relatively high burnup compared to historic arisings while others will have been treated into new wasteforms to prepare them for long term storage or disposal to a geological disposal facility.

There are obvious financial and operational benefits in higher package payloads for both the facility and transport phases of operation. There are, however, a number of challenges to overcome to achieve this for the wide range of materials in question. A new transport package has been designed by International Nuclear Services (INS) to address these.

From a criticality perspective the primary enhancement of the new package is the inclusion of a high-integrity multiple water barrier. This gives the potential for less restrictive criticality limits on package payload, with a resultant reduction in the overall number of package movements. Package mass limits are also dependent on a number of other factors relevant to meeting IAEA Transport Regulations as well as plant safety requirements. Higher mass limits, coupled with higher burnup materials, require the package body to have an improved shielding capability to keep dose rates within acceptable levels and to reduce neutron interaction within arrays of packages. Similarly consideration has been given to how the package is loaded and unloaded to reduce the associated dose uptake.

The paper will present a more detailed account of the features of the package design relevant to criticality safety, shielding and dose assessment and give examples of the improvements that have been made.

INTRODUCTION

A new Type B package, the INS3578 package, has been designed by International Nuclear Services (INS) for the transport of unirradiated fissile material. Where packages have previously been designed for specific applications the INS3578 package has been designed for acceptable use by a wide customer base.

The remit of the package design includes the following:

1. The ability to carry a high payload within a small volume.
2. To be easy to handle, load and unload.
3. To be able to transport a wide variation in fissile materials and containers with corresponding high safety case boundaries. The package is designed to be able to transport unirradiated fuel, material from reprocessing operations and residues from experimental and decommissioning activities in the following forms.
    a. Uranium, plutonium and mixed Pu+U materials.
    b. Metal, pellets, powders, ceramics and alloys with a corresponding wide range of densities.
    c. The full range of uranium and mixed oxide enrichments.
    d. A wide variation in Pu isotopic composition. This ranges from material derived from low burnup material (the limiting case for criticality) to high burnup material (limiting for shielding), some of which is also long-aged with a correspondingly high Am-241 content.

There are obvious financial and operational benefits in having higher package payloads and higher numbers of packages in a consignment for both the facility and transport phases of operation:

1. Fewer costly transport operations will be required and/or a smaller fleet of packages will be required with reduced capital and maintenance costs.
2. If transport limits are the determining factor on the mass of fissile material within containers, this may enable the overall number of containers to be reduced. This in turn may:
    a. Reduce the operational lifetime of the facility producing the packages.
    b. Reduce the size of any storage facilities required either at the donor and/or receipt facility.
    c. Reduce the number of container handling operations within the donor and receipt facilities.

Beyond the requirements of the IAEA Transport Regulations, the package design must also take into account the needs of operational facilities:

1. The operational dose uptake, in particular that associated with loading and unloading operations given the potentially increased payloads.
2. Where practicable to avoid the necessity to construct new facilities or for substantial modifications to existing facilities in order to accommodate a new package.

To achieve this, the package design team within INS has worked closely with potential customers, including Sellafield Limited.

The desire for high mass limits for such a wide range of fissile contents, within the constraints of the package remit, places great importance on the package design to ensure that criticality, dose rate and dose uptake requirements can be met. The features of the package design that enable this remit to be met are discussed below, with particular focus given to their relevance to criticality safety, shielding and dose assessment.

PACKAGE DESCRIPTION

The design of the INS3578 package can be seen in Figure 1. A more detailed description of the engineered features of the package, including the high integrity multiple water barrier, can be found in Reference 1. A brief outline is given here of the features relevant to the criticality and shielding assessments.

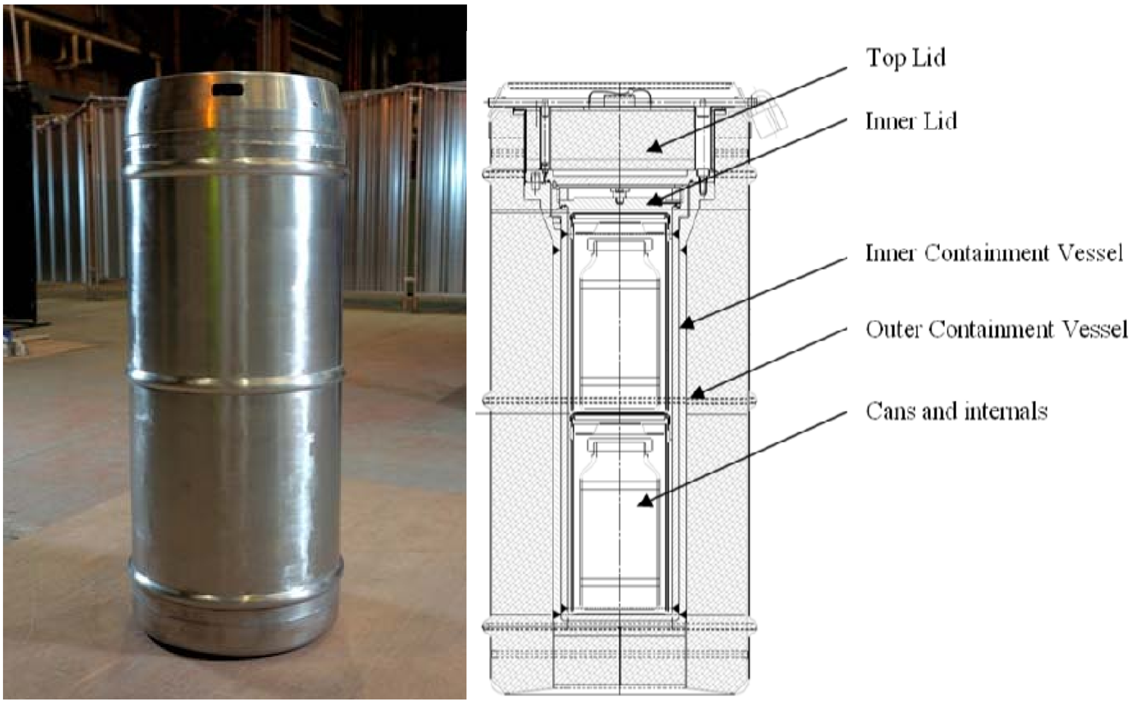

Figure 1. INS3578 Package

The package is cylindrical with an outer diameter of around 400mm and a height of 1000mm (approximately 16 and 39 inches respectively). The inner steel containment vessel (CV) body has an internal diameter of 172mm and height of 663mm, giving it a capacity of 15.5 litres. While it is anticipated that initially the inner CV will mainly be used to transport two containers, each of approximately 3 litres capacity, the option exists to transport other containers of varying sizes either singly or as multiples with the use of spacers or liners.

The inner CV sits in a steel outer CV body. The lidding arrangement for these two bodies provides a high integrity multiple water barrier. The outer CV body is surrounded by neutron shielding material, which also provides impact protection, and encased in the steel outer shell of the package. As the package is being designed with the flexibility to handle high burnup material it incorporates plates running through the neutron shielding material to allow heat to be conducted away from the CV.

CRITICALITY SAFETY ANALYSES

Modelling Assumptions

Criticality safety calculations were performed using MONK9A and the JEF2.2 Nuclear Data Library. Schematic examples of the models used to assess the INS3578 package are shown in Figure 2. Various aspects of the package were simplified in a conservative fashion with the model used being largely reduced to a set of concentric cylinders. This avoids the need to make detailed justification about how certain package features may be affected by accident conditions, where these have little effect to the criticality safety assessment. Some of the major modelling assumptions are outlined below.

The fissile material was modelled as a single accumulation within the CV body, in the absence of the cans in which it would normally be contained, i.e. no credit was taken for these either in restricting the fissile geometry or in any poisoning or diluent effect their presence may have. There is no particular penalty in this approach as the derived safe mass limits are considerably higher than currently intended to carry. It also means the licence application is relatively insensitive to the design of can used.

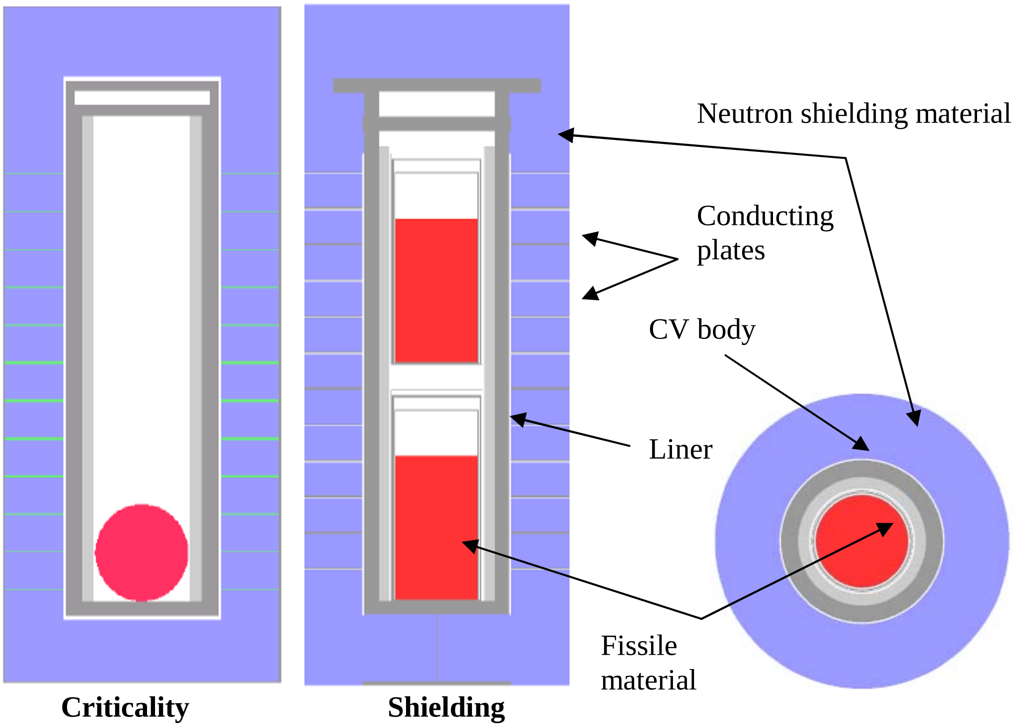

Figure 2. Cross-sections through example criticality and shielding models

The conducting plates were modelled explicitly. These have limited thickness (few mm) and were shown not to significantly increase neutron interaction between packages. Sensitivity analysis was performed to bound manufacturing tolerances in the neutron shielding material around the plates, around the CV body and outer shell of the package.

For package arrays the packages were modelled in an infinite three-dimensional hexagonal close-packed array. Sensitivity analysis was performed to determine the optimum orientation of packages within the array and the placement of the fissile material within the individual packages.

The package is designed with a high integrity multiple water barrier (MWB). With the MWB in place bulk moderator ingress into the inner CV container can be assumed not to occur under either normal or accident conditions of transport. Survey calculations were performed for a range of moderator contents as follows:

1. For moderators that may be present in the CV body with a MWB in place:
    a. The intrinsic moderator content of the fissile material.
    b. Packaging materials (e.g. polythene bags) that may be present in some containers.
    c. Residual moderating material that may be present within the inner CV body.
2. Assuming bulk water ingress into a single package to give an indication of the effect on package limits if the MWB was not utilised.

Normal Conditions

Under normal conditions of transport there is very little interaction between the contents of packages, even when assuming generous manufacturing tolerances in the neutron shielding material. This should not come as a surprise. The fissile material between adjacent packages is separated by around 170mm (> 6 inches) of neutron shielding encased in several cm steel – a very effective neutron flux trap.

This makes it relatively easy to confirm that package limits derived for normal conditions are sensible by simple comparison with single unit, fully water reflected handbook data (Figure 3).

1. Actual safe limits for the INS3578 package (Figure 4) are higher than the handbook data as the combination of geometry and/or reflection that the fissile material can attain within the CV body is less onerous than a fully water reflected sphere.
2. For PuO_2 powder systems, which typically have a density below $4g(PuO_2)cm^{-3}$, the mass that can be transported is dictated by can volumes, rather than criticality safety limits. At higher densities criticality safety limits on individual cans may be dictated by operational plant limits, rather than transport limits, as these would normally include sufficient safety margin to be able to place at least 2 cans in close proximity.

Accident conditions

The two key factors to demonstrate under accident conditions are:

1. The continued integrity of the MWB in preventing the ingress of bulk moderator into the fissile material.
2. That the degree of damage sustained by the package body does not lead to significant increased neutron interaction between packages, either from deformation of the materials or degradation of the neutron shielding material.

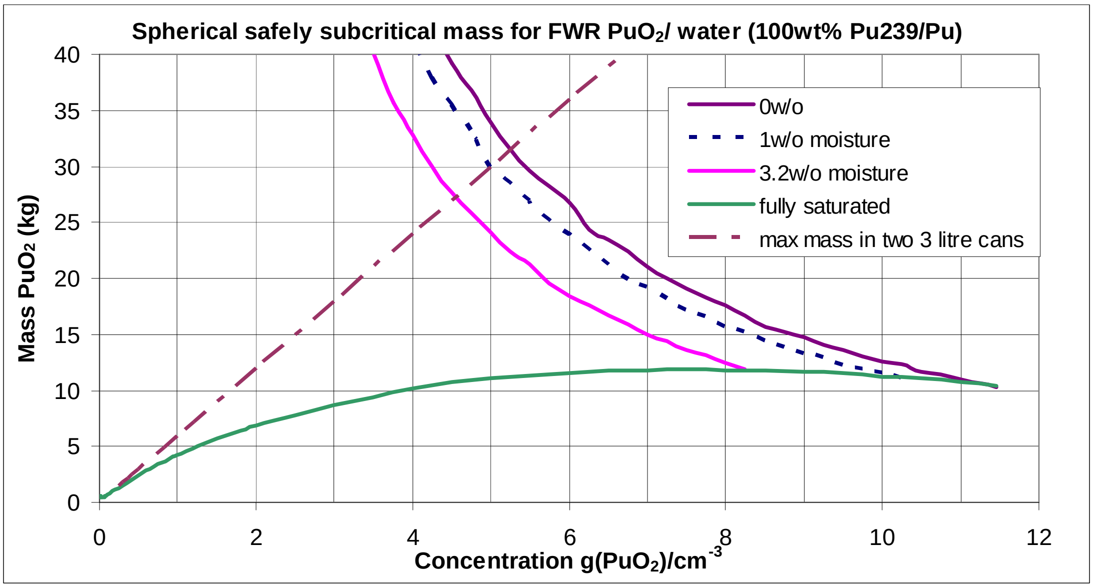

Figure 3. Indicative Effect on Package Mass Limits of Moderator Content

A combination of physical testing, theoretical analysis and sensitivity analysis within the criticality assessment has been performed. As would be expected these show that removal or degradation of the neutron shielding material (particularly the hydrogen content) from the model affects the degree of interaction. However, the predicted damage is such that package limits are not significantly reduced from those derived under normal conditions, even assuming an infinite array of packages.

Given the low degree of neutron interaction between packages, the single package accident condition assuming moderator ingress into all void spaces within the package, including into the fissile material, would normally produce the limiting case. The effect of this on package limits can be large. However, given the MWB in the INS3578 package this degree of water ingress need not be considered.

Figure 3 shows the effect on safely subcritical mass of limited moisture content for PuO_2. For limited moderation systems the lowest package limits will typically occur at higher densities. Here the MWB makes little difference as the fully saturated case corresponds to a low moisture content (zero moisture content at full theoretical density). The safely subcritical mass for the fixed, limited moisture systems increases sharply as density reduces. It becomes readily apparent that for lower density materials, such as powders, the safely subcritical mass becomes considerably larger than could physically be transported in a single package with a MWB. Conversely, the safely subcritical mass for the fully saturated system reduces as density reduces as the corresponding weight percent moisture content increases. Similar trends occur for other fissile materials.

Summary of Results

Results indicate that package limits will be higher than existing packages, without the need to introduce restrictions, for example, on the number of packages in a consignment or on isotopic composition. Indeed Figure 4 indicates that, other than for high density Pu and PuO_2, anticipated payloads will not be constrained by criticalityrelated package mass limits. Thus, from a criticality perspective, the design of the package meets the intent to have a single package with high fissile mass limits for a wide range of materials.

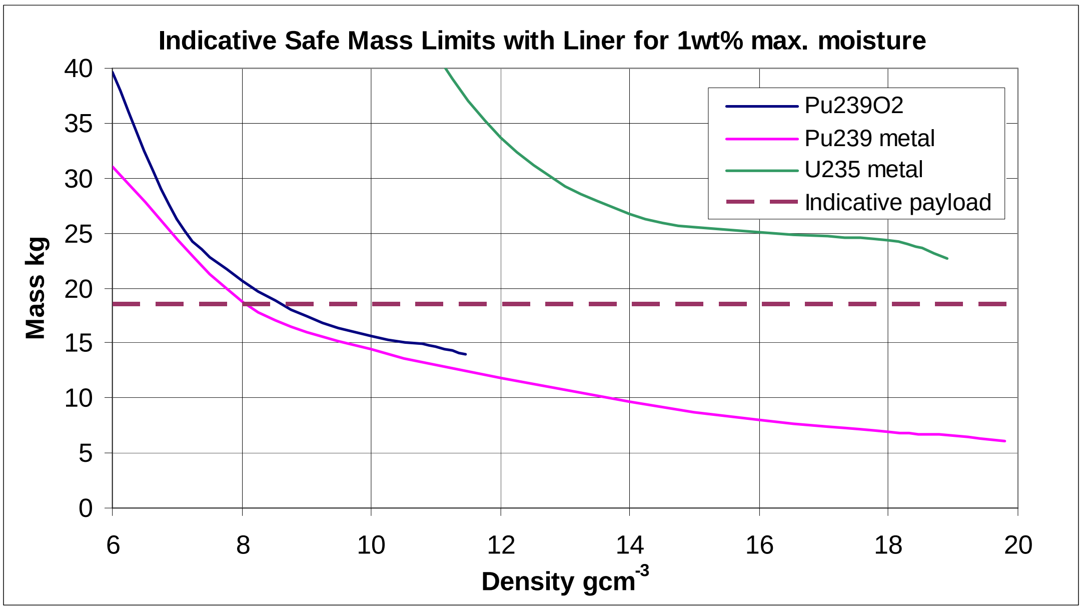

Figure 4. Indicative Package Limits

SHIELDING AND DOSE ANALYSES

Experience on operational plant at Sellafield has been that dose rates around existing transport packages meet transport regulations. However, depending on the particular source material being moved and the number of movements required these can be associated with significant operator dose uptake. To satisfy the combination of a desire for higher mass limits and increases in the age and burn-up histories of the potential payload (i.e. higher source terms) requires improved shielding performance compared to existing packages. This presents a design challenge as the increased radiation source from higher age and burn-up of material goes hand in hand with higher heat generation. The plates incorporated into the package design allow heat to be conducted away from the CV but are sufficiently thin not to present a significant weak path through the neutron shielding.

The philosophy for the INS3578 is to provide sufficient shielding for the intended package content that:

1. The dose rate limits in the IAEA Transport Regulations are met, i.e.
    a. A maximum dose rate of 2mSvh^{-1} on the surface of the Transport Package.
    b. A maximum dose rate of 100μSvh^{-1} at 2m (6.5ft) from the edges of the vehicle transporting the Transport Package. This is usually taken to be 2m from the surface of the Transport Package.
2. Doses to personnel during transport are acceptable.
3. Operational doses in on-site facilities from the handling of the package are shown to be acceptably low and to be As Low As Reasonably Practicable (ALARP – the UK equivalent to ALARA). This includes:
    a. Dose rates local to storage areas for loaded packages.
    b. Doses associated with loading, unloading and handling packages.

The materials being carried, as described above, are a wide range of Pu and U bearing radioactive sources. The main radiological dose rate issues are associated with both neutrons and gammas. The choice of shielding materials is important as the lighter the final package, the better the handling abilities.

1. Hydrogenous shielding materials are provided in the main package body to attenuate fast neutrons. The quantities of shielding are such that thermal neutron sources are not an issue.
2. Gamma shielding is primarily provided by the steel CV and outer skin of the Package.
3. Am-241, generated from decay of Pu-241, emits a low energy gamma ray. During transport this is typically not of concern due to the bulk shielding of the transport package. However, this may form a significant dose component during lidding and delidding operations of the package and during loading and unloading of the fissile material cans from the CV, where the shielding provided by the lid is removed. The design of the package is such that the inner lid is partially recessed rather than being directly on top of the package. This means that with the lid removed the shielding inherent in the top of the package body will ameliorate dose rates in the vicinity around the top of the package.

Package

Source terms were generated for a range of fissile materials anticipated to be transported in the package. These were calculated using a combination of the FISPIN 10 and ORIGEN (from SCALE version 5) source generation codes.

The shielding analyses were performed using the codes MCBEND15 and Attila. Particular attention was given to the regions around the conducting plates to ensure that any shielding weaknesses were identified. Figure 2 shows a schematic of one of the models used, holding two cans of fissile material.

The shielding assessment for the package initially assumed a payload of two cans, both containing the maximum mass intended to be transported, coupled with the worst case source material (PuO_2 derived from high burnup material). If this could be shown to be acceptable it would provide a bounding analysis for other materials currently identified. The source assumptions were subsequently refined to take into account results of thermal analysis and radionuclide data (A2 values) for a variety of sources requiring transfer, including Pu and U rich residues. It was shown that the combination of maximising both fissile mass and using a worst case source term would not take place in practice. Thus either:

1. For the worst case source material a lower maximum fissile mass would be permissible within the inner CV body. This could either be split between two cans or potentially contained in a single can.
2. The maximum fissile mass would only be carried for less restrictive source material.

Transportation

INS3578 packages will be transported in stillages, four of which will fit into an associated transport container. There are currently two stillage options, one capable of holding six packages in a 3x2 array and the second capable of holding nine packages in a 3x3 array. Thus the Transport Container has a capacity of 24 or 36 packages.

A sensitivity study has been performed to consider the effect of shielding in managing the dose incurred by personnel when a transport container is being transported on a road vehicle. While dose rates in the cab of a vehicle are relatively high in comparison with on-site criteria, the resultant dose uptake will be low due to the frequency and time of the journey.

Results

The package shielding keeps both neutron and gamma dose rates well within the required targets (Table 1), including the regions around the conducting plates. Secondary gamma dose rates were shown to be insignificant.

Table 1. Dose rates around the INS3578

			Dose rates μSvh^{-1}				
			INS3578				**IAEA Criteria**
			Neutron	**Gamma**	**Total**		**Total**
Side	**Contact**		217	84	301		2000
	1m		11	4.4	15.4		N/A
	2m		3.3	1.4	4.7		100
Below	**Contact**		194	81	275		2000
	1m		3.8	1.8	5.6		N/A
	2m		1.0	0.5	1.6		100
Above	**Contact**		34.6	9.5	44.1		2000
	1m		1.1	0.4	1.5		N/A
	2m		0.4	0.1	0.5		100

Gamma dose rate contours (calculated using Attila) are shown in Figure 5 to demonstrate the effect of removing the package lid. It can be seen that, as would be expected, dose rates clearly increase above the package. However, the recessed lid design limits dose rates to operators standing to the sides of the package.

A comparison of predicted dose rates was performed between the INS3578 package and a similar size package currently used on the Sellafield site. For the same source material:

1. Dose rates at contact and 2m from the side of the package on the INS3578 are ~3-4 times lower for the INS3578.
2. Dose rates above the package, relevant for loading and unloading operations are ~9 times lower for the INS3578.
3. A noticeable reduction of gamma radiation illustrates the indirect impact of a double containment boundary.
4. The lower dose rates around the INS3578 package will result in reduced operational doses.

The shielding on individual Transport Packages helps restrict dose rates around the transport container/ vehicle. For the first anticipated shipment dose rates for a full load are less than 100μSvh^{-1} on the container surface, which is well within the UK transport criterion. Likewise the dose rate at 2 metres is less than 30μSvh^{-1}. This allows the flexibility to transport large numbers of packages in a container without placing significant additional shielding requirements on the vehicle and stillages.

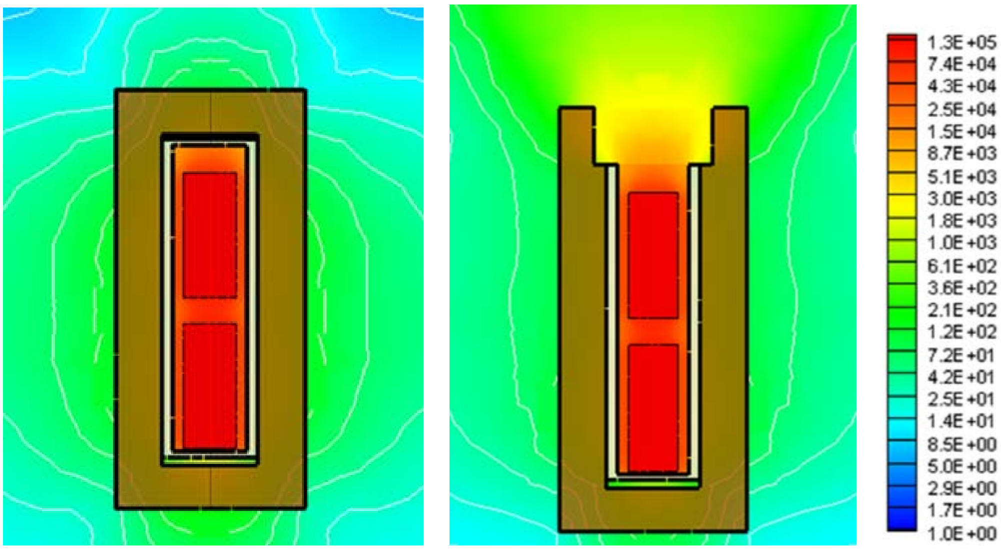

Figure 5. Dose Rate Contours around Package

CONCLUSIONS

The INS3578 package has been designed to be able to transport a wide variation in fissile materials and containers with corresponding high safety case boundaries. From a shielding and criticality perspective the key features of the package which contribute to this are:

1. Increased shielding performance of the package body leading to lower surrounding dose rates and reduced neutron interaction between packages.
2. The inclusion of a high integrity multiple water barrier. This means that bulk moderator ingress into the fissile material can be assumed not to occur during either normal or accident conditions of transport. This in turn considerable simplifies the criticality assessment.

The flexibility this permits will lead to considerable financial and operational benefits.

REFERENCES

1. Impact of a double containment boundary requirement on small type B(U) package safety case. B Acker. PATRAM 2013.