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DEVELOPMENT OF A RANGE OF STANDARDISED DISPOSAL CONTAINERS FOR HIGH LEVEL WASTE AND SPENT FUEL DEEP DISPOSAL IN THE UK

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ABSTRACT

The Nuclear Decommissioning Authority (NDA) has established the Radioactive Waste Management Directorate (RWMD) to manage the delivery of geological disposal for higher activity radioactive wastes as required under UK Government policy. 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.

Advantages have been identified by the development of a new range of disposal containers for HLW, AGR and PWR Spent Fuel and the revised disposal container features include; diameter, length, handling feature at both ends, balancing of radiation dose to backfill, construction method and closure arrangement. The advantages include simplified construction and standardisation of handling and emplacement operations at a GDF, simplified procedures, reduced costs, reduction in the number of waste packages, a smaller GDF footprint and a reduction in the material of construction and backfill material.

A project to develop these standardised disposal container designs was carried out in 2011-2012. The work developed two variants of these designs to be compatible with a range of environments, with a ‘corrosion resistant’ variant to provide complete containment of the waste for over 100,000 years and a ‘corrosion allowance’ variant to provide complete containment of the waste for the duration of about 10,000 years. Three internal configurations were considered - for HLW in waste vitrified product (WVP) canisters, AGR spent fuel in slotted fuel cans and PWR spent fuel. The ‘corrosion resistant’ variant has a copper containment boundary with structural cast iron internals, and the ‘corrosion allowance’ variant is a carbon steel construction with internal basket for location of the contents.

This paper presents the conceptual designs of the standardised disposal containers and describes the challenges addressed in the development, when consideration was given to manufacture, shielding and structural performance.

1 INTRODUCTION

The Nuclear Decommissioning Authority (NDA) has established the Radioactive Waste Management Directorate (RWMD) to manage the delivery of geological disposal for higher activity radioactive wastes as required under UK Government policy. 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.

High Level Waste (HLW) and Spent Fuel (SF) from Advanced Gas-cooled Reactors (AGRs) and Pressurised Water Reactors (PWRs) differ in size and shape, and the existing reference designs accommodate these differences by packaging the materials into containers for disposal with markedly different external dimensions. Advantages have been identified by the development of a new range of disposal containers for HLW, AGR and PWR Spent Fuel and the revised disposal container features include; diameter, length, handling feature at both ends, balancing of radiation dose to backfill, construction method and closure arrangement. The developed design concepts would have differing internal configurations to accommodate HLW, AGR SF and PWR SF. The advantages of the new developed design concepts include:

- reduction in the number of disposal containers and GDF footprint.
- reduction of the extent of excavations, spoil generated and materials used for construction.
- common construction for both the disposal container and the deposition hole.
- redundancy in handling features for ease of emplacement operations at a GDF.

A project to develop these standardised disposal container designs was carried out in 2011-2012. The work developed two variants of these designs to be compatible with a range of environments, with a ‘corrosion resistant’ variant to provide complete containment of the waste for over 100,000 years and a ‘corrosion allowance’ variant to provide complete containment of the waste for the duration of about 10,000 years. Three internal configurations were considered - for HLW in waste vitrified product (WVP) canisters, AGR spent fuel in slotted fuel cans and PWR spent fuel. The ‘corrosion resistant’ variant has a copper containment boundary with structural cast iron internals, and the ‘corrosion allowance’ variant is a carbon steel construction with internal basket for location of the contents.

This paper presents the conceptual designs of the standardised disposal containers and describes the challenges addressed in the development, when consideration was given to manufacture, shielding and structural performance.

2 PROJECT TEAM

The 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.

3 OVERVIEW OF THE DISPOSAL CONTAINERS

It is envisaged that High Level Waste (HLW) and Spent Fuel (SF) would be packaged and disposed within robust disposal containers [1]. For the higher strength rock illustrative disposal system design, it has been assumed that the disposal containers would be based on the SKB copper/cast-iron insert disposal container design. For the illustrative disposal system designs in a lower strength sedimentary rock and an evaporite rock, it has been assumed that the disposal container would be based on the NAGRA steel disposal container design.

HLW and SF from Advanced Gas-cooled Reactors (AGRs) and Pressurised Water Reactors (PWRs) differ in size and shape, and the existing reference designs accommodate these differences by employing containers with different external dimensions and internal details.

The objective of the present project is to develop two standardised disposal container design variants to conceptual level:

- Variant 1: Corrosion Resistant Disposal Container Design - copper/cast iron insert disposal container concept based on the SKB KBS-3 disposal container concept
- Variant 2: Corrosion Allowance Disposal Container Design - steel disposal container concept based on the NAGRA disposal container concept

Each Variant will have three Internal Configurations:

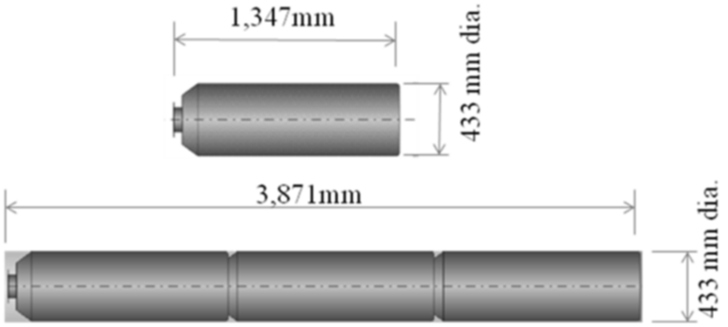
- Internal Configuration 1 – for HLW in waste vitrified product (WVP) canisters
- Internal Configuration 2 – for AGR SF in slotted fuel cans
- Internal Configuration 3 – for PWR SF.

4 WASTE CONTENT TYPES

The contents to be accommodated in the disposal containers are as follows:

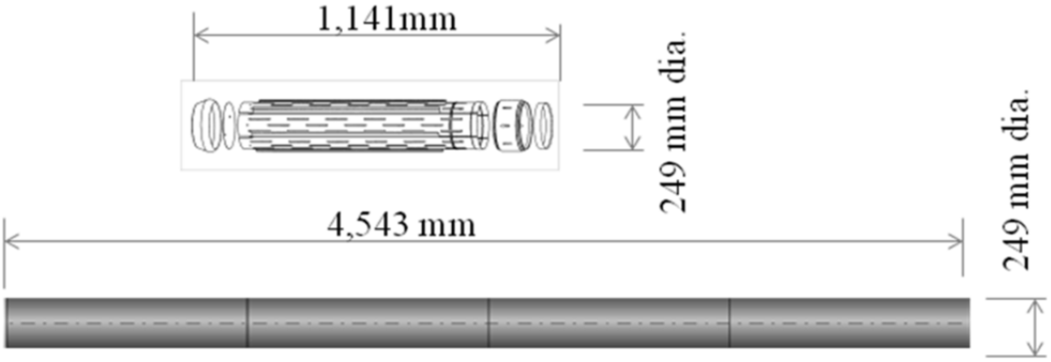
4.1 HLW in WVP canisters

The disposal containers accommodate three HLW WVP canisters aligned along the axis of the disposal container. The envelope dimensions of three stacked HLW WVP canisters are 0.433m in diameter by 3.871m tall. The gross mass of each HLW WVP canister is 550kg. Therefore, the total mass of three HLW WVP canisters is 1650kg.



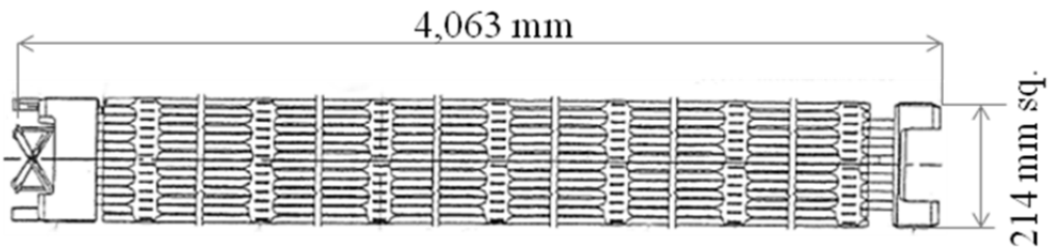
4.2 AGR SF in slotted fuel cans

The disposal containers accommodate 16 slotted fuel cans with AGR SF, arranged in 4 columns with 4 cans in each column. The envelope dimensions of 4 stacked slotted fuel cans are 0.249m diameter by 4.543m tall. The gross mass of a slotted fuel can with AGR SF is 176kg. The total mass of 16 slotted fuel cans with AGR SF is therefore 2816kg.



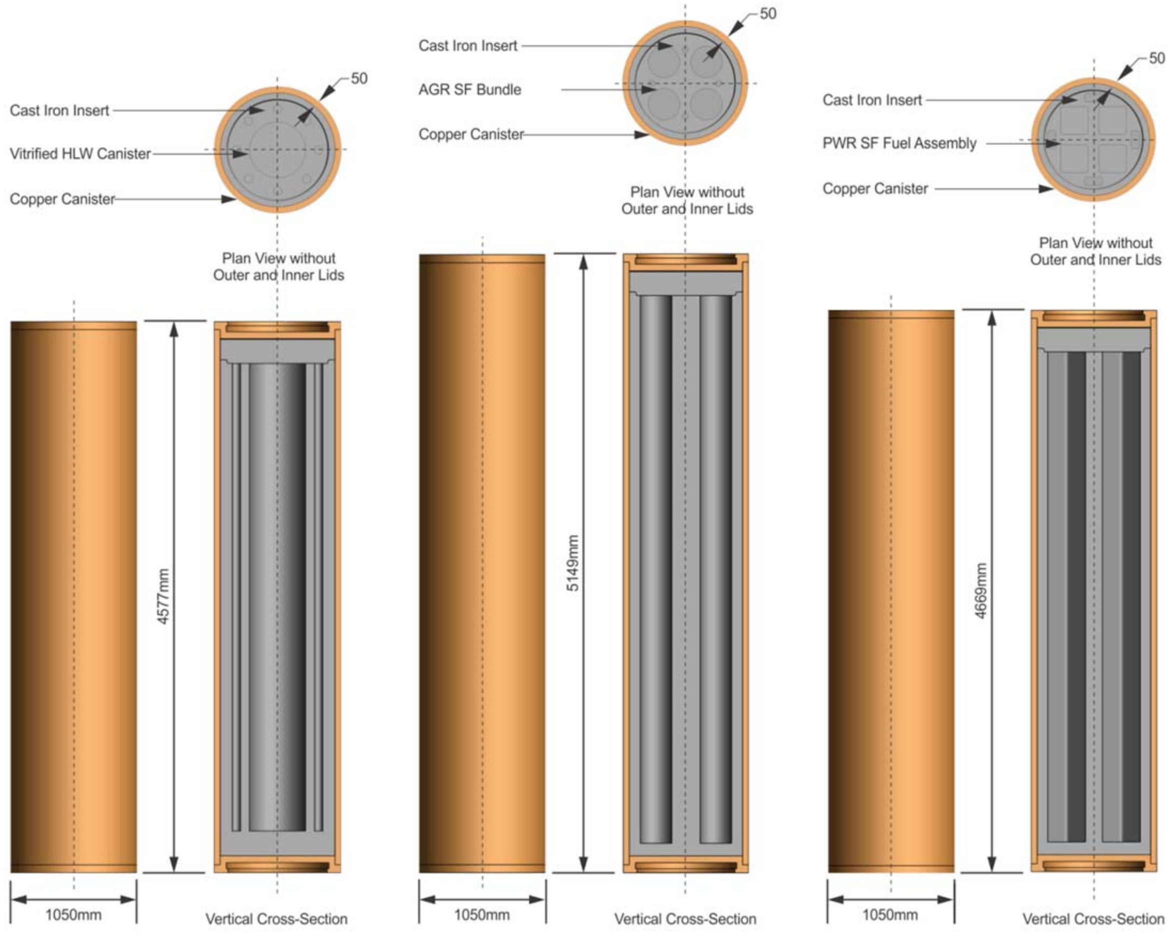
4.3 PWR SF

The disposal containers accommodate four PWR spent fuel assemblies in a 2x2 array. The envelope dimensions of each PWR spent fuel assembly are 0.214m x 0.214m in plan and 4.063m high. The gross mass of each PWR spent fuel assembly is 677kg. The total mass of four PWR spent fuel assemblies is therefore 2708kg.



5 VARIANT 1 DISPOSAL CONTAINERS

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



HLW Waste Container **AGR SF Waste Container** **PWR SF Waste Container**

Figure 1 - Variant 1 Disposal Containers

Each disposal container consists of a copper outer lid, a steel inner lid, a copper outer cylinder body, and an inner cast iron insert with carbon steel tube receptacles.

5.1 Description

5.1.1 Outer Body and Outer Lid

The outer body and outer lid of the Variant 1 containers are made of copper. The external and internal diameters of the outer body are 1050 mm and 950 mm respectively, giving a wall thickness of 50 mm.

The thickness of both ends is 57mm (not including the lifting features around the perimeter of the ends).

Since the disposal containers are tailored for each waste type, the overall length of the outer body is different for different waste content types.

The bottom plate is welded to the bottom of the outer body during the fabrication process. The outer lid is welded to the body after loading the waste contents.

The lifting feature is equipped on the exterior surface of both ends of the disposal container.

5.1.2 Inner Lid

The inner lid design is common for all of the Variant 1 disposal containers. It is made of carbon steel of 200 mm thick with elastomeric double O-ring seals, a leak check hole, a quick connector (for air purging) and 16 bolt holes (for fastening the inner lid to the cast iron inserts with 16 M16 bolts). The 200mm thickness is necessary for radiation shielding when HLW WVP canisters are loaded in the container. In addition to the shielding function, the inner lid is required to perform a temporary containment function during the outer lid welding process after the waste contents have been loaded. The leak check hole and double O-ring seals are also for this temporary containment function.

The inner lid has a spigot of 30mm for ease of location onto the insert and to enhance impact performance. The inner lid is fastened to the cast iron insert by 16 M16 bolts. When the cavity air of the insert is substituted for an inert gas (e.g. helium gas), the air is evacuated first through the quick connector and then helium gas is injected into the cavity. The quick connector is located away from the centre of the inner lid so that the hole in the inner lid for the quick connector (which acts as a shielding weakness) does not line up with the axis of the HLW WVP canisters.

5.1.3 Cast Iron Inserts

The cast iron inserts consist of a cast iron body, receptacle pipe(s) for accommodating the waste content and cooling pipes to aid cooling of the insert during the casting process. The receptacle tube(s) and the cooling pipes are made of carbon steel and closed off at the bottom.

The external diameter of the cast iron insert is 948mm and the overall length varies between 4118mm and 4690mm depending on the waste content. The receptacle tubes are 10mm thick. The cooling pipes in the cast iron insert to aid cooling of the insert during the casting process.

The 16 M16 inner lid bolts fasten into bolt threads around the periphery of the top of the cast iron insert.

5.2 Manufacturing Considerations

The Variant 1 disposal container designs employ copper for the outer corrosion barrier and nodular cast iron for the inner structural element of the container. The Variant 1 disposal container designs, to an extent, are based on the development and manufacturing experience gained in support of the Swedish spent fuel programme reported by SKB [2], who developed the design, materials and manufacturing processes for spent fuel disposal containers over a period extending more than 30 years and, more recently, the work of Posiva. The manufacturing and material considerations are reported in detail in [2] and [3] which describe the Swedish and Finnish developments, respectively.

5.2.1 Manufacture of Copper Corrosion Barrier

It was shown by SKB and Posiva that the copper corrosion barrier could be made by several hot metal working routes including open die forging and extrusion, but ideally was best produced by a pierce and draw hot working method. In this method, a cast, solid, cylindrical, copper billet is heated, pierced and drawn through a die of appropriate diameter with an internal mandrel controlling the inside diameter and wall thickness. This produces a seamless copper tube or a hollow section with the potential to make an integrated bottom and possibly avoiding the need for attaching a base by welding. SKB have also demonstrated a potential method for attaching a copper base using friction stir welding (FSW).

The grade of copper selected by SKB and later adopted by Posiva was an oxygen-free, high conductivity, grade deliberately alloyed with a small amount of phosphorous (30-100ppm) to improve creep ductility in the anticipated service temperature range. The material was specified to have a hot worked and recrystallised fine grained microstructure to minimise ultrasonic attenuation and facilitate inspection and detection of weld flaws. The material is described by EN1976:1988 [4] for the grades Cu-OFE or Cu-OF1 with the additional requirements of:

O < 5 ppm, P 30–100 ppm, H < 0.6 ppm and S < 8 ppm.

It is proposed that, for manufacture of the Variant 1 disposal container designs, the same copper alloy and one of the hot forming manufacturing routes are employed. Forging and extrusion of copper parts of the required size can be sourced in the UK, whilst the pierce and draw process cannot. The major constraint is the maximum ingot size that can be cast by the copper supplier, which is currently 16 tonnes. To produce the SKB/Posiva container (finished weight ~7 tonnes) by the pierce and draw method with an integral base required a 13.4 tonne ingot.

It is proposed that the copper lid (and base, if required) are produced by hot forging to the approximate net shape and machined all over to provide the required geometry, handling feature and fit-up for welding. Hot forging of the lids (and bases) is relatively straight-forward and can be sourced from many small forges. The starting billet size for forging lids and bases (350mm diameter x 1200mm in length) is readily available.

The outer surfaces, ends and internal bore of the copper containers will also be required to be machined for reasons of inspection, avoidance of critical surface flaws and the need to accurately fit a cast iron insert with a minimal radial gap. The accuracy and surface finish requirements are readily achievable by current industrial practice, although boring a blind-ended container with an integral base presents some challenges.

In summary, it has been demonstrated by SKB and Posiva that the copper corrosion barrier proposed in the Variant 1 disposal container designs can be manufactured using existing plant and sourced from several suppliers in both the UK and Europe, with the main constraint being the ready availability of ingots of sufficient size in the copper grade required.

5.2.2 Manufacture of Insert

The manufacture of the type of cast iron inserts in the Variant 1 disposal container designs has been studied and demonstrated by SKB and Posiva in support of the Swedish and Finnish national programmes and the results are immediately applicable. The selection of nodular graphite was based on the combination of strength and ductility obtainable with this material together with the requirement to cast a relatively complex section with appropriate quality and homogeneity.

The SKB and Posiva studies have shown that, for the PWR/EPR (4 square channels), BWR (12 square channels), and VVER-440 (12 round channels) fuel designs, one piece inserts can be made reliably. However, the investigation illustrated the need to control the detailed design to ensure uniformity of the cooling rate during casting, solidification and cool down. The morphology of the graphite, and therefore the properties obtained, in this type of cast iron is affected by the cooling rate from casting, as is the homogeneity and soundness. For this reason, cooling tubes were introduced into the design of the thicker inserts to promote more uniform cooling and development of a consistent microstructure and graphite morphology.

After an extensive study, the material selected for the inserts by SKB/Posiva was a nodular cast iron grade EN-GJS-400-15U [5] with some composition restrictions introduced to reduce risk of radiation embrittlement. Steel guide tubes were cast integrally with the iron insert to provide an accurate guide for the spent fuel structure and these were made from tubular hot finished hollow section steel to EN10210-1 S355J2H [6]. Over 70 units have since been produced successfully and thus this method of manufacture can be considered mature and available from several foundries in the Europe and UK.

One of the key considerations with the use of nodular graphite cast iron is that it is not readily weldable without significant pre-heat (which is impractical in this application) and therefore fixing of temporary closure lids must be achieved by mechanical fastening. This is highlighted in the Variant 1 disposal container designs.

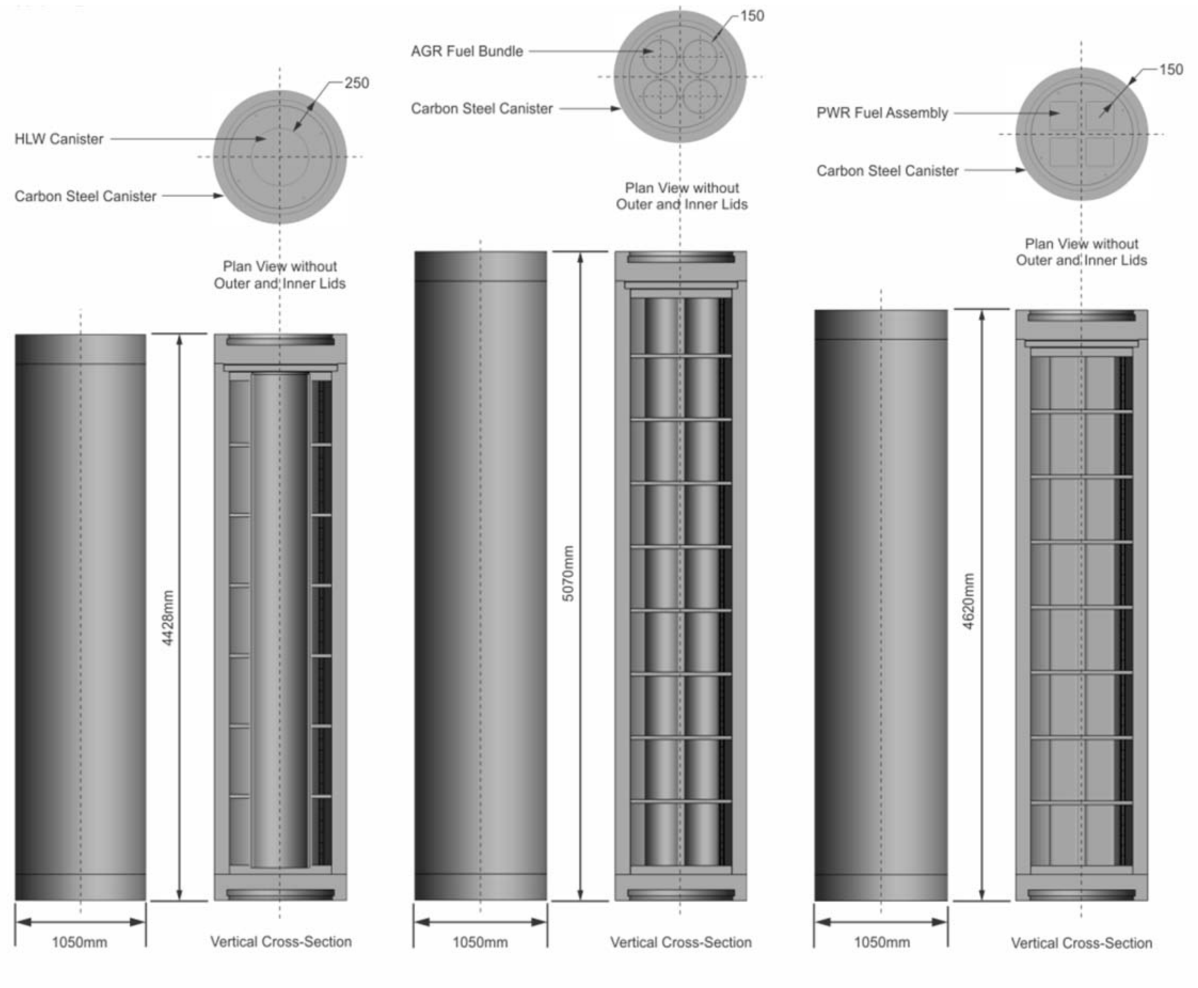
In summary, it is proposed that manufacture of the Variant 1 insert designs follows the SKB/Posiva solution in the use of casting of nodular graphite cast iron with integral steel guide channels produced from Electric Resistance Welded (ERW) stock product. Steel inner lids will be produced from an appropriate grade of hot rolled steel plate to EN10025 S355 [7]. It is recognised, however, that some further development of the casting method will be required to demonstrate that the same degree of homogeneity and properties achieved in the SKB/Posiva insert designs are attainable for the detailed designs proposed for the Variant 1 cast iron insert designs.

6 VARIANT 2 DISPOSAL CONTAINERS

The Variant 2 disposal containers are shown in Figure 2..

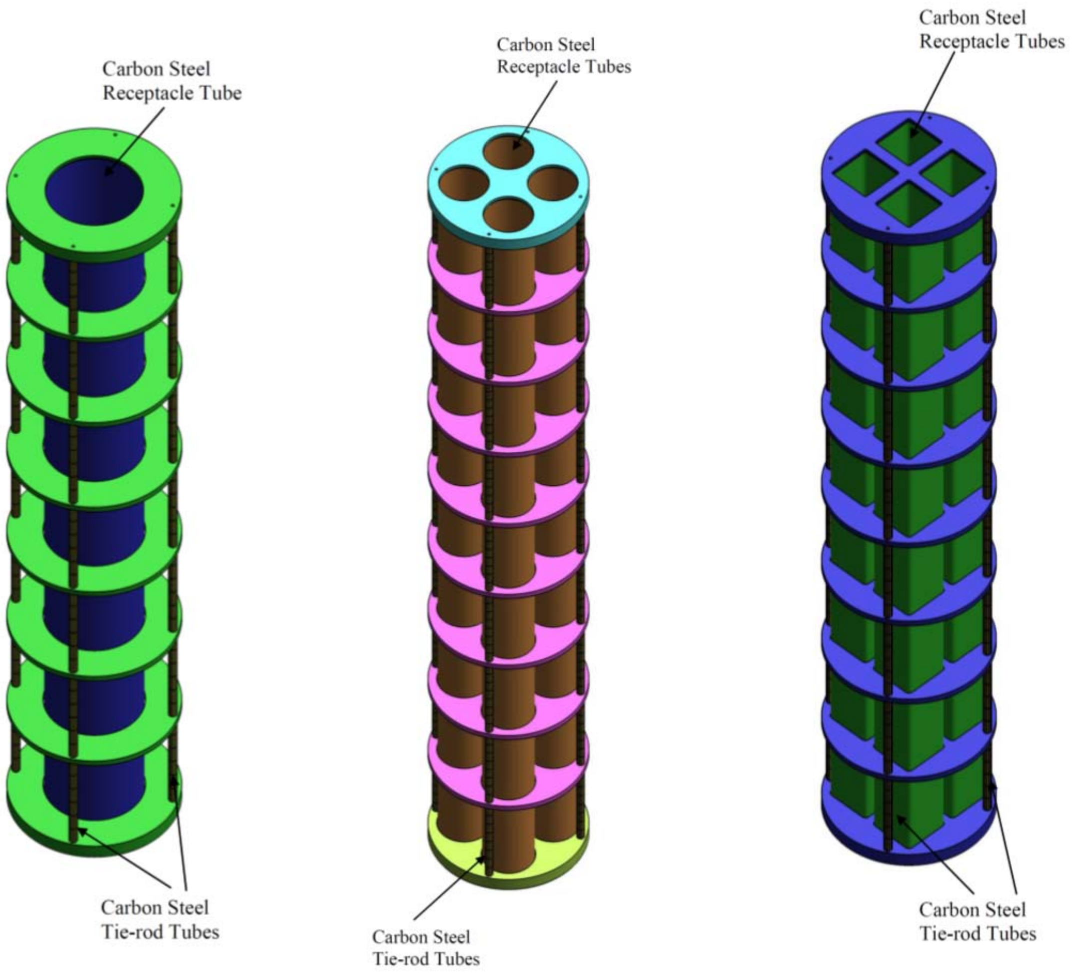
They consist of an outer forged steel lid, an inner steel plate lid, a carbon steel outer cylinder body and a carbon steel “tube and plate” basket.

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



HLW Waste Container **AGR SF Waste Container** **PWR SF Waste Container**

Figure 2 - Variant 2 Disposal Containers



Internal basket of the HLW Waste Container

Internal basket for thee AGR SF Waste Container

Internal basket of the PWR SF Waste Container

Figure 3 – Internal basket of the Variant 2 Disposal Containers

6.1 Description

6.1.1 Outer Body and Outer Lid

The outer body and outer lid of the Variant 2 containers are made of carbon steel. The external and internal diameters of the outer body are 1050mm and 810mm respectively. The thickness of the shell is 120mm. The thickness of the outer lid is 150mm and that of the bottom is 120mm.

The disposal container is tailored for each waste content type, so the overall length of the outer body is different for different waste content types.

The bottom plate is welded to the bottom of the outer body during the fabrication process. The outer lid is welded to the body after loading the waste contents.

6.1.2 Inner Lid

The inner lid design is common for all of the Variant 2 containers.

It is made of carbon steel of 50mm thick with elastomeric double O-ring seals, a leak check hole, a quick connector (for air purging) and 16 bolt holes (for fastening the inner lid to the carbon steel outer body). The inner lid is required to perform a temporary containment function during the outer lid welding process after the waste contents have been loaded. The leak check hole and double O-ring seals are also for this temporary containment function.

The inner lid is fastened to the outer body by 16 M16 bolts. When the cavity air of the disposal container is substituted for an inert gas (e.g. helium gas), the air is evacuated first through the quick connector and then helium gas is injected into the cavity.

6.1.3 Baskets

The baskets for the different waste contents all consist of receptacle tubes for the waste contents, top and bottom plates, between six and eight support plates, tie rod pipes and tie rods to hold the whole basket assembly together. All the components of the basket are made of carbon steel. No welding is required in the basket assembly.

The thickness of all the receptacle tubes is 10mm and they sit in a 20mm deep recess in the bottom plate of the basket. The top of the receptacle tube sits within the top plate of the basket, which has a 20mm thick lip to cover the top edge of the receptacle tube.

The support plates are evenly spaced between the top plate and bottom plate to support the receptacle tube along its length. The thickness of each support plate is 30mm.

Between the support plates and top and bottom plates there are tie rod tubes which maintain the spacing of the support plates. The tie rod tubes have an outer diameter of 40mm and an internal diameter of 35mm (i.e. a wall thickness of 2.5mm). There are four 30mm diameter tie rods that pass through the tie rod tubes and the support plates. These four tie rods are used to hold the basket assembly together. Nuts on the ends of the tie rods are tightened against the top and bottom plates, effectively ‘clamping’ the top and bottom plates of the basket to the receptacle tube.

6.2 Manufacturing Considerations

The Variant 2 disposal container designs employ carbon steel as the combined corrosion barrier and structural element with an internal basket structure to support and maintain separation of the fuel (in the case of the AGR and PWR spent fuel disposal containers).

This arrangement has been studied (although to a lesser extent than the copper option) by several other organsations, but it is recognised that the use of steel for long term geological burial of spent fuel and high level nuclear waste has a number of advantages.

6.2.1 Outer cylinder

The Variant 2 disposal container designs use a thick-walled container with an integral base with the intention of providing a corrosion barrier and load bearing structure, which is closed and sealed by welding prior to emplacement and burial. Similar to the copper option, it is this requirement for closure welding that acts as the driver of many of the materials requirements. The design calculations have taken into account the need for resisting long term loss of thickness through corrosion, the hydrostatic and lithostatic loads emanating from long term burial and also radiation shielding issues.

The need for remotely operated closure welding, such as Narrow Gap TIG or Electron Beam (EB) welding processes, and its impact on potential failure mechanisms for the waste package, drive the steel type used for the disposal container to be a plain carbon steel with relatively low tensile properties. The adoption of more highly alloyed, higher strength material brings an attendant risk of stress corrosion and hydrogen assisted cracking mechanisms with added potential for brittle fracture if post weld stress relief cannot be readily performed.

The critical issues in defining the material and manufacturing route for the steel container are that it should be readily weldable (to facilitate closure welding), have uniform, predictable corrosion behaviour in the intended environment, have good inherent integrity and can be produced readily by several suppliers

It is suggested for the Variant 2 disposal container designs that the main container components are produced in forged steel equivalent or similar to ASTM A350 LF2 [8], which is a plain carbon steel that can achieve the required mechanical properties in heavy sections. The precise composition specification may need to be restricted to minimise carbon equivalent and controlled to ensure that impurity elements, such as sulphur and phosphorous and residual gas content, do not impact on weldability, corrosion performance or fracture toughness properties, whilst meeting the minimum requirements for tensile strength.

It is possible that tuning the material composition specification by minor alloy additions would be required, which would be achieved through a development programme conducted with collaboration from the melting and forging companies.

It is possible to produce the component parts designed for the Variant 2 disposal container by a variety of methods. Steel casting, hot forming and welding fabrication, as well as the pierce and draw method, used for the Variant 1 disposal containers are all possibilities. On balance, without more detailed consideration of the requirements listed, it is proposed that open die forging is used to produce the main disposal container body and the lid/base structures.

Producing the parts by casting leads to concerns about inspection and surface flaws, which are particularly undesirable in this application where long term corrosion performance is a paramount and where weld repairs could lead to localised corrosion issues. Similarly, hot pressing the disposal container body halves from plate and welding is a possible route, but introduces a greater risk of weld flaws in the structure.

Open die forging can be used to make a hollow section tubular with integral base, as can the pierce and draw hot forming method, but in both cases any segregation of impurities in the cast forging stock will be concentrated in the centre of the base and potentially lead to a loss of integrity or mechanical heterogeneity in this critical region. The preferred option is to produce a seamless hollow forging and to attach a separate forged steel base by welding. By applying a full homogenising, normalise and temper heat treatment to the assembly, the risk of unacceptable flaws is minimised. The forged product will be fine grained, simple to inspect and have inherent integrity introduced by the large degree of hot work involved in the process of forging. Typically a solid, cast ingot of 700mm diameter would be upset, hollow punched and drawn on a becking bar through a series of stages to produce a hollow tube of approximately 5m in length and 1100mm outside diameter. The lid and base forgings could use the same starting stock (giving consistency of composition) and be forged as simple discs, as shown in Figure 4 below.

Figure 4 - Open die forged steel disc before machining of lid detail

Following forging, heat treatment and inspection, the parts will be machined to produce the design details shown for the Variant 2 disposal container options (see Figure 5). The surface finish and accuracy requirements are not demanding and can be achieved with conventional machining equipment which is readily available with sufficient capacity throughout Europe and in the UK.

Hollow open die forging is commonplace and several facilities exist in Europe and the UK with capacity to produce the component parts listed for the Variant 2 disposal containers.

Figure 5 - Open die forged tube before and after final machining

In summary, it is proposed that the container body and ends for the Variant 2 disposal container designs are produced using open die forging of plain carbon steel to a bespoke specification, but contained within or equivalent to ASTM A350LF2 [8]. Clearly, however, evidence of the suitability of the steel, the preferred closure welding process and its influence on residual stress and properties needs to be developed and demonstrated for deep geological disposal of HLW and SF in steel containers in a similar way to how the copper design has been studied.

6.2.2 Inner Lid and Baskets

The internal structure of the disposal container, including the waste contents support basket and inner lids are all produced from a common structural steel grade. The receptacle tubes are produced from tubular hot finished hollow section steel to EN10210-1 S355J2H [6] of the required dimensions and geometry, whilst the inner lid, support plates and top and bottom plates will be machined from an appropriate grade of hot rolled plate to EN10025 S355 [7].

7 SHEILDING PERFORMANCE

Shielding calculations were carried out to determine dose-rates on the surface of the disposal containers. Calculations were performed for each waste content type: High Level Waste (HLW), AGR spent fuel (AGR) and PWR spent fuel (PWR). The maximum inventories have been used in the calculations, so that the calculated dose-rates are bounding.

There are two design criteria for the surface dose-rate, as given in the Design Specification:

- The dose-rate at the surface of the disposal container is not to exceed 1Gy/hr.
- 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.

The second design criterion is only a desirable target and the other aspects of the disposal container design should not be significantly compromised in trying to meet this design criterion.

7.1 Variant 1 - Copper

The maximum primary gamma-ray dose-rate for the Variant 1 disposal container was calculated to be 0.04Gy/hr, well within the 1Gy/hr limit. This occurs for PWR SF assemblies at the side of the disposal container. The maximum dose-rates at the top and bottom of the container never exceed 0.03Gy/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 no shielding plug is required.

For the Variant 1 disposal canister with HLW, the maximum dose-rates at the top, sides and bottom of the canister are similar (within a factor of 3). For the Variant 1 disposal canister with AGR and PWR spent fuel, the shield thickness at the bottom of the canister is considerably less than at the top. For these cases, the maximum dose-rates at the sides and bottom of the canister are similar (within a factor of 2), but those at the top are much lower (by a factor of around 100 or more).

The secondary “desirable” design criterion (that dose-rates should be similar on the top, sides and bottom of the disposal canisters) has been partially met. The variations in the dose-rate around the Variant 1 disposal canister are judged to be acceptable, since altering the disposal canister design to meet the criterion more fully would compromise other aspects of the design such as the disposal canister size and weight.

7.2 Variant 2 - Steel

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 for HLW 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 no shielding plug is 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.

The secondary “desirable” design criterion (that dose-rates should be similar on the top, sides and bottom of the disposal containers) has been partially met. The variations in the dose-rate around the Variant 2 disposal container are judged to be acceptable, since altering the disposal container design to meet the criterion more fully would compromise other aspects of the design such as the disposal container size and weight.

8 THERMAL PERFORMANCE

The thermal performance of the disposal containers has been assessed for both normal and fire accident conditions in the Geological Disposal Facility (GDF). 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 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 disposal concepts for the GDF [9], the bounding scenario for normal conditions (deposition) is shown to be higher strength rock. Also, of the three types of waste intended for disposal (PWR spent fuel, AGR spent fuel and HLW), 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 in higher strength rock and a bentonite buffer. The limiting condition is found to be the target temperature of 100°C at the interface of the bentonite with the container surface [9].

For Sizewell B fuel with average burnup of non-reprocessed uranium, the initial heat load per container is calculated to be 1477W at 2090, reducing to 1290W at 2100 and to the nominal 1200W value by 2112. By assuming an emplacement date of 2100, the thermal calculations show that the 100°C temperature target is just met for both Variant 1 and 2 disposal containers. The peak temperature is found to occur 50 to 60 years after emplacement.

8.1 Variant 1

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 Variant 1 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 1 disposal container design is therefore claimed to satisfy the thermal performance criteria.

8.2 Variant 2

For accident conditions, the Variant 2 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 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 container design is therefore claimed to satisfy the thermal performance criteria.

9 STRUCTURAL PERFORMANCE

The structural performance of the disposal containers has been assessed and the structural loading scenarios, as defined in the Design Specification [9], 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.

Impact load cases are defined in the Design Specification 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. The integrity of the waste contents was not assessed and was beyond the scope of the present project.

9.1 Variant 1

For the Variant 1 disposal container, the lifting feature was shown to be capable of sustaining the lifting load and, assuming that the lifting operation will be made with contact at three equi-spaced positions, each of the three lifting points will need to have a bearing area of 5855mm^2.

The pessimistic estimate of the internal pressure that would cause failure of the outer body of the Variant 1 disposal container and loss of containment is 14MPa.

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 not break or collapse, for leak tightness to be maintained and for there to be a reasonable margin against rupture or collapse.

There were four different extreme condition loading scenarios (load cases D, E, F and G). 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:

- 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 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 lost. 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.

9.2 Variant 2

For the Variant 2 disposal container, the lifting feature was shown to be capable of sustaining the lifting load and, assuming that the lifting operation will be made with contact at three equi-spaced positions, each of the three lifting points will need to have a bearing area of 621mm^2.

The pessimistic estimate of the internal pressure that would cause failure of the outer body of the Variant 2 disposal container and loss of containment is 71MPa.

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 not break or collapse, for leak tightness to be maintained and for there to be a reasonable margin against rupture or collapse.

There were four different extreme condition loading scenarios (load cases D, E, F and G). 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.

10 CONCLUSIONS

Two standardised disposal container concept designs have been developed:

- Variant 1: Corrosion Resistant Disposal Container Design - copper/cast iron insert disposal container concept
- Variant 2: Corrosion Allowance Disposal Container Design - steel disposal container concept

and each variant has differing internal configurations to accommodate 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 demonstrated.

REFERENCES

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

[2] SKB, Test manufacturing of copper canisters with cast inserts - Assessment report, Technical report TR-98-09, August 1998.

[3] POSIVA OY, Manufacture of Disposal Canisters, POSIVA 2009-03, December 2009.

[4] British Standards Institution, Copper and copper alloys, Cast unwrought copper products, BS EN 1976:1998, August 1998.

[5] British Standards Institution, Founding – Spheroidal graphite cast irons, BS EN 1563:2011, December 2011.

[6] British Standards Institution, Hot finished structural hollow sections of non-alloy and fine grain steels. Part 1: Technical delivery requirements, BS EN 10210-1:2006, May 2006.

[7] British Standards Institution, Hot rolled products of structural steels – Part 2: Technical delivery conditions for non-alloy structural steels, BS EN 10025-2:2004, November 2004.

[8] American Society for Testing and Materials, Standard Specification for Carbon and Low-Alloy Steel Forgings, Requiring Notch Toughness Testing for Piping Components, ASTM A350 / A350M – 12, 2012.

[9] Arup, Development of Standardised Disposal Canister Designs – Design Specification, Doc. Ref. 218762-01-02, Issue 2, May 2012.