DEVELOPMENT OF DISPOSAL CONTAINER DESIGNS FOR DISPOSAL OF HIGH LEVEL WASTE AND LEGACY SPENT FUEL IN THE UK – 15471

Neil Carr*, Chi-Fung Tso**, Conrad Izatt**, Ryoji Asano***, Chris Fry****, George Wright****, Chris Punshon*****.

*NDA, Harwell, United Kingdom
**Arup, London, United Kingdom
***Hitachi Zosen Corporation, Tokyo, Japan
****AMEC, Winfrith, United Kingdom
*****TWI, Cambridge, United Kingdom.

ABSTRACT

Radioactive Waste Management Limited (RWM), a fully owned subsidiary of the Nuclear Decommissioning Authority (NDA), is responsible for the implementation of geological disposal in the UK.

Three illustrative concepts of a geological disposal facility (GDF), corresponding to three generic geological environments - higher strength rock, lower strength sedimentary rock and evaporite rock - have been developed to demonstrate the viability of geological disposal of intermediate level waste, high level waste and spent fuel.

It is envisaged that HLW which has been encapsulated in Waste Vitrification Plant (WVP) canisters, advanced gas-cooled reactor (AGR) SF which has been stripped of their spacers and packaged into slotted fuel cans, and PWR SF will be packaged into disposal containers for disposal. A set of schematic designs of these disposal containers was developed in the late 2000s. The design concept for the higher strength rock environment was based on the joint Posiva/SKB disposal container design, and the design concept for the lower strength sedimentary rock and evaporate rock illustrative environments was based on the disposal container concept from Switzerland's National Cooperative for the Disposal of Radioactive Waste (Nagra).

The size, mass and dimensions of the disposal containers in the scheme designs vary significantly. The construction method and the lid closing method also vary between the disposal containers for the different waste contents. A design study has indicated that optimization of the number of HLW WVP canisters and the number of AGR slotted fuel cans in the disposal containers, standardizing construction method and closure arrangement across the containers for each geology type, providing handling features at both ends of the disposal container, and balancing of shielding around the containers, could bring significant advantage to the overall GDF programme by reducing the number of disposal containers, reducing GDF footprint, and reducing the extent of excavations, spoil generated and materials that are required for construction.

A project to develop the scheme designs to conceptual level was carried in 2011 to 2013. In this project, the above changes were taken into account, technical underpinning of the designs was carried out and manufacturing method was considered.

Two disposal container variants for different host rock environments have been developed:

- Variant 1, for compatibility with the higher strength rock illustrative disposal system design. This is constructed from copper, with a cast iron insert and is based on the joint Posiva/SKB

disposal container design.

- Variant 2, for compatibility with the lower strength sedimentary rock and evaporite rock illustrative disposal system designs. This is a steel container based on the NAGRA disposal container design.

Each variant has three internal configurations to accommodate 3 HLW vitrified canisters, 16 consolidated cans of AGR SF and 4 PWR spent fuel assemblies.

These designs have been shown to bring significant benefit to the GDF designs, bringing a significant reduction to the operating programme and GDF programme cost, including reducing the number of disposal containers by 33% for HLW, 50% for AGR SF and reducing the size of the GDF footprint by 25%.

INTRODUCTION

Radioactive Waste Management Limited (RWM), a fully owned subsidiary of the Nuclear Decommissioning Authority (NDA), is responsible for the implementation of geological disposal in the UK.

Three illustrative concepts of a geological disposal facility (GDF), corresponding to three generic geological environments - higher strength rock, lower strength sedimentary rock and evaporite rock - have been developed to demonstrate the viability of geological disposal of intermediate level waste (ILW), high level waste (HLW) and spent fuel (SF).

It is envisaged that HLW which has been encapsulated in Waste Vitrification Plant (WVP) canisters, AGR SF which has been stripped of their spacers and packaged into slotted fuel cans, and PWR SF will be packaged into disposal containers for disposal [1]. A set of schematic design of these disposal containers had been developed in the late 2000s. The design concept for the higher strength rock environment was based on the joint Posiva/SKB disposal container design and the design for the lower strength sedimentary rock and evaporate rock environment was based on the disposal container concept from Nagra.

The mass and dimensions of the disposal containers in the scheme design vary significantly. The construction method and the lid closing method also vary between the disposal containers for the different waste contents. A design study has indicated that optimization of the number of HLW WVP canisters and the number of AGR slotted fuel cans in the disposal containers, standardizing construction method and closure arrangement across the containers for each geology type, providing handling features at both ends of the disposal container, and balancing of shielding around the containers, could bring significant advantage to the overall GDF programme by reducing the number of disposal containers, reducing GDF footprint, and reducing the extent of excavations, spoil generated and materials that is required for construction.

A project to develop the scheme designs to conceptual level was carried in 2011 to 2013. In this project, the above changes were taken into account, technical underpinning of the designs was carried out and manufacturing method was considered.

PROJECT TEAM

The work was carried out by a project team consisted of the following organisations:

- Arup:
  - Overall project management.
  - Development of Design Specification.
  - Assessment of structural performance.
- Hitachi Zosen Corporation:
  - Design of disposal containers.
  - Consideration for manufacture.
- TWI:
  - Consideration for manufacture.
  - Design of disposal containers.
- AMEC:
  - Assessment of thermal performance.
  - Assessment of shielding performance.

THE DESIGNS

Conceptual designs of two variants of disposal containers have been developed to suit a range of geological host rock environments.

Each variant has three internal configurations:

- for three canisters of HLW in waste vitrified product (WVP) canisters
- for sixteen cans of consolidated AGR spent fuel in slotted fuel cans
- for four PWR spent fuel assemblies.

VARIANT 1 DISPOSAL CONTAINERS

The Variant 1 disposal containers are shown in Figure 1 below:

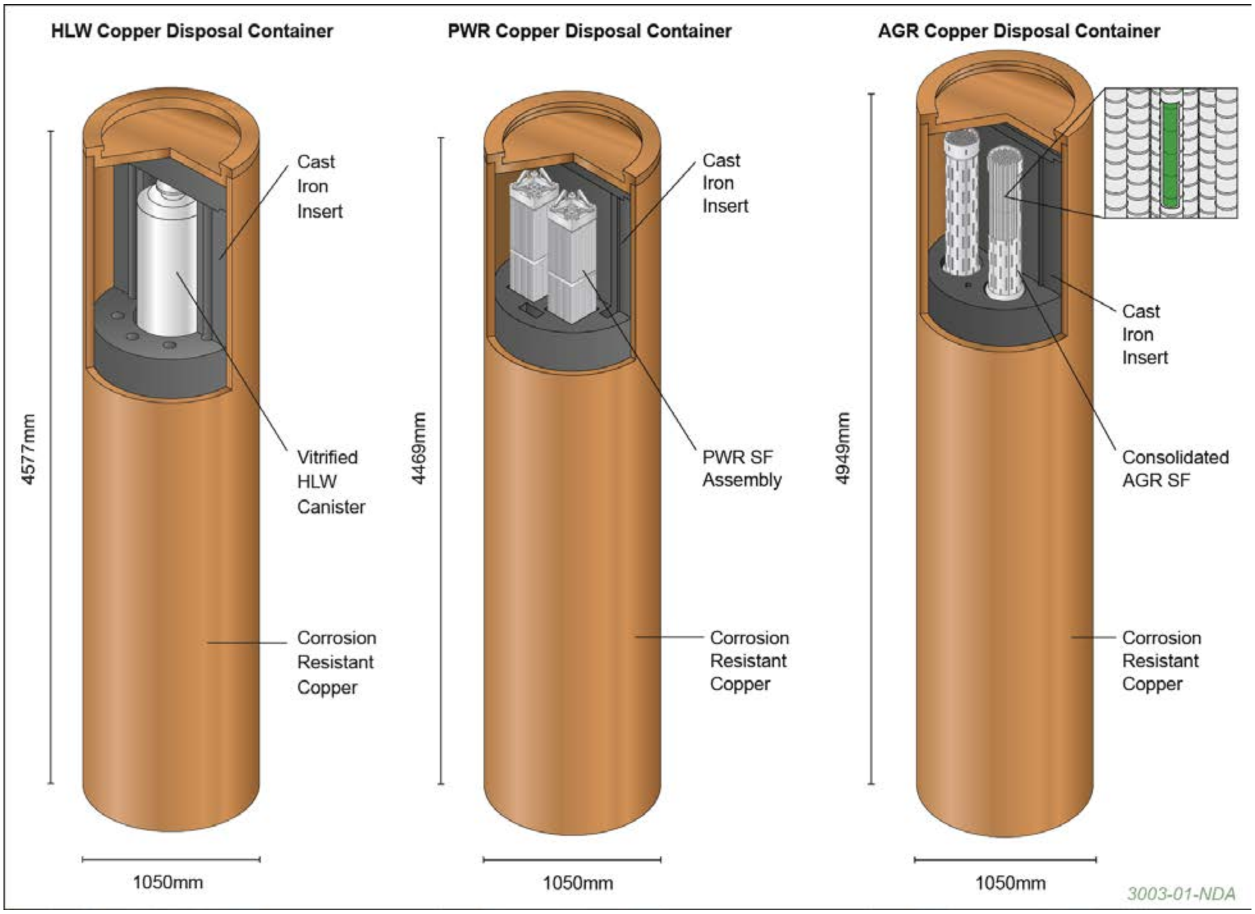


Figure 1 - Variant 1 Disposal Containers

Each disposal container consists of a fully welded copper container comprising of a copper outer lid and a copper outer cylinder body, a steel inner lid and an inner cast iron insert with carbon steel tube receptacles to accommodate the waste contents.

Structural integrity of the disposal container is provided by the steel inner lid and the inner cast iron insert, whereas containment is provided by the copper shell.

Copper has been chosen for its corrosion resistance, to provide the required protection to the inner steel lid and cast iron insert over the intended timescale.

The copper outer body consists of a cylindrical body and a bottom plate. It is envisaged that the bottom plate will be welded to the bottom of the outer body in the manufacturing plant during the manufacture process, and the outer lid will be welded to the body at the packaging plant after loading of the waste contents.

Identical lifting features are provided at both ends of the disposal container so the disposal containers can be handled at both ends and horizontally.

The cast iron insert and the inner steel lid provide the bulk of the structural rigidity of the disposal containers. The cast iron inserts consist of a cast iron body, carbon steel receptacle tube(s) for accommodating the waste content and cooling pipes to aid cooling of the insert during the casting process.

The inner steel lid is made of carbon steel and it is fitted with elastomeric double O-ring seals at the perimeter, a leak check hole and a quick connector for air purging. It is to be connected to the cast iron insert by 16 x M16 bolts. Its thickness has been chosen to provide the necessary radiation protection. In addition, it also performs a temporary containment function during the outer lid welding process after the waste contents have been loaded. Containment function is provided by the fully welded high integrity copper shell.

VARIANT 2 DISPOSAL CONTAINERS

The Variant 2 disposal containers are shown in Figure 2.

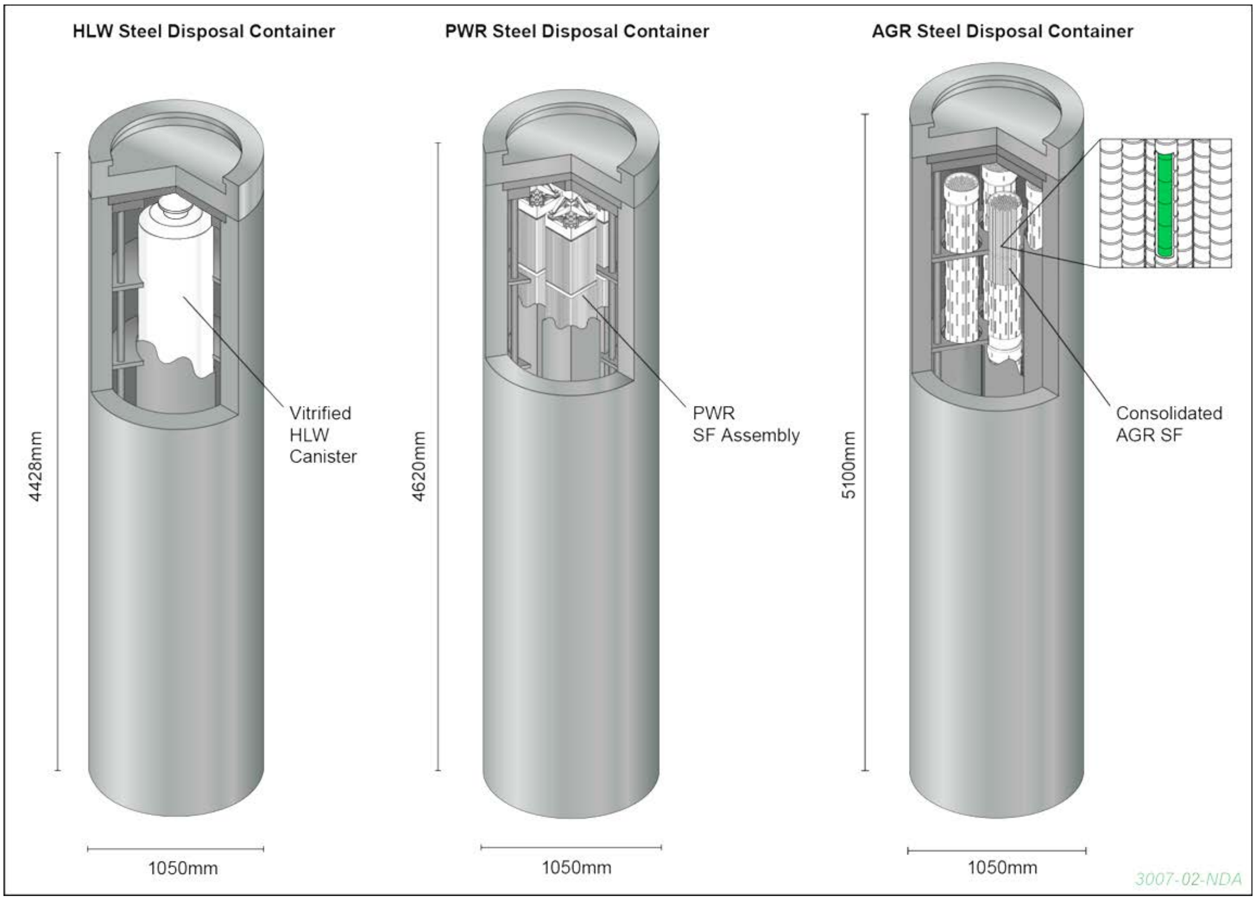


Figure 2 - Variant 2 Disposal Containers

Each container consists of a fully welded steel container consisting of an outer forged steel lid and a carbon steel outer cylinder body, an inner steel plate lid, and a carbon steel basket. The thickness of the outer lid and outer shell have been chosen such that after corrosion over the required timescale have taken place, the disposal container can still perform satisfactorily in its containment, shielding, structural and thermal functions.

The baskets for the three contents are shown on their own in Figure 3.

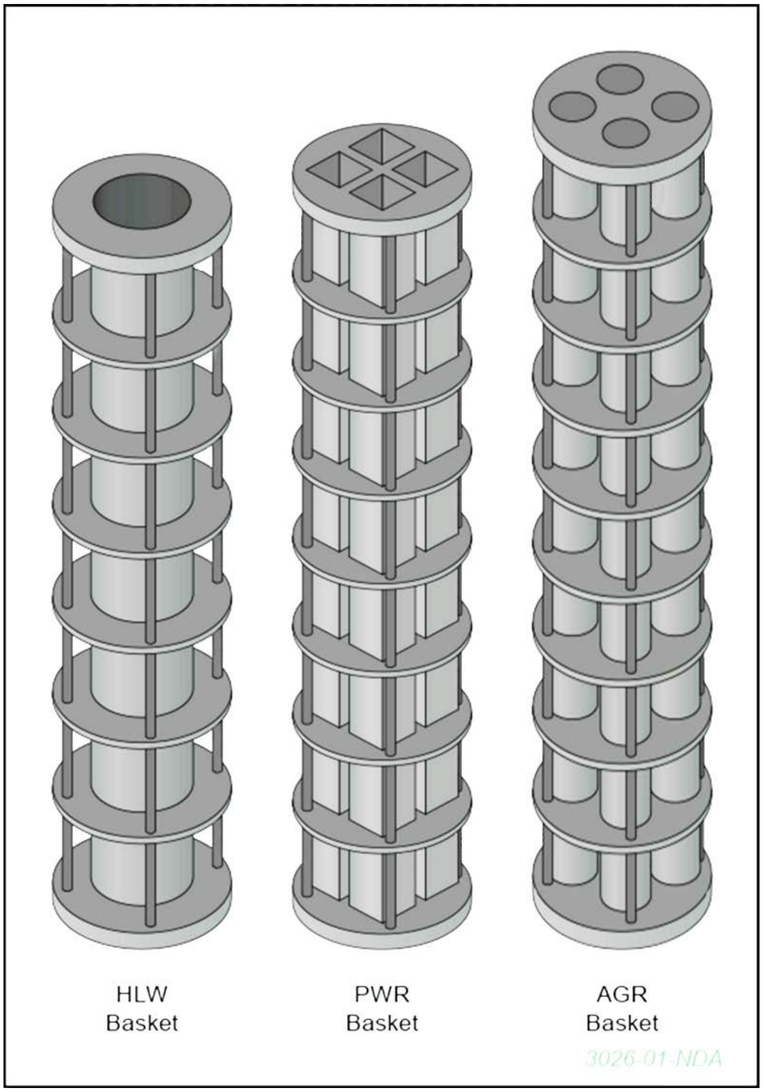


Figure 3 – Internal basket of the Variant 2 Disposal Containers

For Variant 2 disposal containers, containment is provided by the carbon steel body and the forged carbon steel lid, which will be connected by friction stir welding after loading of the waste contents.

The purpose of the inner lid is to provide temporary containment after the waste contents have been loaded and before the outer lid has been welded to the outer shell. The inner lid is common for all of the Variant 2 disposal containers. It is made of carbon steel and it is fitted with elastomeric double O-ring seals, a leak check hole and a quick connector for air purging. It is connected to the carbon steel outer body by 16 x M16 bolts.

The waste contents are located in the basket in the disposal containers which will maintain their position during all handling and loading scenarios. The baskets for the different waste contents all consist of receptacle tubes for accommodating the waste contents, and their positions are maintained by a top plate, a bottom plate and a set of evenly spaced support plates, which are in turn connected by a set of tie rods and spacer tubes.

SHEILDING PERFORMANCE

During transport, the disposal containers are not required to provide a specific level of shielding since the disposal container waste packages will be transported to the GDF in a Disposal Container Transport Container (DCTC) which will provide radiation shielding, and they will be handled remotely in the GDF. However, it is desirable for the dose-rate at the surface of the disposal container waste packages not to exceed 1 Gy/h - the rate of absorbed dose which causes pore water radiolysis in the Bentonite buffer around a disposal container. In addition, it is desirable that the dose-rate at the ends of the disposal containers is similar to that at the sides of the disposal containers.

Shielding calculations were carried out to determine dose-rates on the surface of both variants of disposal containers and for each waste content type.

The maximum envisaged inventories have been used in the calculations, so that the calculated dose-rates are bounding.

Variant 1

The maximum primary gamma-ray dose-rate for the Variant 1 disposal container was calculated to be 0.2Gy/hr, well within the 1Gy/hr limit. This occurs for PWR SF assemblies at the bottom of the disposal container. The maximum dose-rates at the top and bottom of the container never exceed 0.08Gy/hr.

The maximum neutron dose-rate was less than 0.0004Gy/hr, negligible compared to the primary gamma-ray dose-rate. Secondary gamma-ray dose-rates were also negligible.

The Variant 1 disposal container design has a recess in the inner lid for the purge valve and this causes a shielding weakness in the lid. Calculations have been carried out to show that this dose-rate is still well within the 1Gy/hr limit. Thus, although the recess is a weakness in the shielding, the 1Gy/hr limit is not exceeded, so the provision for additional shielding is not required.

With HLW content, the maximum dose-rates at the top, sides and bottom of the disposal container are similar. With AGR SF and PWR SF contents, the maximum dose-rates at the sides and bottom of the container are similar to within a factor of 2, but those at the top are lower by a factor of around 8.

Variant 2

The maximum primary gamma-ray dose-rate for Variant 2 was calculated to be 0.38Gy/hr, well within the 1Gy/hr limit. This occurs when the disposal container is loaded with HLW and found at the side of the disposal container. The maximum dose-rates at the top and bottom of the container never exceed 0.04Gy/hr.

The maximum neutron dose-rate was less than 0.001Gy/hr, negligible compared to the primary gamma-ray dose-rate. Secondary gamma-ray dose-rates were also negligible.

The Variant 2 disposal container design has a recess in the inner lid for the purge valve and this causes a shielding weakness in the lid. However, the dose-rates above the recess will be bounded by those at the side of the disposal container since the shield thickness above the inner lid and at the side of the container is the same. Thus, although the recess is a weakness in the shielding, the 1Gy/hr limit is not exceeded, so the provision for additional shielding is not required.

For the Variant 2 disposal container, in all cases, the shielding at the top and bottom of the disposal container is of similar thickness, whilst that at the side is less. Hence the maximum dose-rates at the top and bottom are similar, whilst those at the side are higher by a factor of 10 or more.

THERMAL PERFORMANCE

For transport, the disposal containers will be packaged in disposal container transport containers (DCTCs). The normal and accident thermal conditions in the GDF (when the disposal containers are not contained in DCTCs) are bounding and therefore thermal conditions during transport need not be considered.

For normal conditions after deposition in the GDF, including the post-closure period, the temperatures generated by the heat load from the containers' inventory must not impair the containment of the containers nor adversely affect the performance of the surrounding materials (buffer and host rock). For a postulated accident prior to emplacement, in which a container is exposed directly to a fire of 1000 deg C for 60 minutes at the GDF site, the containment must again remain intact. In both cases, the containers are required to withstand any excess pressures caused directly by the elevated temperatures.

The approach in the thermal assessment calculations was to identify a worst case scenario and to demonstrate that the thermal criteria were met for this case. Of the three types of waste intended for disposal, the bounding case is shown to be PWR spent fuel.

Finite element models were therefore created for the Variant 1 and 2 disposal container designs containing PWR spent fuel, with vertical emplacement for the Variant 1 in higher strength rock and horizontal emplacement for the Variant 2 in lower strength sedimentary rock, both with a bentonite buffer. The limiting condition is the target temperature of 100°C at the interface of the bentonite with the container surface.

For Sizewell B fuel with average burnup of non-reprocessed uranium, the initial heat load per container is calculated to be 1477W in the year 2090, reducing to 1290W in the year 2100 and to the nominal 1200W value by the year 2112.

For the Variant 1 disposal container in higher strength rock, by assuming an emplacement date of 2137 (at which date the heat load would be 861W), the thermal calculations show that the 100°C temperature target is just met, with the peak temperature found to occur about 360 years after emplacement.

For the Variant 2 disposal container in lower strength sedimentary rock, by assuming an emplacement date of 2118 (at which date the heat load would be 1041W), the thermal calculations show that the 100°C temperature target is just met, with the peak temperature found to occur 11 to 25 years after emplacement. (Note: Following completion of this work further development of the illustrative designs has been undertaken by RWM and a revised the target temperature for lower strength sedimentary rock has been established, consistent with the NAGRA concept and defined as 125 Deg C at the mid-point within the buffer between disposal container and host rock.)

For accident conditions, the Variant 1 disposal container was modelled subject to an all-engulfing 1000°C fire lasting one hour. The highest temperatures were found to be below 900°C on the outer surface and 400°C in the fuel channels. Estimates have also been made of the temperatures in the fuel pins/HLW and of corresponding internal pressures.

The calculations demonstrate that there will be no significant temperature gradients (which might affect containment) across the walls of the disposal container, either for fire conditions or following deposition. Internal pressures are predicted to be modest. The temperatures reached by the containment are significantly below the melting points.

The Variant 1 disposal containers satisfy the thermal performance criteria.

For accident conditions, the Variant 2 disposal container was also modelled to subject to an all-engulfing 1000°C fire lasting one hour. The highest temperatures were found to be below 780°C on the outer surface and 480°C in the fuel channels. Estimates have also been made of the temperatures in the fuel pins/HLW and of corresponding internal pressures.

The calculations demonstrate that there will be no significant temperature gradients (which might affect containment) across the walls of the Variant 2 disposal container design, either for fire conditions or following deposition. Internal pressures are predicted to be modest. The temperatures reached by the containment are significantly below the melting points.

The Variant 2 disposal containers also satisfy the thermal performance criteria.

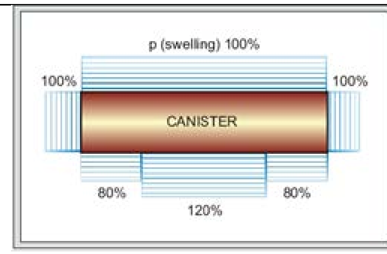
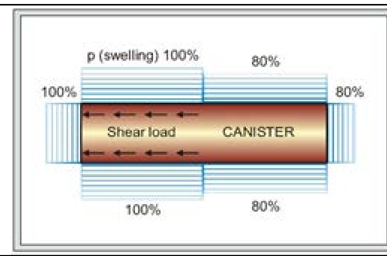
STRUCTURAL PERFORMANCE

For transport, the disposal containers will be transported in DCTCs. In both normal and accident conditions, the repository conditions will be bounding.

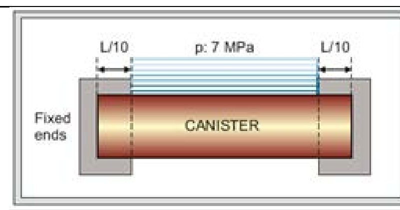
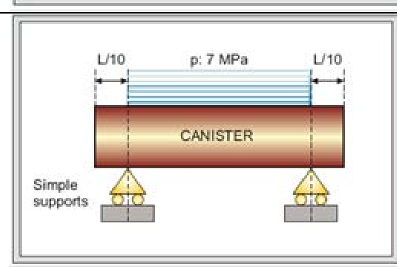
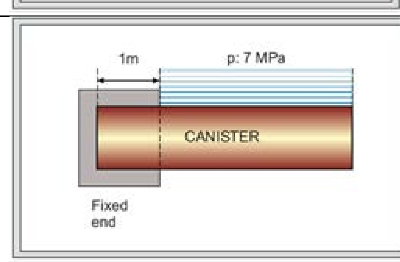
The structural loading scenarios in the repository are organised into the following categories:

- Lifting.
- Containment failure pressure.
- Normal condition external pressurisation. These loading scenarios arise from Bentonite swelling pressure and hydrostatic load at depth.
- Extreme condition external pressurisation. These loading scenarios arise from ice overburden in the post closure phase of the GDF.
- Impact accident.

There are three normal condition external pressurization load cases and they are as follows:

Load case	Description	Illustration
A	Uniform external pressure of 17 MPa due to a design basis hydrostatic pressure of 10MPa and a design basis swelling pressure of 7MPa	-
B	External pressurisation distribution with fully developed swelling pressure on one side of the disposal container's cylindrical surface, swelling pressure elevated by 20% along the central half of the other side of its cylindrical surface, swelling pressure reduced by 20% along the end quarters of the other side of its cylindrical surface and fully developed swelling pressure on the ends of the disposal container.	
C	External pressurisation with fully developed swelling pressure over the lower half of the disposal container, swelling pressure reduced by 20% over the upper half of the disposal container and the net upward force due to the difference in pressure on the top and bottom ends applied as shear force along the cylindrical surface on the bottom half of the disposal container	

There are four extreme condition external pressurization load cases and they are as follows:

Load case	Description	Illustration
D	A uniform external pressure of 47MPa, due to a design basis hydrostatic pressure of 10MPa, a design basis swelling pressure of 7MPa and a hydrostatic pressure due to a 3km icecap.	-
E	With the Disposal Package rigidly fixed at both ends and over 1/10th of the length of the cylindrical surface nearest the ends, the Disposal Package shall be subject to a uniformly distributed external pressure of 7MPa, design basis swelling pressure, on one side of the remaining Disposal Package surface.	
F	With the Disposal Package simply supported at two points, each being 1/10th of the length of the Disposal Package from the ends, the Disposal Package shall be subjected to a uniformly distributed external pressure of 7MPa, design basis swelling pressure, on one side of the disposal container surface between the two simple supports.	
G	With the Disposal Package rigidly fixed at one end surface and 1m along the cylindrical surface at the same end, the Disposal Package shall be subjected to a uniformly distributed external pressure of 7MPa, design basis swelling pressure, on one side of the Disposal Package surface along one side of the remaining Disposal Package cylindrical surface.	

The above load cases have been adopted from the SKB/Posiva design ahead of when the specific load case for the UK GDF becomes available.

Impact load cases are defined as follows:

A. Impact in an axis vertical orientation onto a flat unyielding target after a free fall from 8m.
B. Impact onto a flat unyielding target after toppling freely from an upright position.
C. Impact onto a mild steel ledge mounted on a flat unyielding target, after toppling freely from an upright position.
D. Impact in an axis horizontal orientation onto a flat unyielding target after a free fall from 5.5m.

For the impact accident loading scenarios, the requirement was for the disposal container to maintain containment.

Variant 1

In all three of the normal condition external pressurisation loading scenarios, the maximum stresses in the cast iron and carbon steel components of the Variant 1 disposal container were well below the allowable stresses. Therefore, the Variant 1 disposal container design meets the structural requirements for the normal condition external pressurisation loading scenarios.

For the extreme condition external pressurisation loading scenarios, the requirement was for the disposal container to withstand the loading without gross failure or collapse, for leak tightness to be maintained and for there to be a reasonable margin against rupture or collapse.

In the first three of the extreme condition loading scenarios (load cases D, E and F), the maximum plastic strains in the components of the Variant 1 disposal container were well below the material failure strains. Therefore, the Variant 1 disposal container design meets the structural requirements for these three extreme condition external pressurisation loading scenarios.

For extreme condition load case G, the Variant 1 disposal container was unable to sustain the full loading, with the resulting failure of the containment. However, if the strength of the bentonite around the disposal container were accounted for, then it might be possible to show that the disposal container would satisfy the criteria under the revised loading scenario. Therefore, this external pressurisation load case G should be reviewed to establish whether it is reasonable and applicable for the UK disposal systems.

In three of the impact accident loading scenarios (impact load cases A, B and D), the deformations due to the impact were such that no loss of containment was expected. Therefore, the Variant 1 disposal container design meets the structural requirements for these three impact accident loading scenarios.

In impact accident loading scenario C, the disposal container topples onto a mild steel ledge and three different impact locations on the disposal container were assessed:

- Case C1 – The mild steel ledge was placed so that the initial impact location was approximately mid-way along the length of the disposal container.
- Case C2 – The mild steel ledge was placed so that the initial impact location was approximately in line with the inner lid.
- Case C3 – The mild steel ledge was placed so that the initial impact location was on the outer lid, close to the lifting feature.

In impact load cases C1 and C2, the deformations due to the impact were such that no loss of containment was expected. Therefore, the Variant 1 disposal container design meets the structural requirements for impact accident load cases C1 and C2.

However, in impact load case C3, the deformation around the lifting feature was quite large and it is likely that the copper material will fail and containment will be breached. The Variant 1 disposal container is unable to maintain containment in impact load case C3. Significant modifications to the design of the Variant 1 disposal containers would be required if containment were to be maintained. Therefore, it is advisable that the facility in which the disposal containers will be operated be designed such that this impact accident scenario could not happen.

Variant 2

In all three of the normal condition external pressurisation loading scenarios, the maximum stresses in the cast iron and carbon steel components of the Variant 2 disposal container were well below the allowable stresses. Therefore, the Variant 2 disposal container design meets the structural requirements for the normal condition external pressurisation loading scenarios.

For the extreme condition external pressurisation loading scenarios, the requirement was for the disposal container to withstand the loading without gross failure or collapse, for leak tightness to be maintained and for there to be a reasonable margin against rupture or collapse.

In the first three of the extreme condition loading scenarios (load cases D, E and F), the maximum plastic strains in the components of the Variant 2 disposal container were well below the material failure strains. Therefore, the Variant 2 disposal container design meets the structural requirements for these three extreme condition external pressurisation loading scenarios.

For extreme condition load case G, the Variant 2 disposal container was unable to sustain the full loading, with the resulting failure of the containment. However, if the strength of the bentonite around the disposal container were accounted for, then it might be possible to show that the disposal container would satisfy the criteria under the revised loading scenario. Therefore, this external pressurisation load case G should be reviewed to establish whether it is reasonable and applicable for the UK disposal systems.

In three of the impact accident loading scenarios (impact load cases A, B and D), the deformations due to the impact were such that no loss of containment was expected. Therefore, the Variant 2 disposal container design meets the structural requirements for these three impact accident loading scenarios.

In impact accident loading scenario C, the disposal container topples onto a mild steel ledge and three different impact locations on the disposal container were assessed:

- Impact Load Case C1 – The mild steel ledge was placed so that the initial impact location was approximately mid-way along the length of the disposal container.
- Impact Load Case C2 – The mild steel ledge was placed so that the initial impact location was approximately in line with the inner lid.
- Impact Load Case C3 – The mild steel ledge was placed so that the initial impact location was on the outer lid, close to the lifting feature.

In all three of these impact load cases (C1, C2 and C3), the deformations due to the impact were such that no loss of containment was expected. Therefore, the Variant 2 disposal container design also meets the structural requirements for these impact accident load cases.

CONCLUSIONS

Two disposal container concept designs have been developed to suit a range of geological host rock environments:

- Variant 1: copper/cast iron insert disposal container concept
- Variant 2: steel disposal container concept

Each variant has differing internal configurations to accommodate legacy HLW, AGR SF and PWR SF.

The designs have been shown to be suitable for the disposal of legacy HLW and SF and their manufacturability as well as shielding, thermal and structural performance have been technically underpinned.

REFERENCES

[1] NDA, *Geological disposal – Generic transport system designs*, NDA Report No. NDA/RWMD/046, December 2010