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6 m^3 Concrete Box Studies

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ABSTRACT

Magnox Limited is intending to use 6 m^3 Concrete Boxes (CBs) for the packaging and disposal of Intermediate Level radioactive Waste (ILW) at a number of sites. Current plans include their use at Berkeley, Chapelcross, Harwell, Hinkley Point A and Winfrith. The 6 m^3 CB is constructed of reinforced concrete and has a cast in-situ reinforced concrete lid, placed after the waste has been loaded and encapsulated with grout. The 6 m^3 CB must exhibit long-term durability for surface storage of ILW, meet transport requirements as IP-2 transport packages and satisfy Radioactive Waste Management Limited (RWM) requirements for impact accidents in the Geological Disposal Facility (GDF). Magnox plans to entomb some wastes, but the impact performance of 6 m^3 CBs with entombed wastes is yet to be substantiated. A number of entombment concepts have been considered and development of waste packaging proposals at Magnox led to the adoption of waste immobilisation in "Sacrificial Bins". This Sacrificial Bin concept was then developed and is the preferred option for the majority of Magnox wastes in 6 m^3 CBs. This paper will describe the finite element analysis work carried out to evaluate the Sacrificial Bin packaging concept for the transport normal condition scenario (0.3 m base down drop) and GDF impact accident scenarios.

INTRODUCTION

Magnox Ltd. (Magnox) is intending to use 6 m^3 Concrete Boxes (CBs) for the packaging and disposal of Intermediate Level radioactive Waste (ILW) at a number of sites. Current plans include their use at Berkeley, Chapelcross, Harwell, Hinkley Point A and Winfrith.

The 6 m^3 CB is to be approved as an Industrial Package Type 2 (Type IP-2). The 6 m^3 CB is constructed of reinforced concrete and has a cast in-situ reinforced concrete lid, placed after the waste has been loaded. Two variants of the 6 m^3 CB have been designed:

- A normal density (ND) box which uses CEM 1 Portland Cement and is designed to carry lower dose rate waste;
- A high density (HD) box which uses CEM 1 Portland Cement incorporating a magnetite aggregate, thus providing satisfactory shielding for higher dose rate wastes.

Both box types must exhibit long-term durability for surface storage of ILW, meet transport requirements as IP-2 transport packages and satisfy RWM requirements for impact accidents in the Geological Disposal Facility (GDF). Acceptability for the waste package lifecycle will be gained through the RWM Letter of Compliance (LoC) process that assesses the proposals for the various lifecycles of the waste package.

A previous variant of the 6 m^3 CB that was used to package wastes at Windscale Advanced Gas-cooled Reactor (WAGR) met RWM requirements and a Final Stage LoC was granted for intimately immobilised wastes. Magnox currently plans to intimately immobilise wastes, but also entomb some wastes. The impact performance of 6 m^3 CBs with entombed wastes is yet to be substantiated.

An optioneering session was held to review the options for entombment of Steam Generating Heavy Water Reactor (SGHWR) wastes at Winfrith Site and further development of waste packaging proposals at Magnox led to the adoption of waste immobilisation in “Sacrificial Bins”. This Sacrificial Bin concept was then developed and is the preferred option for Magnox wastes from Berkeley and Winfrith in 6 m^3 CBs.

This paper discusses the work carried out to evaluate the impact performance of the Magnox 6 m^3 CB with Sacrificial Bin internal configuration in the Normal Conditions of Transport 0.3 m drop impact and the GDF impact accident drop scenarios.

6 m^3 CONCRETE BOX WITH INTERNAL CONFIGURATION OF SACRIFICIAL BIN

6 m^3 Concrete Box

As shown in Figure 1, the Magnox 6 m^3 CB consists of three main components: a reinforced concrete body and a cast in-situ reinforced concrete lid, the casing assemblies and the twistlock assemblies. The 6 m^3 CB has external dimensions of 2438 mm x 2210 mm on plan and 2200 mm tall. The body has a minimum concrete wall thickness of 240 mm and an internal volume of 5.47 m^3. The walls, base and lid are reinforced on both interior and exterior faces with steel reinforcing bars. Steel casing assemblies (or collars) are provided to cover the top and bottom quarters of the 6 m^3 CB walls, preventing damage to the edges and corners during handling operations. The C40/50 concrete of the body and lid is cast against the collars, while studs welded to the collars provide a connection between the collars and the concrete. Twistlock pockets are provided in the eight corners of the 6 m^3 CB for lifting and tie-down during transport. The top and bottom twistlock pockets in each corner of the 6 m^3 CB are aligned vertically and connected by tie bars. The bottom twistlock pockets extend beyond the container base by 10 mm to provide four “feet”.

A steel soffit is placed on top of the 6 m^3 CB body, sitting on the top edges of the 6 m^3 CB body and sealing the interior of the 6 m^3 CB. The soffit essentially acts as formwork for the base of the 6 m^3 CB lid. The soffit is a 3 mm thick steel sheet with folded-up tabs around the edges that rest on the top inside edges of the 6 m^3 CB body walls. Four 25 mm x 25 mm x 3 mm thick steel angles are welded to the top surface of the soffit to stiffen the soffit sheet.

The 6 m^3 CB was modelled with a combination of solid elements (concrete and twistlock assemblies), thin shell elements (collars and soffit) and beam elements (reinforcement bars and studs). The coupled interaction between the reinforcement bars and the concrete of the 6 m^3 CB is modelled using a constraint definition, which constrains the reinforcement beam elements to the solid concrete elements without the need for sharing the same nodes.

Since this work was carried out, the design of the Magnox 6 m^3 CB has been modified to aid manufacturing and a programme of finite element analyses to demonstrate the impact performance of the final designs will be carried out.

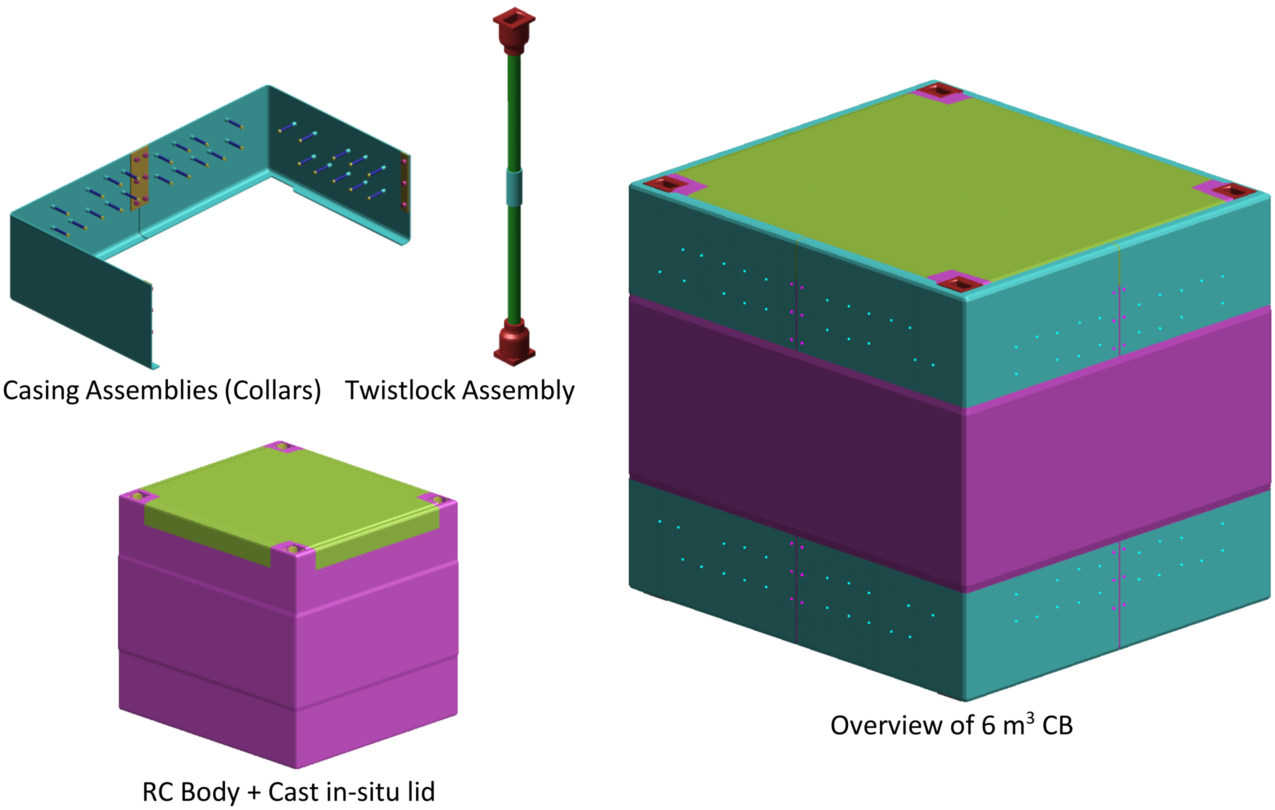

Figure 1. Components of 6 m^3 CB

Sacrificial Bin

In this Sacrificial Bin concept, the waste is encapsulated inside the Sacrificial Bin, but the Sacrificial Bin is entombed inside the 6 m^3 CB.

As shown in Figure 2, the Sacrificial Bin is a mild steel welded construction comprised of six panels, one for each side of the cuboid. The top sheet has a large circular central opening 900 mm in diameter for the ingress of waste and grout. A sealing face ring with an outer diameter of 1320 mm fits around the circular opening and provides a more substantial interface for the retrieval module to establish a seal to the bin. In the centre of the Sacrificial Bin, there is a grout tube welded to the base sheet to allow easy ingress of grout through the waste to the bottom of the bin. The Sacrificial Bin is modelled using thin shell elements.

The work is based on an early conceptual design of the Sacrificial Bin. Since this work was carried out, the design of the Sacrificial Bin has been developed and a programme of finite element analyses to demonstrate the impact performance of the final designs will be carried out.

Encapsulated Wasteform

Figure 2 also shows an overview of the FE mesh of the encapsulated wasteform and the capping grout that is inside the Sacrificial Bin. The encapsulated wasteform occupies 4.05 m^3 (90 %) of the 4.5 m^3 internal volume in the Sacrificial Bin, and the layer of capping grout 0.23 m^3 (5 %) is added on top.

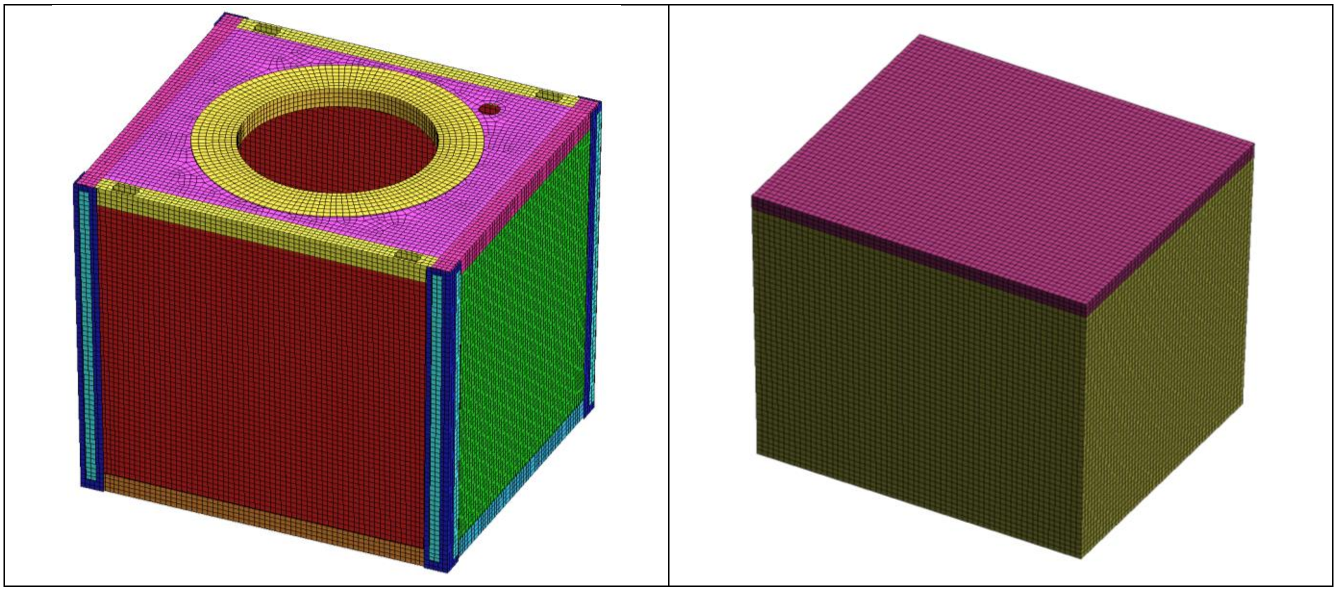

Figure 2. Overview of FE mesh of Sacrificial Bin (on left) and of encapsulated wasteform (yellow) and capping grout (pink) (on right)

Total Mass of 6 m^3 CB

The maximum waste package mass of the Magnox 6 m^3 CB is 50 tonnes. However, the majority of the Magnox 6 m^3 CB waste packages are likely to be around 30 tonnes. Therefore, some drop scenarios were also analysed at the reduced total mass as this is likely to improve the impact performance. The breakdown of the waste package masses is given in Table 1.

Table 1. Mass breakdown of 6 m^3 CB

Component	**HD waste package mass [t]**	**ND waste package mass [t]**
6 m^3 CB (including twistlock assemblies, collars, soffit and reinforcement bars)	26.12	17.38
Sacrificial Bin	0.81	0.81
Encapsulated Wasteform and Capping Grout	23.09	11.81
Total	**50.02**	**30.00**

Normal Conditions of Transport 0.3 m drop

For the Normal Conditions of Transport 0.3 m drop, the HD variant 6 m^3 CB was modelled with the maximum gross waste package mass of 50 tonnes and dropped in the flat base orientation.

Assessment criteria for Normal Conditions of Transport 0.3 m drop

The success criterion for the Normal Conditions of Transport 0.3 m drop is no loss or dispersal of the contents from the IP-2 packages. The following criteria have been adopted for assessing the performance of the 6 m^3 CB:

- No major breach in the 6 m^3 CB package.

- No through-thickness cracks wider than 0.5 mm throughout their lengths in the 6 m^3 CB. Research carried out by Magnox [1] concluded that concrete cracks less than 0.5 mm in width would not lead to loss or dispersal of particulates from unpressurised waste packages.
- Plastic strain in the reinforcement should not exceed 5 % (or 4.9 % true plastic strain), which is based on the minimum elongation to failure given in the material specification of the reinforcement bars [2].

Results

Under the impact, the four feet at the bottom of twistlock assemblies act like buffers and effectively make the impact softer. The 6 m^3 CB lid deflects downwards and rebounds during the impact. The maximum relative sagging displacement of 6 m^3 CB lid (relative to the top of the 6 m^3 CB body) is about -2.2mm and the maximum relative hogging displacement is about 2.7mm, indicating there is no significant relative deflection between the 6 m^3 CB lid and body.

Figure 3 shows the maximum crack widths for each element at any time during the whole impact event. It is a conservative plot of the cracks, as apparent through-thickness cracks shown in the plot do not necessarily mean that a through-thickness crack actually existed at any particular time. It just indicates that at some point in the impact, cracks in the concrete elements existed, but not necessarily at the same time. The plot shows the maximum crack widths using cross-section views through the 6 m^3 CB. It can be seen that there are no through-thickness cracks greater than 0.5 mm in the 6 m^3 CB. Therefore, no particulates are predicted to be released from this 6 m^3 CB waste package. It should also be noted that the soffit will act as an additional barrier to radioactive particulates from dispersing through any concrete cracks in the 6 m^3 CB lid.

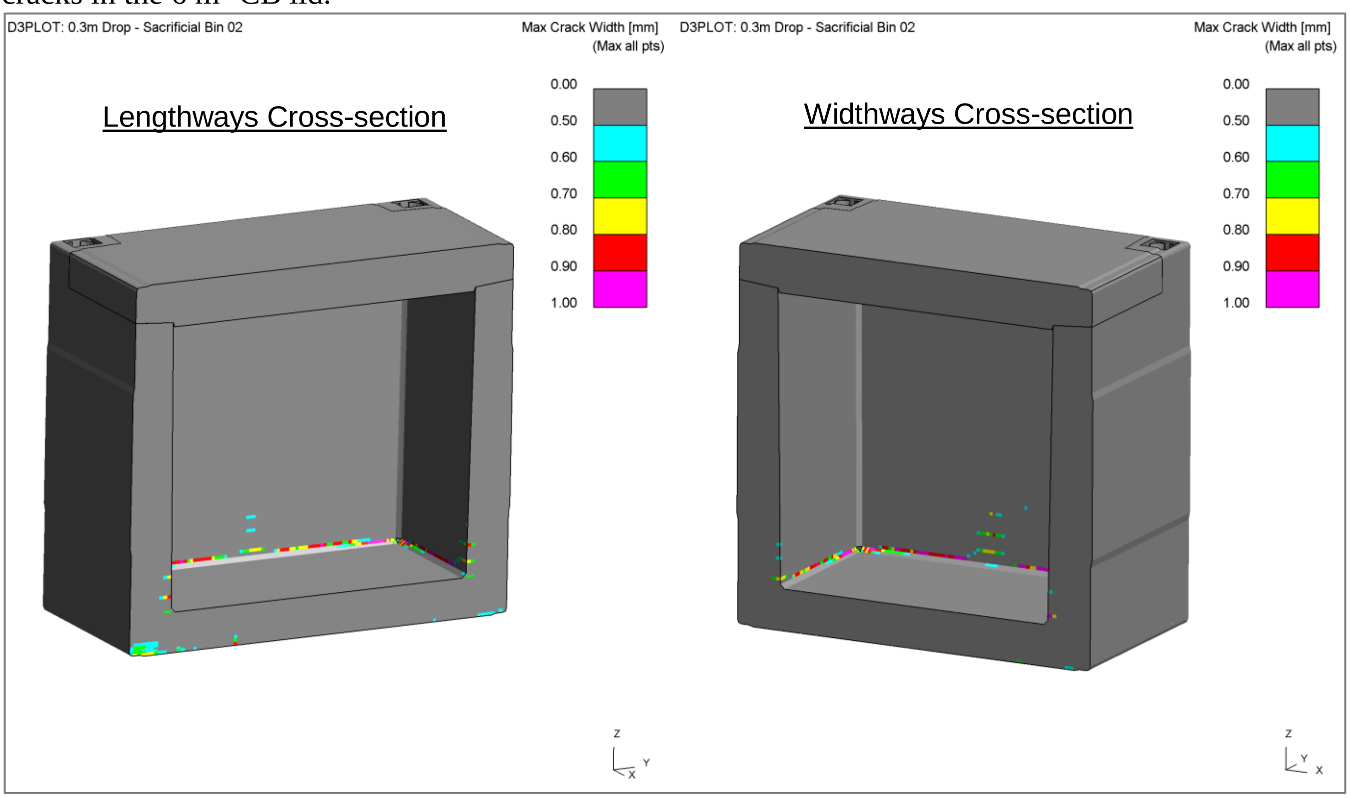

Figure 3. Maximum crack width in the 6 m^3 CB at any time; Cross-section views

The plastic strains in the steel reinforcement of 6 m^3 CB are very small, with a maximum of about 1.0 %. The plastic strain in the Sacrificial Bin is also small, with a maximum of about 0.84 %. Thus, the plastic strains predicted in the steel reinforcement bars and other steel components of the 6 m^3 CB are much smaller than the corresponding plastic strain to failure for the materials.

GDF Impact Accident of 10 m Drop onto a Flat Unyielding Target

For the GDF Impact Accident of a 10 m drop onto a flat unyielding target, the initial analyses were based on the maximum gross mass of the 6 m^3 CB of 50 tonnes and the minimum specified material properties for the reinforcement bars. However:

- Many of the waste packages will be 30 tonnes or less;
- The minimum specified failure strain for the grade B500B steel reinforcement bars is 5 %, as defined in BS 4449:2005 [2], whereas the best estimate value for the failure strain of the reinforcement bar material is significantly higher at about 15 % [3], as shown in Table 2.

Therefore, three different analysis cases were run to evaluate the impact performance of 6 m^3 CB and understand the improvement that may result from the reduced total mass of waste package and an increased ductility of the steel reinforcement. These analysis cases are shown in Table 3.

Table 2. Reinforcement Bar Material Properties

Reinforcement bar material properties	Yield stress	Maximum stress	Failure Strain
Minimum specification properties [2]	500	530	5 %
Best estimate properties [3]	535	620	15 %

Table 3. Analyses for GDF impact accident of a 10 m drop onto a flat unyielding target

Analysis Case	Total Mass	Concrete Density	Reinforcement bar properties
Case 1	50 tonnes	High Density	Minimum specification properties
Case 2 – Reduced Package Mass	30 tonnes	Normal Density	Minimum specification properties
Case 3 – Best estimate properties	30 tonnes	Normal Density	Best estimate properties

The three analysis cases were run using the lid-edge drop orientation of the Magnox 6 m^3 CB. Previous work had shown that this drop orientation resulted in the greatest damage to the 6 m^3 CB and the largest opening between the 6 m^3 CB lid and body and was the most likely to result in significant pathways for the release of waste contents. Figure 4 shows an overall view of Magnox 6 m^3 CB at the start of the analysis.

Assessment criteria for GDF impact accident scenarios

The following RWM criteria have been adopted for assessing the performance of the 6 m^3 CB in the GDF impact accident scenarios:

- The calculated Release Fraction (RF) is shown to give on- and off-site doses resulting from the release of radionuclides to be As Low As Reasonably Practicable (ALARP) and should meet

Basic Safety Levels (BSLs). This work determined the RF for impacted material assuming 100 % release of this material from the package;

- The waste package behaves in a predictable and progressive manner;
- No gross loss of waste contents.

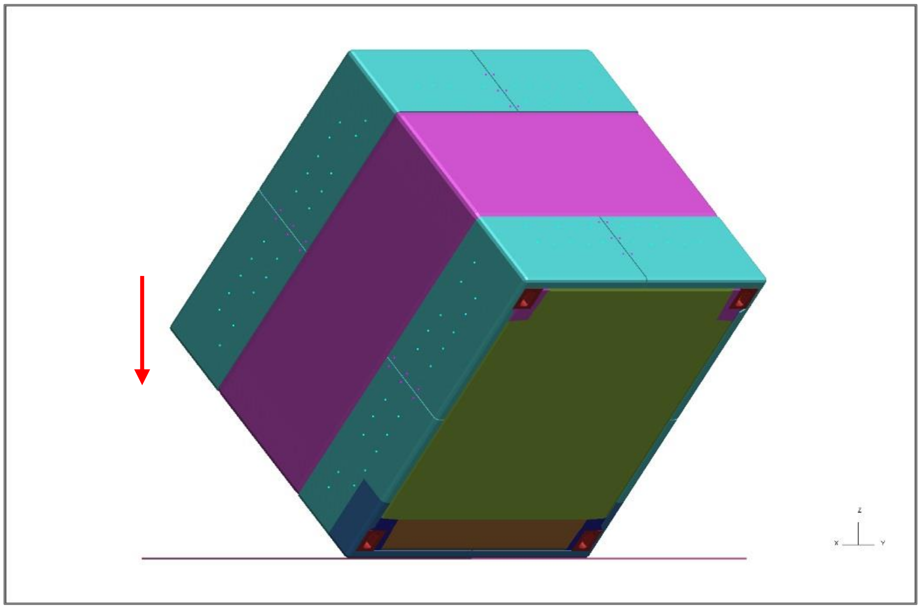

Figure 4. Overall view of 6 m^3 CB in 10 m lid edge drop onto flat unyielding target

Analysis Results

Analysis Case 1, shown in Figure 5, results in the greatest amount of deformation. The concrete around the impacted edge is crushed and the 6 m^3 CB lid is pushed sideways during the initial impact. The momentum of the Sacrificial Bin bears onto the underside of the 6 m^3 CB lid, causing outward bending in the 6 m^3 CB lid. Most of the reinforcement bars connecting the lid and 6 m^3 CB body along the sides fail due to the bending of the 6 m^3 CB lid and large gaps open up between the 6 m^3 CB lid and body. At the end of the analysis, the 6 m^3 CB lid is only connected to the 6 m^3 CB body along the edge opposite the impacted edge and the 6 m^3 CB lid experiences a large flexural deflection. In addition, some of the reinforcing bars in the outer layer of the lid failed around the bend in the 6 m^3 CB lid.

Analysis Case 2, shown in Figure 6, results in similar deformation modes to Analysis Case 1, but with a reduced magnitude due to the reduced package mass. Most of the reinforcement bars connecting the lid and 6 m^3 CB body along the sides still fail due to the bending of the 6 m^3 CB lid and large gaps still open up between the 6 m^3 CB lid and body, although smaller than in Analysis Case 1.

Analysis Case 3, shown in Figure 7, demonstrates a significantly improved impact performance. Due to the increased ductility in the reinforcement bars, most of the reinforcement bars connecting the 6 m^3 CB lid to the body remain intact. There is much less relative outwards deflection of the 6 m^3 CB lid and the 6 m^3 CB lid remains attached to the 6 m^3 CB body. Although there are gaps along the interface between the 6 m^3 CB lid and body, the steel collars will still cover the concrete and to some extent, prevent the waste from being released. For Analysis Case 3, although pathways for release of particulates exist, the calculated RF is likely to be considered tolerable. Therefore, the Magnox 6 m^3 CB is likely to meet the

RWM assessment criteria since there is no gross loss of waste contents and the waste package behaves in a predictable and progressive manner.

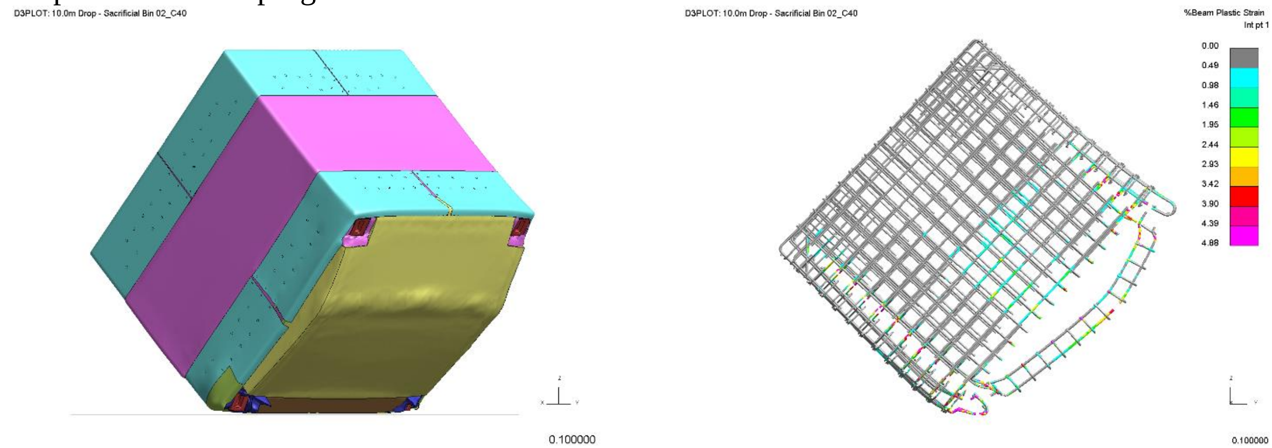

Figure 5. Deformation of the 6 m^3 CB at the end of analysis in Case 1 (left); Plastic strain in the reinforcement bars at the end of analysis in Case 1 (right)

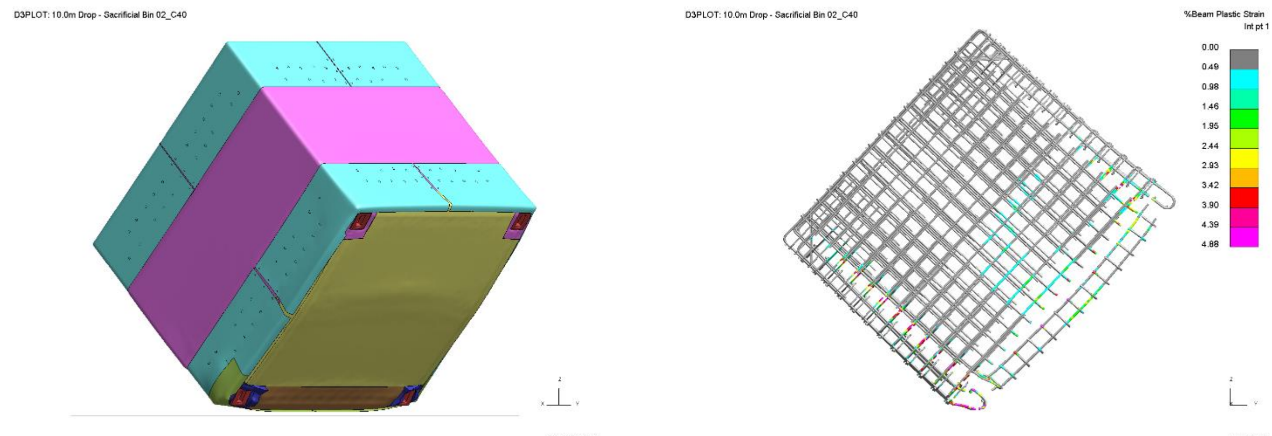

Figure 6. Deformation of the 6 m^3 CB at the end of analysis in Case 2 (left); Plastic strain in the reinforcement bars at the end of analysis in Case 2 (right)

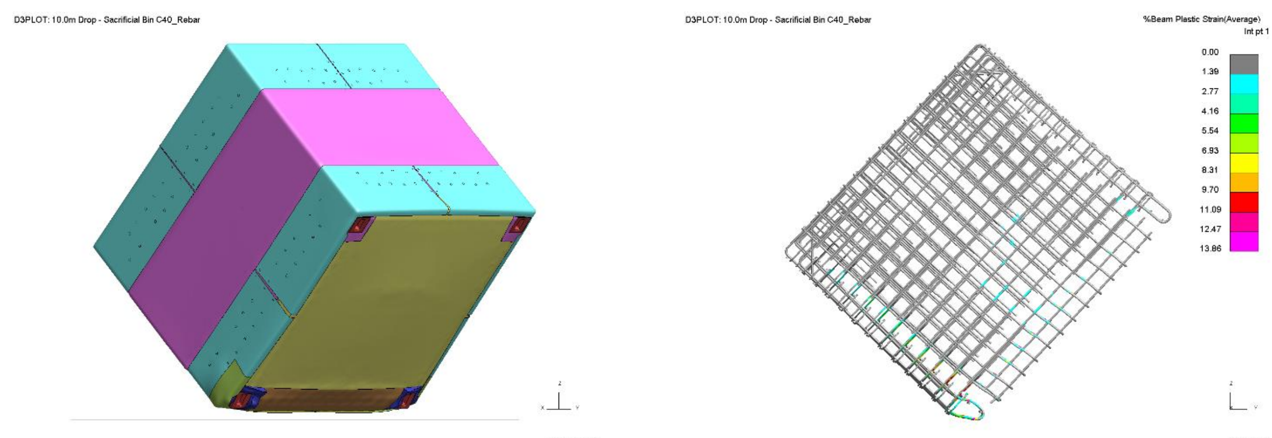

Figure 7. Deformation of the 6 m^3 CB at the end of analysis in Case 3 (left); Plastic strain in the reinforcement bars at the end of analysis in Case 3 (right)

GDF IMPACT ACCIDENT OF 7 m DROP ONTO AN AGGRESSIVE TARGET

For the GDF impact accident of a 7 m drop onto an aggressive target, two different analysis cases were investigated: one with minimum reinforcement bar properties and the other with best estimate reinforcement bar properties, as shown in Table 4.

Table 4. Analyses in GDF Impact Accident of a 7 m drop

Analysis Case	Total Mass	Concrete Density	Reinforcement bar properties
Case 1 – Reduced Package Mass	30 tonnes	Standard Density	Minimum specification properties
Case 2 – Best estimate properties	30 tonnes	Standard Density	Best estimate properties

For the aggressive target, the most aggressive feature for the GDF impact accident 7 m drop is the corner of a 4 metre box, as shown in Figure 8. A finite element model of a 4 metre box [4] was used for the analyses with the permission of RWM. The stiffest and most aggressive variant of the 4 metre box was used, which corresponded to the variant with the thickest concrete shielding of 200 mm. To reduce analysis computational time, the 4 metre box was reduced to a half model.

The 6 m^3 CB is orientated with the lid down at 15 degrees to the horizontal, with its centre of gravity aligned vertically above the point of impact, as shown in Figure 8. A previous study of this drop scenario had concluded that this orientation the 6 m^3 CB produced the most deformation in the Sacrificial Bin and resulted in the most impact energy being absorbed.

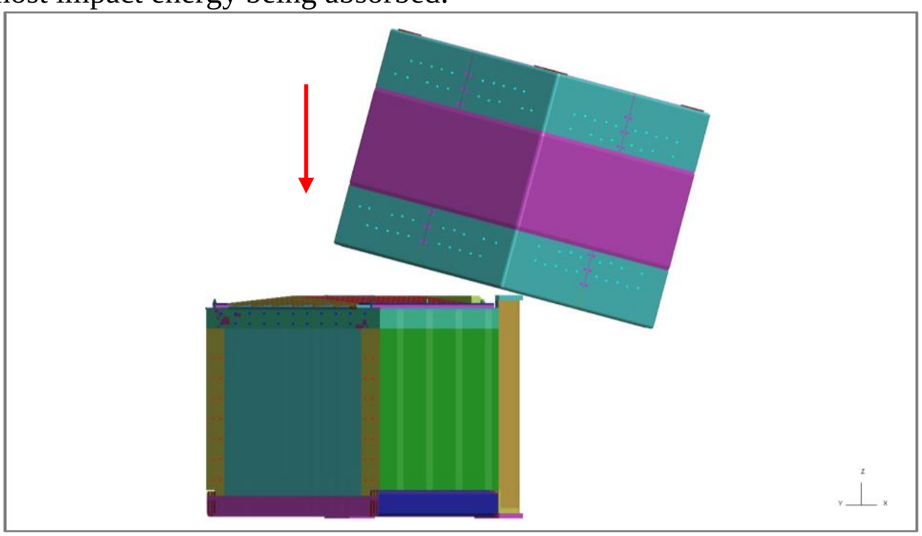

Figure 8. Overall view of 6 m^3 CB in 7 m drop onto an aggressive target

Analysis Results

The overall impact behaviour for the two analysis cases, shown in Figure 9 and Figure 10, are not significantly different. During the initial impact, the concrete around the impacted area at the centre of 6 m^3 CB lid is crushed and pushed inwards, forming a large dent in the lid and failing the reinforcement bars in the lid. The impacted corner of the 4 metre box is also crushed and squashed downwards. Subsequently, the dent in the 6 m^3 CB lid also impacts the capping grout and encapsulated wasteform inside the Sacrificial Bin. The magnitude of the dent in the 6 m^3 CB lid causes tearing of the relatively thin soffit.

The deformations in Analysis Case 2 are slightly lower than those in Analysis Case 1 due to the increased ductility in the reinforcement bars. However, the reduction is not sufficient to prevent tearing in the soffit. The large dent in the 6 m^3 CB lid and the tearing in the soffit around the dent are likely to result in significant pathways for the release of particulates through the 6 m^3 CB lid.

For the GDF 7 m drop onto an aggressive target, although pathways for release of particulates exist, the calculated RF is likely to be considered tolerable. Therefore, the Magnox 6 m^3 CB is likely to meet the RWM assessment criteria since there is no gross loss of waste contents and the waste package behaves in a predictable and progressive manner.

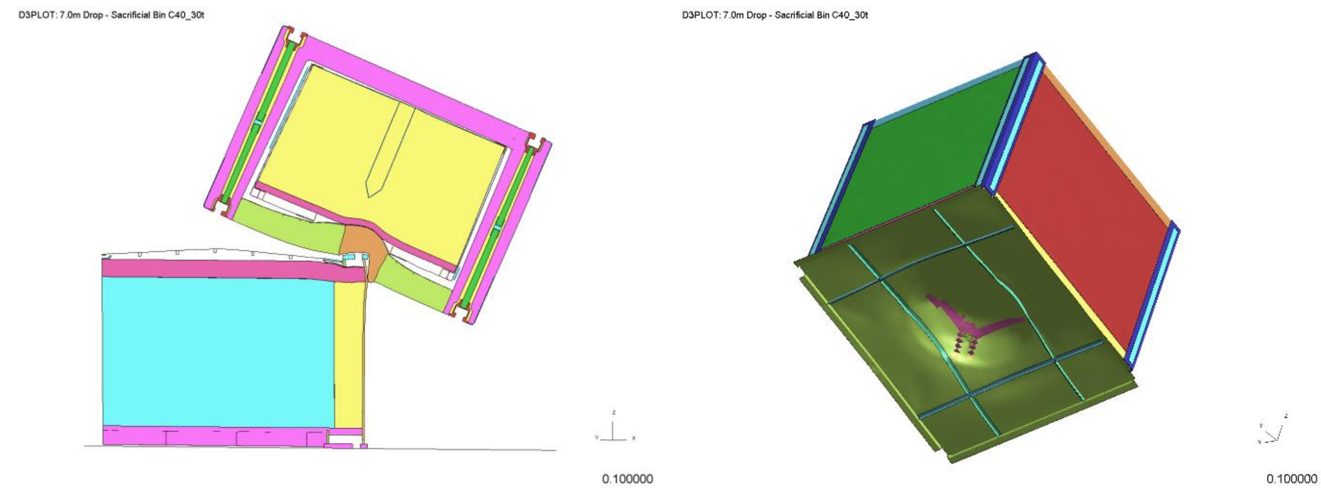

Figure 9. Deformation of the 6 m^3 CB at the end of analysis in Case 1 (left); Deformation of the soffit and Sacrificial Bin at the end of analysis in Case 1 (right)

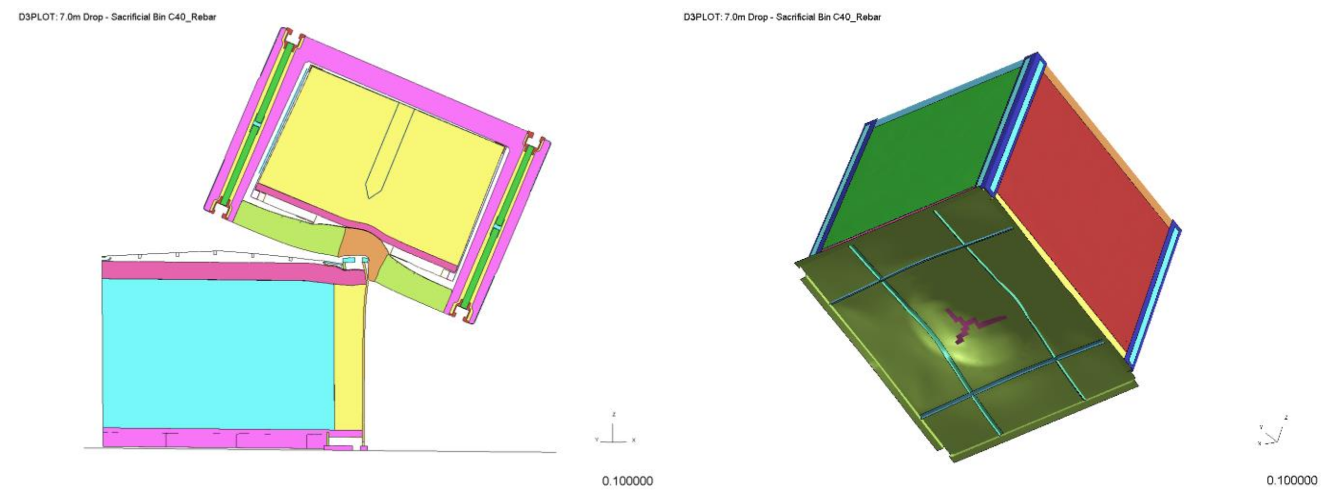

Figure 10. Deformation of the 6 m^3 CB at the end of analysis in Case 2 (left); Deformation of the soffit and Sacrificial Bin at the end of analysis in Case 2 (right)

CONCLUSIONS

A number of finite element analyses have been carried out to investigate the impact performance of the Magnox 6 m^3 CB, with the Sacrificial Bin internal configuration, in the Normal Conditions of Transport 0.3 m drop and GDF impact accident scenarios. The main conclusions from these analyses are:

- For the Normal Conditions of Transport 0.3 m drop, there are no through-thickness cracks in the 6 m^3 CB larger than 0.5 mm at any time during the impact event and the performance of Magnox 6 m^3 CB complied with the assessment criteria.
- For the GDF impact accident 10 m drop onto a flat unyielding target, a Magnox 6 m^3 CB, with a gross mass of 50 tonnes and minimum reinforcement bar properties, the analysis showed that most of the reinforcement bars connecting the lid to the body failed. There is significant bending in the lid outwards and large gaps between the lid and the body. Reducing the gross mass of the waste package to 30 tonnes improved the impact performance, but the overall behaviour was similar and there were still large gaps between the lid and the body.
- For the GDF impact accident 10 m drop onto a flat unyielding target, a Magnox 6 m^3 CB, with a gross mass of 30 tonnes and best estimate material properties for the reinforcement bars, the analysis showed that most of the reinforcement bars connecting the lid to the body remained intact and the lid remained attached to the body, although there were still gaps between the lid and the body. For this waste package configuration, the Magnox 6 m^3 CB is likely to meet the RWM assessment criteria.
- For the GDF impact accident 7 m drop onto an aggressive target, the analyses show there is significant damage to the impacted area of the 6 m^3 CB lid with a large dent formed, tearing of the soffit and crushing of the encapsulated wasteform. The use of best estimate material properties for the reinforcement bars, as opposed to minimum specified material properties, resulted in a reduction in the deformations, although the overall behaviour was similar. With the large dent in the 6 m^3 CB lid and tearing of the soffit, significant pathways for the release of particulates could potentially exist. However, for this GDF impact accident scenario, the Magnox 6 m^3 CB is likely to meet the RWM assessment criteria.

Further modifications to the designs of the Magnox 6 m^3 CB and the Sacrificial Bin are being developed and a programme of finite element analyses to demonstrate the impact performance of the final designs will be carried out.

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