Radioactive Waste Management

RWM TECHNICAL NOTE No. 23383092

Generic Design Assessment

Summary of Disposability Assessment for Wastes and Spent Fuel arising from Operation of the UK ABWR

November 2016

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Conditions of Publication

Generic Design Assessment: Summary of Disposability Assessment for Wastes and Spent Fuel arising from Operation of the UK ABWR

1 Introduction

The 2008 White Paper on Nuclear Power [1], together with the preceding consultation [2], established the process of Generic Design Assessment (GDA), whereby industry-preferred designs of new nuclear power stations would be assessed by regulators in a pre-licensing process. Hitachi-GE Nuclear Energy, Ltd (Hitachi-GE), a strategic global alliance between Hitachi Limited and General Electric (GE) founded in 2007, is proposing to develop and construct nuclear reactors in the UK based on the United Kingdom Advanced Boiling Water Reactor (UK ABWR) design, and has, therefore, requested assessment of the design under the GDA process.

An important aspect of the GDA process is the consideration of the disposability of the higher-activity solid radioactive wastes and spent fuel that would be generated through reactor operation. Consequently, regulators have indicated that a "*requesting party should obtain and provide a view from the Nuclear Decommissioning Authority (NDA) (as the authoritative source in the UK in providing such advice) on the disposability in a geological disposal facility of any proposed arisings*" of higher-activity wastes or spent fuel [3].

In accordance with regulatory guidance, Hitachi-GE has requested that Radioactive Waste Management Limited (RWM), a wholly-owned subsidiary of the NDA, provides advice on the disposability of the higher-activity wastes and spent fuel expected to arise from the operation of the UK ABWR. The assessment of the disposability of the higher-activity wastes and spent fuel from the UK ABWR is based on information on wastes and spent fuel, and proposals for waste packaging supplied by Hitachi-GE, supplemented as necessary by relevant information available to RWM.

The principal conclusions of this GDA Disposability Assessment are presented in this Summary Disposability Report, together with the details of the wastes and their characteristics, as applied in the assessment. More comprehensive details of the information supplied to RWM by Hitachi-GE, measures taken by RWM to supplement this information, assessment methods and the detailed conclusions of the GDA Disposability Assessment will be provided in a separate Assessment Report for the UK ABWR.

The GDA Disposability Assessment process is summarised in Appendix A and comprises three main components: a review to confirm the waste and spent fuel properties; an assessment of the compatibility of the proposed waste packages with concepts for the geological disposal of higher-activity wastes; and identification of the main outstanding uncertainties, and associated research and development needs, relating to the future disposal of the wastes. A summary of the radionuclide assessment inventories, wasteform descriptions and packaging assumptions for intermediate level waste (ILW) and spent fuel derived for the purposes of this GDA Disposability Assessment are set out in Appendix B.

It is recognised that, at this early stage in the development of reactor designs and operating regimes, all proposals are necessarily outline in nature. However, this Disposability Assessment has made assumptions to allow the production of a comprehensive and detailed data set describing the ILW and spent fuel to be generated from operation and decommissioning of a UK ABWR. At a later stage, more specific and detailed proposals will be required for endorsing waste packaging proposals through the existing Letter of Compliance process [4].

The number and type of new build reactors that may be constructed in the UK is currently not defined. The inventory for disposal is used by RWM to plan for the disposal of historical and currently arising wastes, and wastes from new nuclear build reactors [5]. This GDA

Disposability Assessment has evaluated the implications of a single UK ABWR and, to illustrate the potential implications for geological disposal of constructing and operating a fleet of such reactors, consideration has also been given to the wastes from a fleet of four UK ABWRs operating for 60 years. This is consistent with current plans to construct two UK ABWRs at Wylfa and two at Oldbury. In order to assess the implications of operation of a fleet of four UK ABWRs, the wastes expected to arise from these reactors have been compared to wastes for disposal from new nuclear build reactors with an equivalent generating capacity in the existing inventory. This illustrative approach is considered to be a straightforward and pragmatic assumption for this assessment, and no inference should be drawn for wider UK planning purposes.

2 Nature of the ILW and Spent Fuel

Hitachi-GE has provided information on the ILW and spent fuel expected to arise from a UK ABWR operating for 60 years, with two different fuel assembly burn-up scenarios: 60 GWd/tU and 50 GWd/tU. In line with the White Paper [1], spent fuel from a new nuclear power programme is assumed to be managed by direct disposal after a period of interim storage.

Three general categories of higher-activity waste and spent fuel are identified:

- Operational ILW: ILW arising from the operation of a reactor.
- Decommissioning ILW: ILW arising from the eventual decommissioning of a reactor.
- Spent fuel: Used nuclear fuel arising from reactor operation.

Based on the stated assumptions, Hitachi-GE has provided information for the following eight types of operational ILW[1]:

- Condensate Filter Facility (CF) Crud.
- Low Conductivity Waste (LCW) Crud.
- Reactor Water Clean-up (CUW) Resin.
- Fuel Pool Cooling Clean-up (FPC) Resin.
- Post-operational Decontamination (DEC) Resin.
- Hafnium (Hf) Control Rods.
- Boron Carbide (B_4C) Control Rods.
- Mixed Metal ILW.

Hitachi-GE has indicated that the decommissioning ILW should be assumed to comprise the more highly activated steel components that make up two waste streams:

- Reactor pressure vessel internals.
- Reactor pressure vessel.

Information on decommissioning ILW has been assessed based on separation of the wastes into these two waste streams. Decommissioning ILW also comprises a small volume of stainless steel filter housings, which are assessed as additional material in the two decommissioning ILW streams. In practice, decommissioning wastes will comprise a mix of ILW and low-level waste (LLW), but, following discussion with Hitachi-GE, it has been agreed

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1 "Operational" ILW includes some of the ILW generated during post-operational decontamination operations, i.e. Post-operational Decontamination Resins, and small quantities of CUW and FPC resins. These wastes have been assessed alongside the operational ILW as they are of a similar chemical and physical form to the ion exchange resins generated during operations.

to make the conservative assumption that decommissioning wastes will be managed as ILW. Further development of decommissioning plans in the future will provide an improved understanding of the expected quantities of ILW, although that detail is not required for this GDA Disposability Assessment.

The fuel used in a UK ABWR is expected to consist of ceramic UO_2 pellets encased in Zircaloy-2 cladding to form a fuel rod. It has been stated by Hitachi-GE that fresh natural uranium will be enriched to manufacture the fuel, i.e. recycled uranium is not assumed in the GDA application. The UK ABWR is expected to use the GE14 type of fuel assembly, which comprises a 10x10 array of fuel rods, consisting of 78 full-length fuel rods, 14 part-length rods which span roughly two-thirds of the active core, and two large central water rods occupying the remaining 8 pin locations, all housed in a zirconium alloy channel, which is specifically assumed as Zircaloy-2 in the assessment. As indicated above, information on spent fuel has been supplied by Hitachi-GE based on an assumed fuel assembly burn-up of 60 GWd/tU and 50 GWd/tU. The two radionuclide inventories developed from the information assume that all fuel assemblies would achieve this burn-up. Hitachi-GE has indicated that, in practice, 60 GWd/tU would represent the maximum of a range of burn-up values for individual fuel assemblies.

3 Proposals for Waste Packaging

Hitachi-GE has put forward proposals for the packaging of operational ILW based on the well-established current practice for similar wastes in the UK. The Disposability Assessment has assumed that crud and resin wastes would be grout cemented into $3m^3$ Drums using in-drum, lost-paddle mixing to ensure a homogeneous wasteform, and that control rods and mixed metal ILW would be grout cemented into $3m^3$ Boxes. The operational crud and resin waste streams would be packaged as they arise. The $3m^3$ Drums and Boxes would need to be transported in a reusable shielded transport overpack to meet the requirements of the transport regulations.

The proposals for the packaging of decommissioning ILW are based on the use of UK standard waste containers consistent with RWM standards and specifications. The reactor vessel ILW is assumed to be grout cemented into 4m Boxes with 200-mm thick concrete walls. Following consideration by RWM of the dose rates from waste packages, it has been concluded that reactor internals ILW would need to be grout cemented into $3m^3$ Boxes.

The GDA Disposability Assessment for the spent fuel from the UK ABWR was based on it being over-packed for disposal. For the purposes of this assessment, disposal using robust disposal containers manufactured from either copper or steel has been considered. It has been concluded that each disposal container would contain twelve fuel assemblies from a UK ABWR. It is further assumed that the spent fuel would be delivered to the disposal facility packaged in the disposal containers, which in turn would be transported in a reusable transport container.

Proposals for packaging ILW and spent fuel are described in more detail in Appendix B.

4 Radionuclide Inventory of ILW and Spent Fuel

The information supplied by Hitachi-GE on the radionuclide inventories of the identified ILW and spent fuel has been used to derive assessment inventories for the various proposed waste packages, including package-specific inventories for the ILW and spent fuel. These inventories are summarised in Appendix B. In all cases, to ensure a full coverage of potentially significant radionuclides, it has been necessary to supplement the information supplied by Hitachi-GE using additional information available to RWM. The assessment inventories are intended to characterise the range of waste package inventories, taking account of the potential variability between packages, and other uncertainties. Typically, an assessment inventory includes a best-estimate (average) and bounding (maximum) inventory for a waste package to encompass such variability and uncertainty.

The uncertainties in the inventories arise from numerous sources, for example the detailed reactor operating regime adopted, including fuel burn-up, and the waste package loadings that would be achieved in practice. The GDA Disposability Assessment has used best endeavours to bound this uncertainty and thereby provide robust, conservative conclusions. It is anticipated that information on the inventories associated with the ILW and spent fuel would be refined as the design of the reactors and their operating regimes are developed further. Such information, together with more refined packaging proposals, would be considered at an appropriate time in the future through the Letter of Compliance process.

Uncertainties that will need to be addressed at later stages of assessment include information on the detailed compositions of the steels used for the control rods and mixed metal ILW, most notably the concentration of cobalt in the steels. Currently, a pessimistic value for cobalt concentration has been used as Hitachi-GE did not provide an accurate concentration.

Reactor water chemistry could have a significant impact on the crud and resin waste streams, and inventory calculations for these waste streams applied Hitachi-GE's proposed UK ABWR-specific water chemistries, based on data supplied by Hitachi-GE but supplemented by RWM.

For decommissioning ILW, consideration should be given to the potential for some of the reactor vessel steels being consigned to LLW management routes. Hitachi-GE activities of reactor pressure vessel ILW considered activation of the pressure vessel steels. In addition to activation, contamination of the steels could occur, for example, through deposition of corrosion products on the surface of the pressure vessel. Therefore, the impact of contamination was included in the enhanced inventories used to assess the reactor pressure vessels in this Disposability Assessment. When refined inventories are developed for use in more detailed stages of the Letter of Compliance process, the potential for contamination of reactor pressure steels would need to be considered further alongside activation inventories.

The spent fuel assembly inventories have been checked by RWM using independent calculations and confirmed to be conservative. The spent fuel inventory supplied by Hitachi-GE is based on ORIGEN v2.2 modelling using Japanese nuclear data libraries. ORIGEN is a state-of-the-art isotope depletion and decay analysis code used internationally for safety analysis and licensing studies of used fuel facilities. There are some differences between the arrangement of fuel assemblies in a UK ABWR and the arrangement modelled in the data libraries used by Hitachi-GE, but the neutron spectra used in the modelling are considered to be representative. The RWM calculations used ORIGEN-ARP, which includes a 2D cross-section of the GE14 fuel assembly and produces a conservative estimate of radionuclide inventories.

RWM has concluded that the inventory data supplied by Hitachi-GE, augmented by supplementary data as required, has provided a robust and conservative data set sufficient to provide confidence in the calculations of the GDA Disposability Assessment.

This Disposability Assessment of the UK ABWR is the first time that disposal of wastes from a boiling water reactor has been considered in the UK; the most similar reactor that has previously been considered is the Pressurised Water Reactor (PWR). Boiling water reactors operate at lower pressures than PWRs, and the reactor pressure vessel is larger in volume. This means that there will be a greater mass of decommissioning wastes produced from the UK ABWR relative to a PWR. However, as the gap between the reactor core and the wall of the pressure vessel is filled with a mixture of stainless steel and water, the neutrons emanating from the core will be more strongly attenuated, resulting in lower activation of the steels in the reactor pressure vessel. The resulting wastes will therefore be less active and, assuming like-for-like packaging, would give lower dose rates. Fuel assemblies used in a UK

ABWR are smaller than those used by PWRs. This would result in a larger number of spent fuel assemblies being packaged in each disposal container.

In PWRs, control rods are incorporated as part of the fuel assembly and might be managed alongside the spent fuel. In the UK ABWR, control rods are inserted between every four fuel assemblies, and are expected to be managed separately as ILW. Owing to their proximity to the fuel assemblies, these components see a high neutron flux and will need to be packaged and managed appropriately.

Despite the differences between the UK ABWR and PWRs, both designs are light water reactors, with fuel pellets fabricated from uranium dioxide with similar enrichments of U-235, and with broadly similar energy outputs. Both designs use zirconium-based cladding, and stainless and carbon steel, zirconium-based and Inconel metals in the spent fuel assembly and reactor vessel. Therefore, it is to be expected that the radionuclides listed in the waste and spent fuel inventories and the activities of these radionuclides will be broadly similar. This is borne out by a comparison of radionuclide inventories for the most active ILW stream and for spent fuel from the two reactor types, which is presented in Appendix B.

5 Assessment of Proposed ILW Packages

The proposals for the packaging of ILW are based on solid wasteforms that provide for the immobilisation of the activity associated with waste. Detailed arguments and supporting evidence on the performance of the proposed packages are currently not available. This is consistent with expectations for the GDA Disposability Assessment. In future, fully-developed proposals would need to be provided for assessment through the Letter of Compliance process.

The proposed use of cementitious grout for waste conditioning conforms to existing practices for similar wastes in the UK and is expected to produce packages that would be compliant with existing RWM standards and specifications, and, therefore, would be compliant with the systems assumed for transport of waste packages to, and disposal of waste packages in, a geological disposal facility, and also compliant with the associated safety cases for the facility. Meeting these standards and specifications might require specific packaging solutions, e.g. use of suitable loading factors and decay storage, for wastes with relatively high activities, for example the hafnium control rods.

The proposal to use RWM standard waste containers provides compliance with many aspects of the existing standards and specifications. Furthermore, the assessment has assumed that transport of the waste packages would be based on transport in a reusable shielded transport overpack to ensure compliance with the dose-rate limits set out in the IAEA Transport Regulations.

The resin waste streams are bead and powder mixed bed anionic and cationic cross-linked, polystyrene-based resins. Hitachi-GE has not provided information on the functional groups on the resins. Similar resins have been assessed previously, for example for Sizewell B, and deemed to be disposable. The chemical constituents would need to be further defined by the UK ABWR reactor operator in any subsequent Letter of Compliance submission for the ABWR wastes.

The assessment of the long-term disposal system performance in the GDA Disposability Assessment has been based on the assumed characteristics for a generic UK geological disposal facility site. Since the properties of any selected site would need to be consistent with meeting the regulatory risk guidance level [6], based on the approach adopted for Letter of Compliance assessment, this assessment assumed a groundwater flow rate and return time to the accessible environment that would meet regulatory requirements when considering the inventory of historical and currently arising ILW. The additional radionuclide inventory associated with the ILW from a UK ABWR represents only a small fraction of that of the historical and currently arising wastes, particularly for the majority of the radionuclides that determine risk in the long-term. Even considering the conservative approach to inventory assessment and recognising the potential for future optimisation of packaging proposals, the additional risk from the disposal of ILW from a single UK ABWR in a site of the type described would be consistent with meeting the regulatory risk guidance level. The consideration of such a fleet of reactors does not alter this conclusion.

Particular issues that will require further evaluation if and when the plans for the ABWR are taken further include:

- The optimum time for disposal of the ILW and spent fuel. In particular, Hitachi-GE have proposed disposing of the wastes shortly after they arise. For some of the waste streams, this raises concerns in meeting transport limits and operational limits at the GDF. These can be addressed by a period of decay storage for the relevant wastes.
- Hitachi-GE proposed that the RPV decommissioning wastes were packaged in 4m boxes. The evaluations found that a significant period of decay storage would be required before some of the wastes from this waste stream could be transported and placed in the proposed GDF if these containers were used. It was therefore recommended that these wastes should be placed in $3m^3$ boxes and transported in Standard Waste Transport Containers.
- The control rods in the ABWR design differ from those in the previously assessed PWR designs where the potential exists to dispose of with the spent fuel. In the case of the ABWR, the control rods, both hafnium and boron carbide variants, are separate from the fuel assemblies and are proposed to be disposed of as ILW. The nature of these wastes is inherently challenging and they will require a period of decay storage prior to Hitachi-GE's proposal for grout encapsulation in $3m^3$ boxes. While they raise no insurmountable issues precluding disposal, they will need to be subject to further assessment as the disposal plans are further developed.

Overall, the proposals for the packaging of operational and decommissioning ILW have been judged to be potentially viable. While further development needs have been identified, including the need to demonstrate the expected performance of the proposed waste packages, these would be the subject of future assessment under the Letter of Compliance process when further details on the packaging proposals have been developed.

The potential impact of the disposal of UK ABWR operational and decommissioning ILW on the size of a geological disposal facility has been assessed. It has been concluded that the 'footprint area' required to dispose of ILW from a UK ABWR corresponds to approximately 45m of vault length for each UK ABWR (178m for a fleet of four reactors) for higher strength rock. For the illustrative fleet of four UK ABWR reactors, this represents no significant change in the overall footprint compared with current assumptions based on the inventory for disposal.

6 Assessment of Spent Fuel Packages

Hitachi-GE has indicated that the GDA Disposability Assessment for the UK ABWR should assume that the reactor would use fuel elements made from uranium dioxide enriched in U-235, and operated to achieve a maximum fuel assembly average burn-up[2] of 60 GWd/tU and an average burn-up of 50 GWd/tU. These values are regarded as a relatively high burn-up, and are greater than experienced by spent fuel from historical and current LWR operations in

[2] Burn-up will vary along the length of a fuel assembly and the 'fuel assembly average burn-up' is the average of the burn-up along the length of the fuel assembly. Different fuel assemblies will have different 'fuel assembly average burn-ups', and it is possible to define the 'maximum fuel assembly average burn-up' as the maximum of these. For the purposes of the GDA disposability assessment, RWM assume that this 'maximum fuel assembly average burn-up' is achieved by all fuel assemblies, which is a conservative assumption.

the UK. The assessment of spent fuel disposal packages assumed that all of the spent fuel arose at the end of reactor operation; no account was taken for cooling and radioactive decay during interim storage prior to the end of reactor operations. This is a conservative assumption made to simplify the assessment and ensure that the conclusions were robust.

Increased burn-up implies that the fuel is used more efficiently and that the volume of fuel to be disposed of will be smaller per unit of electricity produced. However, increased irradiation leads to individual fuel assemblies with an increased concentration of fission products and higher actinides, leading in turn to assemblies with higher thermal output and dose-rate. This is recognised as an important consideration in the assessment of spent fuel from the UK ABWR when compared to the assessment of lower burn-up fuel, for example from reactors that have operated historically and are operating at the present.

Assessment of spent fuel packaging proposals was based on sealing the spent fuel inside durable disposal containers manufactured from suitable materials, which would provide long-term containment for the radionuclide inventory. Although the container material remains to be confirmed, the Disposability Assessment process considers the potential performance of both copper and carbon steel containers. In the copper container case, it is assumed that a cast-iron insert is used to hold and locate the spent fuel assemblies, and to provide mechanical strength. In the carbon steel container case, a carbon steel “tube and plate” basket is used to hold and locate the spent fuel assemblies.

The disposal container provides one component of the multi-barrier system used to ensure safety following closure of the geological disposal facility. In this assessment, the multi-barrier system is assumed to include additional engineered barriers and the geological barrier. The engineered barriers are designed to be compatible with the environment in which the geological disposal facility is constructed. In higher-strength rocks and lower-strength sedimentary rocks, it is assumed that a bentonite buffer will be emplaced around the waste packages, and engineered plugs will form seals to limit groundwater flow at key locations underground. In evaporite rocks, it is assumed that disposal galleries are backfilled with crushed rock salt, and that seals are placed to limit groundwater flow and radionuclide migration along access ways.

The materials used as part of the engineered barrier system, and the characteristics of the host rock, will affect the thermal criteria used to determine the acceptability of the heat output from waste packages consigned for disposal. In the current generic phase of the programme, generic thermal criteria are used to determine approximate cooling times required before disposal of spent fuel. Different thermal criteria are applied in the illustrative disposal concepts for different host rocks. In higher strength rock, the temperature criterion requires that the temperature of the inner surface of the bentonite buffer should not exceed 100^oC. In lower strength sedimentary rock, the temperature criterion is that the buffer temperature should not exceed 125^oC at its mid-point. In evaporites, the temperature criterion is that the temperature of the host rock should not exceed 200^oC. These limits are consistent with criteria used in disposal programmes in other countries.

Based on a spent fuel waste package containing twelve UK ABWR fuel assemblies and adopting the spacing used in the illustrative designs for higher strength rock, it would require between 50 and 100 years for the activity, and hence heat output, of the UK ABWR fuel to decay sufficiently to meet the existing temperature criterion. This period allows for both the range of predicted ABWR fuel burn-up (50-60GWd/tU) and the range of rock characteristics that may be encountered for a geological disposal facility at 650m.

The cooling time required to meet the temperature criteria in the lower strength sedimentary rock illustrative design has a greater range owing to a greater range in the thermal conductivity of the lower strength sedimentary host rocks that could be used to host a geological disposal facility. The cooling time required in lower strength sedimentary rocks is currently estimated to be between 50 and 130 years. This range is for the same burn-ups as the higher strength rock case.

For the illustrative designs in evaporite host rocks, the cooling time required is estimated to be less than 40 years. This is because of the higher temperature criterion on disposal of spent fuel in evaporitic host rocks and the higher thermal conductivity of evaporitic rocks. Therefore, the cooling times are likely to always be the shortest for disposal of spent fuel in evaporite host rocks.

These cooling times are dependent on a number of uncertainties, in particular the conservative assumptions made in developing the inventory for spent fuel, the uncertainty in the thermal conductivity of the host rock, and the details of the underground design (e.g. package spacing). These uncertainties could be reduced by further work, for example, through refinement of the assessment inventory, by taking into account the cooling of the spent fuel being stored prior to the end of the operational period. Ultimately, cooling times can be managed by consideration of alternative container and geological disposal facility designs. RWM continues to look at the options.

RWM planning for the transport of packaged spent fuel to a geological disposal facility and the subsequent emplacement of the containers is at an early stage of development. Consequently, although the UK ABWR spent fuel may influence the arrangements, for example through the need for additional shielding, it is judged that sufficient flexibility exists in the outline designs for transport of spent fuel disposal packages to a geological disposal facility to allow suitable arrangements to be developed.

The GDA Disposability Assessment has considered how spent fuel disposal packages would evolve in the very long term following closure of a geological disposal facility, recognising that radionuclides would be released only subsequent to a breach in a disposal container. Subsequent to any container failure, the radionuclides associated with the spent fuel would be able to leach into groundwater. The rate at which radionuclides are leached, in combination with the assumed properties of the host rock, the behaviour of individual radionuclides and exposure routes, are then used to assess the potential risk to humans and the environment.

The leaching of radionuclides from spent fuel is characterised by an initial ‘instant release fraction’ (IRF), and by a more general dissolution rate. The IRF is the fraction of the inventory of more mobile radionuclides that is assumed to be readily released upon container failure and is influenced by the properties of the spent fuel. The increased irradiation of the higher burn-up UK ABWR fuel could increase the IRF as compared to that for lower burn-up fuel. Available information on the performance of higher burn-up fuel has been used to provide suitably conservative IRF values for the assessment.

The assessment of long-term disposal system performance in the GDA Disposability Assessment has been based on the assumed characteristics for a generic UK geological disposal facility site. Since the properties of any selected site would need to be consistent with meeting the regulatory risk guidance level, this assessment assumed the same site characteristics as assumed for the existing RWM generic assessment. On the basis of the information provided by Hitachi-GE and conservative calculations of spent fuel waste package performance, it was calculated that the spent fuel from a fleet of four UK ABWR reactors would give rise to an estimated risk below the risk guidance level.

The risks calculated for the disposal of spent fuel reflect the assumed performance of the proposed packaging options. Sensitivity analysis has demonstrated that while the calculated risk would be influenced by the container material performance, coupled with the performance of other engineered barriers and the geological barrier, the risk was calculated to be below the regulatory guidance level. This outcome is insensitive to any impact that the high burn-up experienced by the fuel assemblies would have on the IRF.

RWM recognises that the performance of disposal containers will be an important element of a safety case for the disposal of spent fuel. Consequently, it is anticipated that RWM will continue to develop container designs, including the designs of containers for UK ABWR spent fuel, with the intention of substantiating the robustness of current assumptions and tailoring the designs to whatever site is ultimately identified.

The potential impact of the disposal of UK ABWR spent fuel on the size of the geological disposal facility has been assessed. The industry ambition of 16GW of nuclear new build has been estimated previously to produce spent fuel containers that will fill approximately 202 disposal tunnels in a GDF in high strength rock. The assumed operating scenario for a single UK ABWR gives rise to an estimated 800 spent fuel disposal containers, requiring approximately 18 disposal tunnels for disposal in higher strength rock. For the illustrative fleet of four UK ABWR reactors, representing 5.40GW, this would be equivalent to 72 disposal tunnels. This indicates that the required number of disposal tunnels is within the range assumed for a 16GW fleet of new nuclear build.

7 Conclusions

RWM has undertaken a GDA Disposability Assessment for the higher-activity wastes and spent fuel expected to arise from the operation of a UK ABWR. This assessment has been based on information on the nature of operational and decommissioning ILW, and spent fuel, and proposals for the packaging of these wastes, supplied to RWM by Hitachi-GE. This information has been used to assess the implications of the disposal of the proposed waste packages against the waste package standards and specifications developed by RWM, and the supporting safety assessments for a proposed geological disposal facility. The safety of transport operations, handling and emplacement at a geological disposal facility in the UK, and the longer-term performance of the system have been considered, together with the implications for the size and design of a geological disposal facility.

RWM has concluded that sufficient information has been provided by Hitachi-GE to produce valid and justifiable conclusions. RWM has concluded that ILW and spent fuel from operation and decommissioning of a UK ABWR should be compatible with plans for transport and geological disposal of higher-activity wastes and spent fuel. It is expected that these conclusions would be supported and substantiated by future refinements of the radionuclide inventories of the higher-activity wastes and spent fuel, complemented by the development of more detailed proposals for the packaging of the wastes and spent fuel, and better understanding of the expected performance of the waste packages. At such later stages, it is expected that more specific and detailed packaging proposals would be assessed, and potentially endorsed, through the established Letter of Compliance process for assessment of waste packaging proposals.

The GDA Disposability Assessment for the UK ABWR has not identified any significant issues that challenge the fundamental disposability of the wastes and spent fuel expected to be generated from operation of such a reactor. This conclusion is supported by the similarity of the wastes to the expected arisings from the existing PWR at Sizewell B. Given a disposal site with suitable characteristics, the wastes and spent fuel from the UK ABWR are expected to be disposable.

8 References

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Appendix A
Approach to GDA Disposability Assessment

The GDA Disposability Assessment of the UK ABWR was managed as a structured project using management procedures controlled under the RWM Management System. The project was run in a staged manner, based on three stages, as follows:

Stage 1: Nature and Quantity of Waste

This stage comprised a nature and quantity of waste evaluation and a wasteform evaluation. Work under this stage used information supplied by Hitachi-GE, supplemented by existing RWM experience and extensive discussion with Hitachi-GE regarding the dataset used as a basis for this assessment. In particular, the radionuclide inventory for spent fuel was supplemented by undertaking calculations using ORIGEN-ARP. Thermal modelling of the impact of the disposal of spent fuel on near-field temperatures was undertaken to determine the cooling times required before spent fuel could meet the requirements for disposal in a geological disposal facility.

The nature and quantity of waste evaluation was used to collate data on the properties of operational and decommissioning ILW, and the spent fuel from the UK ABWR, and to define reference cases for evaluation during the GDA Disposability Assessment. In particular, the objective of the nature and quantity of waste evaluation was to establish a suitably detailed understanding of the radionuclide inventory, composition and quantity of wastes, and included:

- peer review of the submitted information;
- identification of any deficiencies and/or inconsistencies in the information;
- confirmation of waste volumes and packaged volumes for disposal.

The objective of the wasteform evaluation was to consider the chemical and physical characteristics of the wasteforms, which required:

- collation of information on proposed conditioning and packaging methods for ILW, including development of techniques as required;
- development of an understanding of organic materials content, potential for gas generation and chemo-toxic content for ILW;
- describing the geometry, material properties and physical and chemical nature of spent fuel.

Stage 2: Disposal Facility Design Assessment

This stage comprised a waste package performance evaluation and a design impact evaluation.

The waste package performance evaluation considered impact and fire performance of waste packages relevant to possible accident scenarios in transport of waste packages to a geological disposal facility and operations in a geological disposal facility, including estimation of release fractions for a range of standard impact and fire scenarios.

The disposal facility design evaluation considered the implications of waste and spent fuel generated from the operation of a UK ABWR on the design of a geological disposal facility, including the following:

- the number of disposal tunnels needed to accommodate the wastes, and the consequent impact on overall geological disposal facility footprint;

- compatibility of waste packaging assumptions with existing design assumptions;
- identification of unique or distinguishing features of the wastes and/or proposed waste packages;
- significance of potential variability in the proposed waste packages;
- consideration of the proposed conditioning or management methods.

Stage 3 Safety, Environmental and Security Assessments

This stage comprised a transport safety assessment, an operational safety assessment, a post-closure safety assessment, consideration of environmental issues, and a security evaluation. The safety, environmental and security assessments considered the compatibility of potential operational and decommissioning ILW, and spent fuel from a UK ABWR with existing assessments of RWM reference disposal concepts. The assessments provide the basis for judging the potential disposability of operational and decommissioning ILW, and spent fuel arising from operation of the UK ABWR.

- the transport safety assessment considered the logistics, regulatory compliance and risk of transport operations, with specific consideration of radiation dose, gas generation, containment and heat output under normal and accident conditions;
- the operational safety assessment considered radiation dose due to accidents, effects of gas generation and criticality safety;
- the post-closure safety assessment considered potential longer term radiological exposure from the groundwater and gas pathways, human intrusion and criticality, and any environmental impacts from chemotoxic species potentially contained in the waste;
- the evaluation of non-radiological environmental issues considered the materials, i.e. resource use, in a geological disposal facility to dispose of the ILW and spent fuel arising from the UK ABWR using the illustrative designs, and commented on proposed waste management strategies and their implications;
- the security evaluation considered the likely security categorisation of the proposed waste packages and commentary on proposals for accountancy and independent verification of the use of nuclear materials.

Appendix B
UK ABWR Operation, Wastes, Packaging Proposals and Package Characteristics

This Appendix provides a summary of the information used in the GDA Disposability Assessment for the UK ABWR. This is based on information supplied by Hitachi-GE, and calculations by RWM to estimate package numbers, inventories and general characteristics.

This section contains the following information:

- summary description of a UK ABWR;
- assumptions regarding the operation of a UK ABWR;
- description of the higher-activity radioactive waste streams and spent fuel that will be generated through operation and decommissioning of a UK ABWR (the ‘assessment inventory’), including volumes, assumptions regarding the packaging of these wastes and estimates of waste package numbers and their characteristics.

In order to place the description of UK ABWR wastes in context, the expected ILW and spent fuel arisings are compared to the reported arisings from Sizewell B. The latter being the sole example of a light water reactor (in this case a pressurised water reactor rather than a boiling water reactor) operated in the UK.

B1 Summary of UK ABWR Design and Operation

The UK ABWR is an evolutionary BWR design with an electrical power output of 1,350 MW(e).

The ABWR design is based on over 50 years’ experience of operating BWRs. In 2007, there were 93 BWRs operating worldwide, with 32 plants operating in Japan and 37 in the United States [B1]. The development of the ABWR design was undertaken in the 1980s, with an Establishment Permit, or licence, being issued in Japan in 1991, and a Design Certification approved and signed into law in the United States in 1997. By 2007, four ABWR units had been constructed and were operational in Japan [B1].

In BWRs such as the ABWR, ordinary (light) water is utilised to remove the heat produced inside the reactor core by thermal nuclear fission. This water also slows down (or moderates) neutrons (the constituents of atomic nuclei that are released in the nuclear fission process). Slowing down neutrons is necessary to sustain the nuclear reaction. The heat produced inside the reactor core causes the water to boil, and the resultant steam drives a steam turbine.

The reactor core, which provides the heat source for steam generation, is housed in a reactor vessel (Figure B1). In the ABWR, reactor coolant is forced through the reactor core using an arrangement of ten pumps mounted internally in the reactor vessel. In previous BWR designs, pumps were housed in external recirculation loops; these have been eliminated in the UK ABWR design. Steam, generated in the reactor, is supplied to the high-pressure turbine and to steam reheaters. The steam leaving the high-pressure turbine passes through a combined moisture separator/reheater, prior to entering a series of low-pressure turbines. Water is collected in drains, combined with exhausted steam, and fed to a condenser and purification system, before circulating back to the reactor through a series of low-pressure and high-pressure pumps.

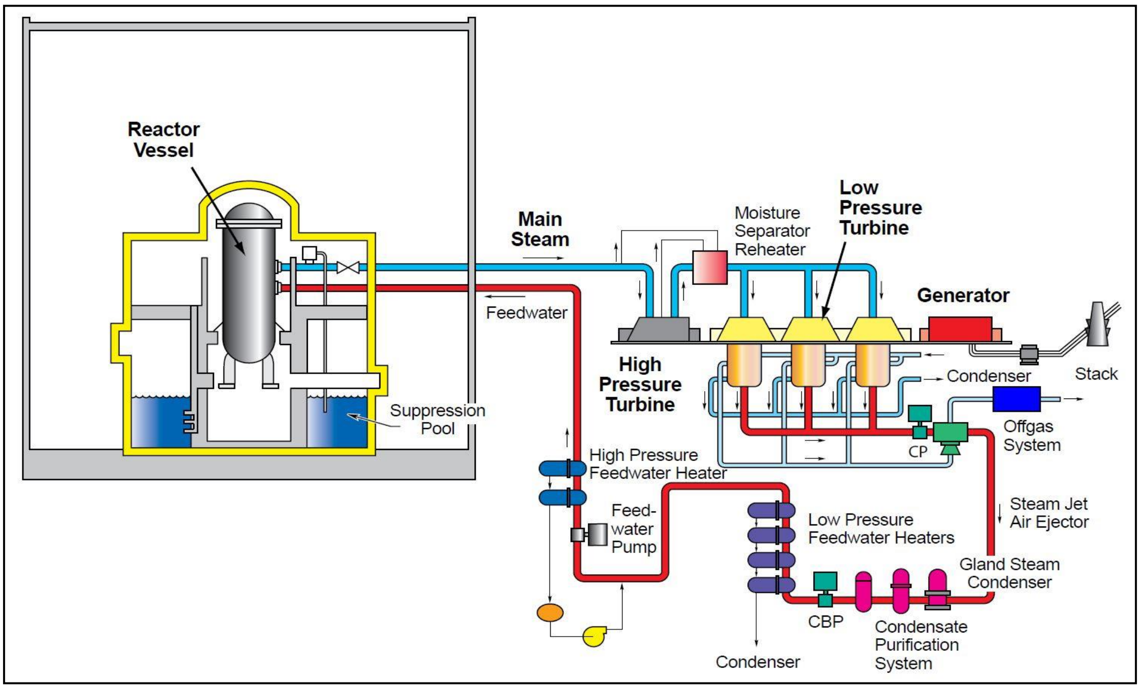

Figure B1 – Principal components of a UK ABWR, reproduced from [B1]

B2 Assumptions

The GDA Disposability Assessment for the UK ABWR was based on the following assumptions:

- The UK ABWR would be operated for 60 years. During the operation of the reactor, nuclear fuel assemblies would be periodically rotated within the reactor core, and then removed and replaced with other fuel assemblies.
- The date at which operation of power production from a UK ABWR would commence in the UK is uncertain. In the GDA Disposability Assessment for the UK ABWR, estimates of time-dependent properties, e.g. those related to radioactive decay, are assessed from time of generation of the waste. Discussion of the implications for management of radioactive waste assumes that the reactors operate from 2020. This is the same assumption that was made for GDA Disposability Assessments made for previous Requesting Parties [B2, B3].
- Spent fuel characteristics have been determined on the assumption, based on advice from Hitachi-GE, that the reactor would be operated to achieve a maximum fuel pin burn-up of 65 GWd/tU. This corresponds to a maximum burn-up for a fuel assembly of 60 GWd/tU, and a maximum average burn-up of 50 GWd/tU. The GDA Disposability Assessment has developed inventories based on assumed average assembly burn-ups of 60 and 50 GWd/tU. This is a conservative approach and ensures that the conclusions from the assessment are bounding of a wide range of possible operational behaviours.
- The fuel used in the UK ABWR will be manufactured from freshly mined uranium (i.e. not reprocessed uranium).
- It is assumed that ILW and spent fuel from the UK ABWR will arrive at a geological disposal facility in a packaged state, ready for disposal.

B3 ILW Streams, Packaging Assumptions, Package Numbers and Characteristics

B3.1 Operational ILW Streams and Packaging Assumptions

Hitachi-GE has indicated that eight operational ILW streams[3] would arise from normal operation of a UK ABWR:

- Cruds: Crud is solid material from the backwashing of filters. It is mainly composed of corrosion and erosion products from the reactor internals (primarily derived from steel alloys) and other water circulation systems within the plant. There are two crud waste streams in the UK ABWR inventory:
  - UKABWR01: Condensate Filter Facility (CF) Crud. CF Crud waste arises in the condensers after the steam has passed through the turbines. The material includes small quantities of corrosion product which may have been carried over with the steam from the reactor vessel.
  - UKABWR02: Low Conductivity Waste (LCW) Crud. The LCW system collects wastes from various sources including the Reactor Building, Turbine Building and Radwaste Building drains, and processes them via filters, demineraliser and sampling tanks. LCW Crud arises from the backwashing of the filters in the LCW system.

  In addition to CF and LCW Crud, the UK ABWR generates other crud waste streams, but these are expected to be classified as LLW. A crud capture system is also incorporated in the spent fuel assembly (the lower tie plate debris filter); this will be disposed of along with the spent fuel.
- Resins: Ion-exchange resins are composed of powder and beads, which are used for removal of dissolved radioactivity from the reactor coolant. There are three resin waste streams in the UK ABWR inventory:
  - UKABWR03: Reactor Water Clean-up (CUW) Resin. CUW Resin is a powder-based polystyrene resin.
  - UKABWR04: Fuel Pool Cooling Clean-up (FPC) Resin. FPC Resin is a powder-based polystyrene resin.
  - UKABWR05: Post-operational Decontamination (DEC) Resin. DEC Resin is a bead-based polystyrene resin.
- Control Rods: The reactor core will contain 205 control rods during operation. The cruciform control rods (Figure B2) contain stainless steel tubes in each wing of the cruciform filled with compacted boron carbide (B_4C) powder. In selected control rods, the boron carbide is replaced with hafnium. The tubes act as pressure vessels to contain the helium gas released by the boron-neutron capture reaction. The tubes are held in cruciform array by a stainless steel sheath extending the full length of the tubes. There are two control rod waste streams in the UK ABWR inventory, one for each type of neutron absorber:
  - UKABWR06: Hafnium Control Rods.
  - UKABWR07: Boron Carbide Control Rods.

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[3] "Operational" ILW includes some of the ILW generated during post-operational decontamination operations, e.g. Post-operational Decontamination Resins. These wastes have been assessed alongside the operational ILW as they are of a similar chemical and physical form to the ion exchange resins generated during operations.

- Activated Metals: This waste stream consists of monitoring probes and neutron sources deployed within the reactor core. These include Local Power Range Monitoring (LPRM) assemblies (these contain fission chamber detectors for monitoring reactor pressures and sensors for monitoring the neutron flux – the Automatic Traversing In-core Probe (ATIP)); Neutron Source Units (which contain antimony and beryllium); and Start-up Range Neutron Monitor (SRNM) assemblies (which contain fission chamber sensors). There is a single activated metal waste stream in the UK ABWR inventory:
    - UKABWR08: Mixed Metal ILW.

The raw waste volumes of each operational ILW waste stream expected to arise through operation of a UK ABWR, as determined by Hitachi-GE, are provided in Table B1.

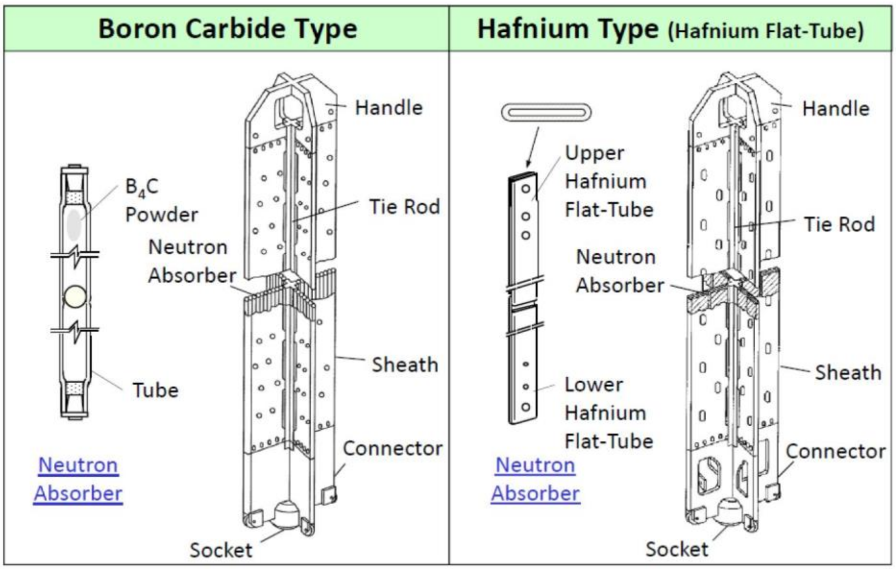


Figure B2 – Illustration of an ABWR control rod, from [B1]

Table B1 – Raw waste volumes for operational ILW from a UK ABWR and identifiers used in the GDA Disposability Assessment for different management scenarios

Waste Stream	Identifier	Raw Waste Volume/Mass
Cruds: CF Crud	UKABWR01	72.0m^3
Cruds: LCW Crud	UKABWR02	18.0m^3
Resins: CUW Resin	UKABWR03	187.6m^3
Resins: FPC Resin	UKABWR04	84.5m^3
Resins: DEC Resin	UKABWR05	67.0m^3
Hafnium Control Rods	UKABWR06	31.65t
Boron Carbide Control Rods	UKABWR07	27.95t
Mixed Metal ILW	UKABWR08	33.00t

To package the Cruds and Resins, it is assumed that the wastes would be grout cemented into 3m^3 Drums. To accommodate all of the wastes arising from a 60-year operational lifetime for a single UK ABWR would require 79 off 3m^3 Drums of Crud and 452 off 3m^3 Drums of Resin. For transport, the 3m^3 Drums would be carried inside a Standard Waste Transport Container (SWTC), which is being developed by RWM to transport such waste packages. The SWTC is proposed to be manufactured in steel with two shielding thicknesses, 70mm and 285mm. It has been calculated that the 3m^3 Drums containing the CF Crud would need to be transported in an SWTC-70 to meet the International Atomic Energy Agency (IAEA) Transport Regulation dose rate requirements. The 3m^3 Drums containing LCW Crud, and CUW, FPC and DEC Resin would need to be transported in an SWTC-285 to meet the IAEA Transport Regulation dose rate requirements.

To package the Control Rods and Mixed Metal ILW, it is assumed that the wastes would be grout cemented into 3m^3 Boxes. To accommodate all of the wastes arising from a 60-year operational lifetime for a single UK ABWR would require 17 off 3m^3 Boxes of Control Rods, and 4 off 3m^3 Boxes of Mixed Metal ILW. The 3m^3 Boxes would need to be transported in an SWTC-285 to meet the IAEA Transport Regulation dose rate requirements.

Both the 3m^3 Drum and 3m^3 Box are standard RWM waste containers and are illustrated in Figure B3.

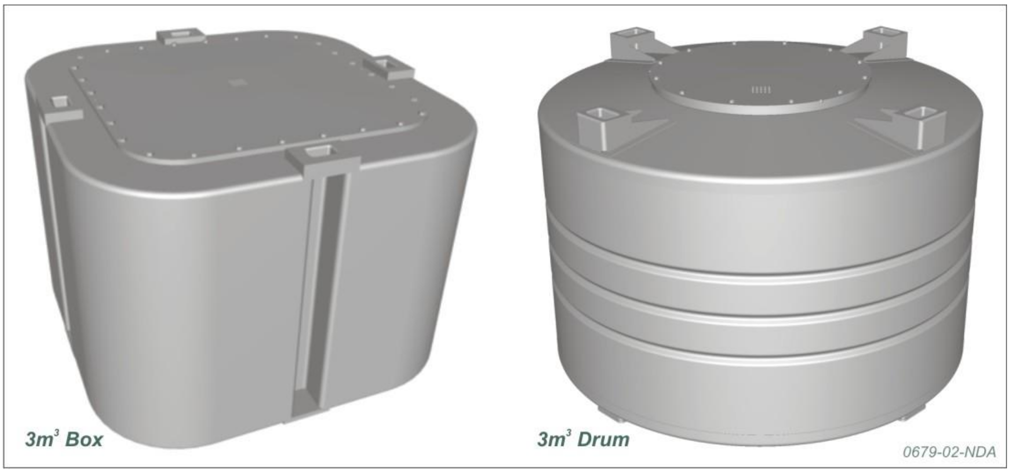


Figure B3 – Illustration of a 3m^3 Box (left) and a 3m^3 Drum (right) as proposed for packaging of operational and decommissioning ILW from a UK ABWR

B3.2 Decommissioning ILW Streams and Packaging Assumptions

The reference decommissioning assumption is that transport of decommissioning waste occurs 40 years after reactor shutdown. Inventory calculations have been undertaken in line with this assumption.

Decommissioning ILW has been assigned to two broad waste streams:

- UKABWR09: Reactor Pressure Vessel Internals: This waste stream consists of in-vessel stainless steel structures that support the reactor core and its safety systems, and manage the flow of coolant into and out of the core. Because the neutron flux falls rapidly with distance from the core, this waste has been subject to a wide range of neutron irradiation levels. Hitachi-GE proposals are for grout encapsulation of this waste in 3m^3 Boxes. Stainless steel filter housings added to the reactor following operation when the reactor would be flooded for decommissioning purposes and with relatively high activity, would also be packaged in $3m^3$ Boxes and are therefore also included in this waste stream[4]. The raw waste mass for this waste stream is approximately 374t, with 126 waste packages required to accommodate the whole waste stream. The $3m^3$ Boxes would need to be transported in an SWTC-285 to meet the IAEA Transport Regulation dose rate requirements.

- UKABWR10: Reactor Pressure Vessel: This waste stream consists of the carbon steel reactor vessel and the stainless steel liner on the inside of the vessel. Hitachi-GE proposals are for cement encapsulation of this waste in 4-metre Boxes with 200-mm concrete walls for shielding. Some stainless steel filter housings with relatively low activity would be packaged in 4-metre Boxes, and have therefore also been included in this waste stream. 39 waste packages would be required to accommodate the whole waste stream. The 4-metre Boxes would be transported as IP-2 packages.

The raw waste masses of the decommissioning ILW waste streams expected to arise through operation of a UK ABWR, as determined by Hitachi-GE, are provided in Table B2. The 4-metre Box is a standard RWM waste container and is illustrated in Figure B4.

Table B2 – Raw waste masses for decommissioning ILW from a UK ABWR and identifiers used

Waste Stream	Identifier	Raw Waste Mass
Reactor Pressure Vessel Internals	UKABWR09	374t
Reactor Pressure Vessel	UKABWR10	646t

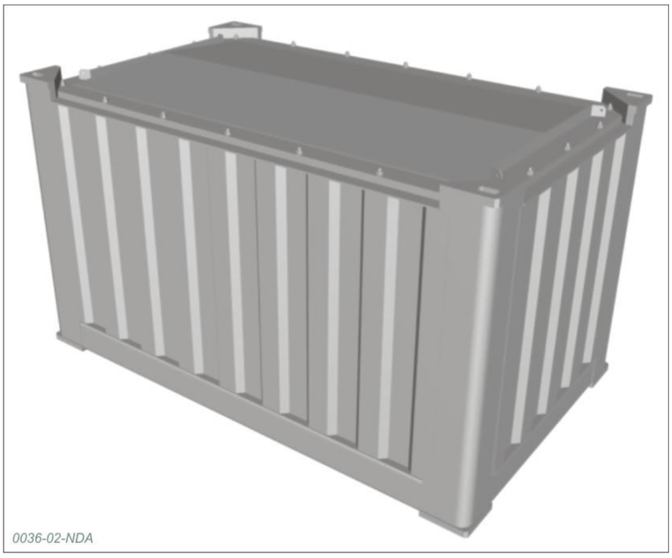


Figure B4 – Illustration of a 4-metre box as proposed for packaging some decommissioning ILW from a UK ABWR

[4] Filter housings are generated during post-operational decontamination operations. These wastes have been assessed as part of the Reactor Pressure Vessel Internals waste stream as they are of a similar chemical and physical form, and would be packaged in a similar manner.

B3.3 ILW Package Numbers and Characteristics

The information supplied by Hitachi-GE on the radionuclide inventories of the identified wastes and spent fuel has been used to derive assessment inventories for the various proposed waste packages. To ensure a full coverage of potentially significant radionuclides it has been necessary to supplement the information supplied by Hitachi-GE with information available to RWM. The assessment inventories are intended to characterise the range of waste package inventories, taking account of uncertainties and variability between packages.

In support of this GDA Disposability Assessment, the assessment inventory included:

- A best-estimate (average) waste package inventory. This inventory, when taken with the number of waste packages, defines the total inventory associated with the waste stream. This inventory is applied during the post-closure assessment and some aspects of operational safety assessment.
- A bounding (maximum) inventory for the waste package. This is used for transport safety assessment and certain aspects of the operational safety assessment where individual waste packages are considered.

The UK ABWR ILW waste package radionuclide-related parameters and waste quantities (package numbers and total packaged volume) are given in Table B3. Radionuclide related parameters (e.g. dose rate) are calculated at the time of arising (i.e. zero-decayed for operational ILW and 40-year-decayed for decommissioning ILW).

For operational ILW (Table B3), information on the raw waste volumes, package types, package numbers and radionuclide contents were derived from consideration of operation of existing BWRs in Japan, Europe and the US. Hitachi-GE provided radionuclide inventories containing the concentration of most of the key radionuclides. These datasets were “enhanced” by estimating the concentration of all of the 112 radionuclides considered by RWM to be significant for radioactive waste management.

Different enhancement approaches were used for each type of material (cruds, resins, control rods, activated metals and reactor pressure vessel steels).

For cruds and resins, Hitachi-GE provided an inventory containing data for 31 radionuclides. The average package concentrations of the other significant radionuclides were estimated by multiplying the concentration of a representative radionuclide by the estimated ratio of the other radionuclide and the representative radionuclide. The estimated ratio was the maximum of ratios for similar waste streams from existing datasets for other LWR wastes. In order to develop a conservative assessment inventory, appropriate for this stage of assessment, the maximum of the submitted specific activity and the scaled activities from the comparator waste streams was used in the assessment inventory. The maximum package activities for cruds and resins were estimated by multiplying the average package activities by 12. This is consistent with previous ratios between average and maximum package activities for cruds and resins, and the approximate uncertainty in the scaling factors applied to estimate the average package activities.

For control rods and activated metals, Hitachi-GE provided an inventory based on ORIGEN modelling of the control rod composition as a homogeneous body and a description of the control rod materials, including elemental compositions of the various steels used in the rods. Although the control rods would be exposed to a variable neutron flux, the calculations assumed that the entire length of the rods was exposed to the maximum core flux. On this basis, the supplied inventory may be conservative. However, no cobalt was included in the steel compositions provided by Hitachi-GE. Co-60 might be a significant contributor to dose during transport and operations, and, therefore, enhancement of the inventory by RWM assumed that the control rod metals contained 0.26% cobalt. This is the concentration of cobalt in Type 304 stainless steel, for which RWM hold detailed precursor composition data. Extension of the supplied radionuclide inventory to the full list of relevant radionuclides was undertaken by scaling inventories using the declared Ni-63 activities. The maximum package activities for control rods and activated metals were based on wastes arising at the end of reactor operation with an additional scaling factor added for uncertainty. One noted omission is Hf-178n, which is not modelled by ORIGEN. In the extended radionuclide inventory, Hf-178n is a significant contributor to dose at short timescales (half-life, approximately 31 years), and, therefore, should be included in future inventories for the UK ABWR.

The assumption that control rod metals contain 0.26% cobalt, leads to relatively high activities for Co-60 in the waste package inventories. The estimated activities can, in certain cases, challenge the limits on transport included in the IAEA transport regulations [4], and the assumptions in RWM's operational safety case. In future, RWM would expect to work with a potential reactor developer to reduce pessimisms in the inventories for control rods and activated metals. This might include consideration of the steel alloys used in the UK ABWR, for example, consideration of low-cobalt steel for the hafnium control rods, as well as the spatial variability of activity across the length of the control rods.

For decommissioning ILW (Table B3), Hitachi-GE provided an activation product inventory for 57 radionuclides. This inventory was based on ORIGEN activation calculations for a Japanese ABWR irradiated for 40 years at a 75% load factor, i.e. 30 Equivalent Full Power Years (EFPY). Analytical formulae were used to extend this inventory for the UK ABWR based on a conservative 60 EFPY irradiation assumption. The Hitachi-GE data for the reactor pressure internals were checked by RWM by performing activation calculations using FISPACT2007. These calculations used an effective neutron flux developed by RWM based on the activities of key radionuclides. The two inventories were in good agreement.

The Reactor Pressure Vessel (RPV) internal stainless steel inventory applied in the GDA Disposability Assessment used the Hitachi-GE radionuclide activities when these exceeded 50% of the RWM activities, and the RWM activities when this was not the case. Independent inventory calculations were not undertaken for the reactor pressure vessel materials, as the check on the reactor pressure vessel internals demonstrated a reliable prediction of the dominant radionuclides, because the steel precursors used by Hitachi-GE were judged to be appropriate, and because the specific activities of the RPV steels are 5-6 orders of magnitude lower than the reactor pressure internals.

In addition to the activation product inventory, the GDA Disposability Assessment has considered the inventory associated with contamination of the reactor pressure vessel and internals. The contamination inventory for the reactor pressure vessel internals is trivial compared to the activation inventory, and, therefore, the inventory submitted by Hitachi-GE has been used in this GDA Disposability Assessment without modification. For the reactor pressure vessel, a contamination inventory was added to the activation inventory, as no contamination inventory was included in the submission.

Table B3 – UK ABWR Waste Stream Data: operational ILW (1) (2)

Waste Stream (3)	Package Type	Number of Packages	Average Package Alpha Activity (TBq)	Average Package Beta/ Gamma Activity (TBq)	Average Package A_2 Content	Average Package Heat Output (Watts)	Average Transport Package Dose Rate at 1m from Package (mSv/hr)	Additional Time Required for Average Package to Decay to the Transport Dose Rate Limit of 0.1 mSv/hr. (years)
The average package data for the 5 wastestreams below are at reactor discharge. These are packaged IEX resins and cruds (sludges). See Table B1.								
UKABWR01	$3m^3$ Drum	79	1.73E-05	2.29E-02	1.56E-02	7.67E-04	6.70E-07	0
UKABWR02	$3m^3$ Drum		2.38E-04	2.73E-01	2.02E-01	9.55E-03	8.53E-06	0
UKABWR03	$3m^3$ Drum	452	7.11E-04	9.17E+00	9.91E+00	1.28E+00	1.52E-03	0
UKABWR04	$3m^3$ Drum		2.80E-04	3.56E+00	3.86E+00	5.00E-01	5.94E-04	0
UKABWR05	$3m^3$ Drum		3.06E-02	1.31E+02	1.97E+02	2.00E+01	8.93E-03	0
The average package data for the 2 waste streams below are at closure plus 6 years. These are packaged hafnium and boron carbide control rods. See Table B1.								
UKABWR06	$3m^3$ Box	17	7.68E-03	2.72E+03	2.97E+04	7.17E+02	5.12E-01	13
UKABWR07	$3m^3$ Box		2.45E-04	1.33E+03	1.09E+03	1.78E+02	1.84E-01	5
The average package data for the wastestream below is at reactor closure plus one year. These are packaged reactor control instrument housings, etc. See Table B1.								
UKABWR08	$3m^3$ Box	4	9.00E-03	1.42E+04	2.00E+04	3.30E+03	2.02E+00	23
The average package data for the 2 decommissioning wastestreams below are at reactor closure plus 40 years. These are packaged RPV stainless steel structures and the RPV and its stainless steel lining. See Table B2.								
UKABWR09	$3m^3$ Box	126	1.58E+00	1.12E+06	1.83E+02	2.04E+01	1.17E-02	0
UKABWR10	4-metre Box	39	5.53E-05	1.09E+01	8.40E-03	8.80E-04	7.91E-04	0
TOTALS		165						

Notes:

(1) The values are for average waste package inventories.

(2) Dose rate refers to that 1m outside an SWTC-285 for all waste streams except UKABWR10. For UKABWR10, the dose rates are 1m outside of a 4-metre Box with 200-mm concrete shielding.

(3) See Section B3.1 for a description of UKABWR01 to UKABWR08 waste streams, and Section B3.2 for a description of UKABWR09 and UKABWR10 waste streams.

B3.4 Comparison of UK ABWR ILW with Sizewell B ILW

In order to place the information on ILW from a UK ABWR in context, a comparison has been made with ILW from Sizewell B, which is a light water reactor (in this case a pressurised water reactor rather than a boiling water reactor) operated in the UK by EdF Energy (Table B4).

The comparison was made for the most active ILW stream in the UK ABWR inventory, as low-activity waste streams are likely to have less influence on the overall conclusions on disposability from the assessment. The waste streams compared were:

- UK ABWR09: RPV stainless steel internals for the UK ABWR.
- 3S306: Decommissioning Stainless Steel ILW for Sizewell B (2013 RWI).

The total activities of these streams were compared against the total activities of the other waste streams for these reactors to ensure that the highest activity streams have been chosen. In the case of the Sizewell B waste streams, 3S306 has an activity that is at least an order of magnitude greater than any other Sizewell B ILW waste stream at 2075 (40 years after reactor shutdown). For the UK ABWR, the stainless steel internals are several orders of magnitude more active than the RPV after 40 years of cooling, and at least an order of magnitude more active than any of the operational ILW waste streams.

The activity of UK ABWR RPV stainless steel internals (stream UKABWR09) is compared with the activity of 3S306 in Table B4. The basis for Table B4 is as follows:

- Radionuclide activities have been estimated for 40 years after reactor shutdown.
- The activity data have been normalised to the total thermal power output of the two reactors (Sizewell B – 3478 MW (thermal) for 40 years, UK ABWR 3926 MW (thermal) for 60 years).
- The radionuclides considered in Table B4 are the top 10 most active in the UK ABWR wastes for which estimates were also available for the Sizewell B PWR wastes.
- The cell colouration displayed in the final column of Table B4 is used to indicate the agreement that presents the ratio of UK ABWR to Sizewell B normalised activities as follows: green < factor of 10, orange > factor of 10.

Table B4 – Comparison of radionuclide activities for Reactor Pressure Vessel Internals from a UK ABWR with Equivalent ILW stream from Sizewell B PWR (3S306)

Nuclide	UK ABWR (UKABWR09) (TBq)	Sizewell B (3S306) (TBq)	UK ABWR (UKABWR09) (TBq per MW (thermal).yr)	Sizewell B (3S306) (TBq per MW (thermal).yr)	(UKABWR09) / (3S306)
Ni63	3.66E+05	3.71E+04	1.55E+03	2.67E+02	5.83E+00
Ni59	3.57E+03	3.23E+02	1.52E+01	2.32E+00	6.53E+00
Co60	3.05E+03	8.06E+02	1.29E+01	5.79E+00	2.24E+00
C14	5.29E+02	3.59E+01	2.25E+00	2.58E-01	8.71E+00
H3	9.11E+01	8.77E+01	3.87E-01	6.30E-01	6.14E-01
Fe55	8.95E+01	1.79E+02	3.80E-01	1.29E+00	2.95E-01
Mo93	8.32E+01	1.21E+00	3.53E-01	8.66E-03	4.08E+01
Nb93m	7.39E+01	3.77E+02	3.14E-01	2.71E+00	1.16E-01
Tc99	7.95E+00	1.21E-01	3.37E-02	8.72E-04	3.87E+01
Nb94	2.19E+00	4.04E+00	9.28E-03	2.90E-02	3.20E-01

As can be seen in Table B4, with the exception of Mo-93 and Tc-99, the activities of all of the radionuclides are similar and within a factor of 10. The presence of Mo-93 and Tc-99 in the UK ABWR RPV stainless steel internals are both due to the result of activation of molybdenum present in the steel alloys. The difference between the UK ABWR and Sizewell B activities for these two radionuclides is therefore expected due to the greater use of molybdenum alloyed steels in the UK ABWR, and the differences in the neutron fluxes used to determine the activation products. RWM has applied conservative upper bound trace element concentrations in the inventory enhancement work.

In addition, Electricité de France (EdF) has quoted a factor of 1,000 uncertainty on Decommissioning Stainless Steel ILW for Sizewell B in their submission for the 2013 UK Radioactive Waste Inventory [B5]. Therefore, the factor of approximately 40 difference between the estimated activities for Mo-93 and Tc-99 in UK ABWR and Sizewell B wastes is considered insignificant and the agreement between the radionuclide inventories is considered to be good.

The practices used in operating a UK ABWR are subject to development, for example the timing of outages and the materials used to treat water in the cooling circuits, and, therefore, the volumes and activities of wastes are only best estimates at this stage. For ILW, the most active waste streams are those from decommissioning, and estimates of decommissioning ILW from a UK ABWR are primarily affected by assumptions regarding the neutron flux in the reactor and the composition of steel used in reactor internals.

In conclusion, radionuclide activity from UK ABWR is dominated by radionuclides within the decommissioning waste streams. Comparison with reported activities in similar wastes and normalised to facilitate a like-for-like comparison, shows that radionuclide activity in UK ABWR waste streams is comparable with that for Sizewell B.

B4 Description of Spent Fuel, Packaging Assumptions, and Package Numbers and Characteristics

B4.1 Description of Spent Fuel

The reactor core of a UK ABWR is comprised of fuel assemblies, control rods and nuclear instrumentation. Control rods and nuclear instrumentation will be managed as ILW, and are discussed above in Section B3. There are 872 fuel assemblies in the reactor core during operation. The fuel assembly consists of a fuel bundle and an interactive fuel channel (Figure B5). The fuel bundle contains the fuel rods and the hardware necessary to support and maintain the proper spacing between the fuel rods. The channel is a Zircaloy-2 box, which surrounds the fuel, and is used to direct the core coolant flow through the bundle. It also provides a smooth surface to guide the control rods as they are inserted.

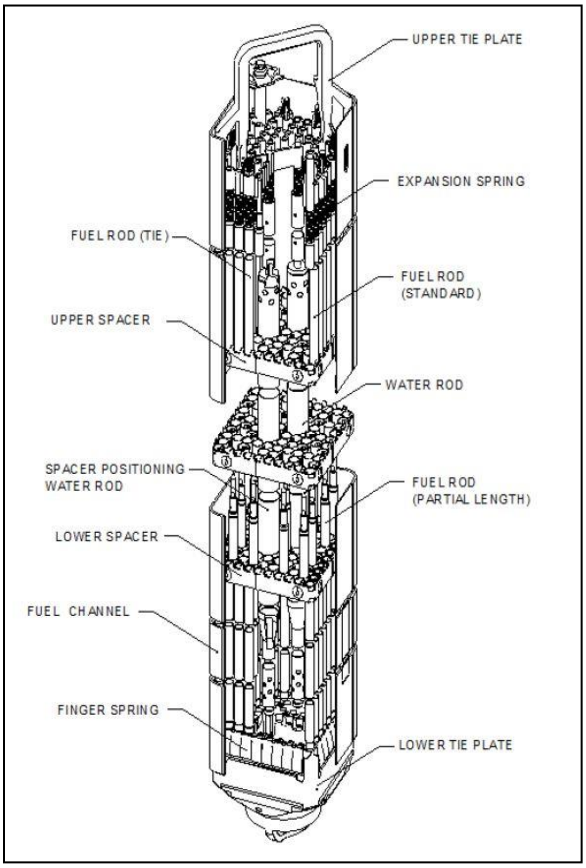
The UK ABWR is expected to use the GE14 type of fuel assembly. This type of fuel assembly is already in use in BWRs in other countries, including Sweden and Finland. Each GE14 assembly is formed by a 10x10 array of 78 full-length fuel rods, 14 part-length rods which span roughly two-thirds of the active core, and two large central water rods. The fuel bundle assembly is held together by eight of the full-length rods located around the periphery; these are referred to as tie rods. The assembly is referred to as the 10x10-8 assembly because the water rods replace eight fuel rods in the array.

The fuel rods consist of seal-welded Zircaloy-2 cladding tubes and end plugs, containing UO_2 pellets. A United States Nuclear Regulatory Commission (USNRC) document describing the GE14 fuel assembly notes that the fuel pin is filled with helium at 44psi to improve heat transfer [B6]. There is also a ~0.25m-long free volume known as the plenum region in the top of each pin. This region is designed to collect volatile fission products that escape from the fuel pellets. The plenum region contains a plenum spring to axially compress the stack of fuel pellets so that they are firmly seated in the fuel rod.

As shown in Figure B5, the height of the fuel pellet stack, i.e. the active height of the fuel assembly, in the full-length and part-length rods is 3.81m and 2.13m respectively. Other dimensional information is provided in Table B5 and mass information is provided in

Table B6. The fuel pellets are enriched relative to the concentration of the fissile isotope, U-235, in natural uranium (0.7 wt%). The average bundle enrichments and batch sizes used in each fuel cycle are a function of the desired cycle length.

The initial ABWR core has an average enrichment ranging from approximately 1.7 wt% U-235 to approximately 3.2 wt% U-235 for cycle lengths ranging from one to two years. For ABWR reload cores using GE14 fuel, the average bundle enrichment is roughly 4.2 wt% U-235 with a reload batch fraction of 35% for a two-year cycle (i.e. 35% of the fuel is reloaded into the core after each cycle) [B1].



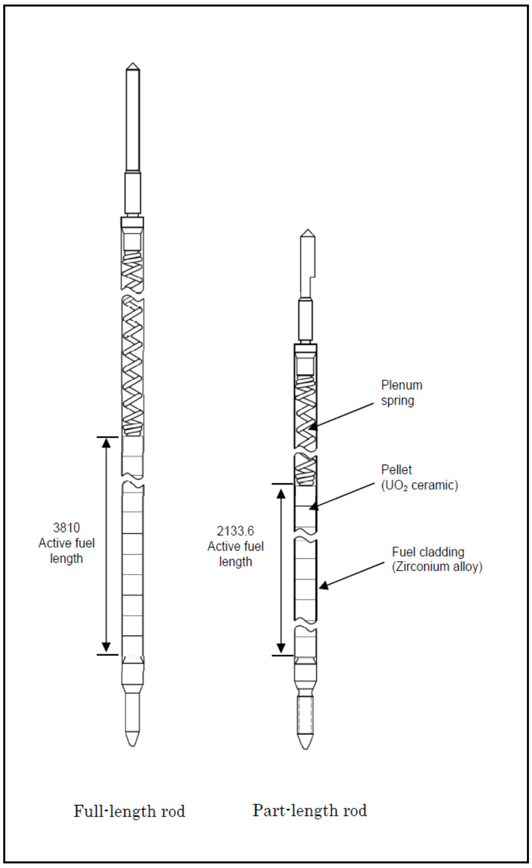


Figure B5 – Illustration of a GE14 fuel assembly, the fuel assembly expected to be used in a UK ABWR; the diagram on the left shows the components of the fuel assembly and the diagram on the right shows the full-length and part-length fuel rods

Table B5 – Dimensional information for UK ABWR fuel assemblies and rods

Fuel Assembly	
External maximum section (mm x mm)	140.16 x 140.16
Maximum length (mm)	4468
Active length (mm)	3810
Overall mass (kg)	298
Uranium oxide mass (kg)	204
Fuel Rod	
Number of fuel rods	92
Fuel rod outer diameter (mm)	10.26
Cladding thickness (mm)	0.660
Pin pitch (mm)	12.95

Table B6 – Estimates of component mass for a UK ABWR fuel assembly

Component of fuel assembly	Material	Mass per assembly (kg)
UO_2	UO_2	204
Gd neutron poison material *	Gd	1.3
Channel box	Zircaloy-2	85.0
Fuel rod cladding	Zircaloy-2	
Water rods	Zircaloy-2	
Spacers	Zircaloy-2	
Zircaloy minor components	Zircaloy-2	
Lower tieplate	Stainless steel	6.7
Upper tieplate	Stainless steel	
Stainless steel minor components	Stainless steel	
Expansion springs	Inconel X-750	0.4
Spacer springs	Inconel X-750	
Inconel X-750 minor components	Inconel X-750	
Additional unspecified material	Unknown	0.5
Total		**298**

* A small fraction of UO_2 pellets contain the burnable neutron poison, Gd_2O_3

B4.2 Spent Fuel Packaging Assumptions

The packaging assumptions for UK ABWR spent fuel are based on concepts developed by RWM to date [B7]. Under these concepts, spent fuel would be over-packed into durable disposal containers manufactured from suitable materials, which would support long-term containment for the radionuclides contained within the spent fuel (Figure B6). Although the container material remains to be confirmed, the assessment has considered the potential performance of copper and steel containers. In the copper container case, it is assumed that a cast-iron insert is used to hold and locate the spent fuel assemblies, and to provide mechanical strength. In the carbon steel container case, a carbon steel “tube and plate” basket is used to hold and locate the spent fuel assemblies.

Based on plans for packaging BWR spent fuel in Finland and Sweden [B8, B9], this GDA Disposability Assessment has assumed that twelve UK ABWR spent fuel assemblies would be packaged in each disposal container. The disposal container would have a length of 4.874m and a diameter of 1.050m; the width of the containers would be identical to the width of containers used to dispose of other types of spent fuel in a UK geological disposal facility [B7]. For the higher strength rock illustrative design, which is considered to be the bounding case, these containers would be emplaced in deposition holes lined with a buffer made from compacted bentonite, which swells following contact with water (Figure B7). The concept is based on the KBS-3V concept developed by SKB for disposal of spent fuel in Sweden [B10].

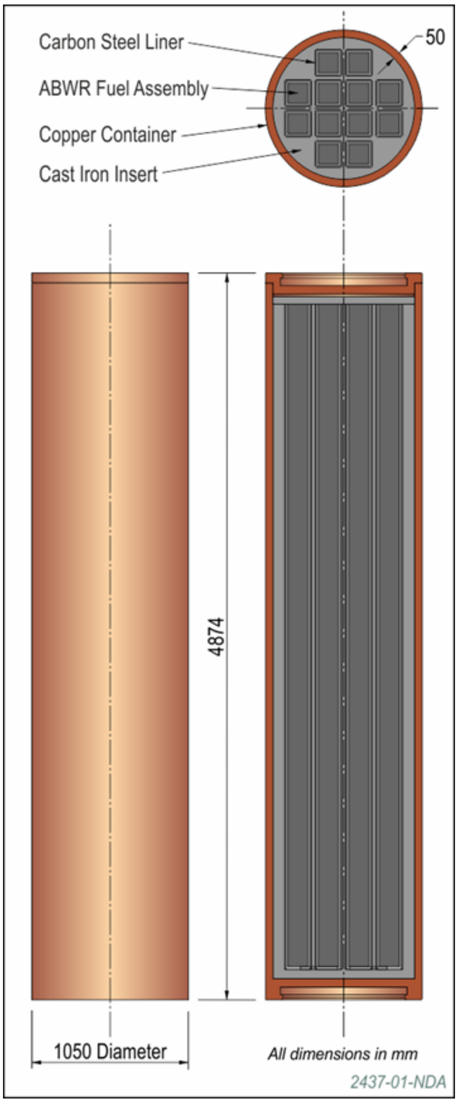


Figure B6 – Illustration of a UK ABWR spent fuel disposal container, assumed for the higher strength rock illustrative design

It is assumed that transport of packaged spent fuel would be undertaken using a concept RWM design for a Disposal Container Transport Container (DCTC) which provides two layers of shielding material:

- Immediately adjacent to the container is a stainless steel gamma shield with thicknesses of 85mm in the radial direction.
- Surrounding the stainless steel gamma shield is a 60-mm-thick neutron shield made of vitrite, a high neutron capture material.

Although the quantitative analyses conducted in the GDA Disposability Assessment for the UK ABWR are based on certain disposal concept assumptions, the implications of alternative disposal concepts have also been considered.

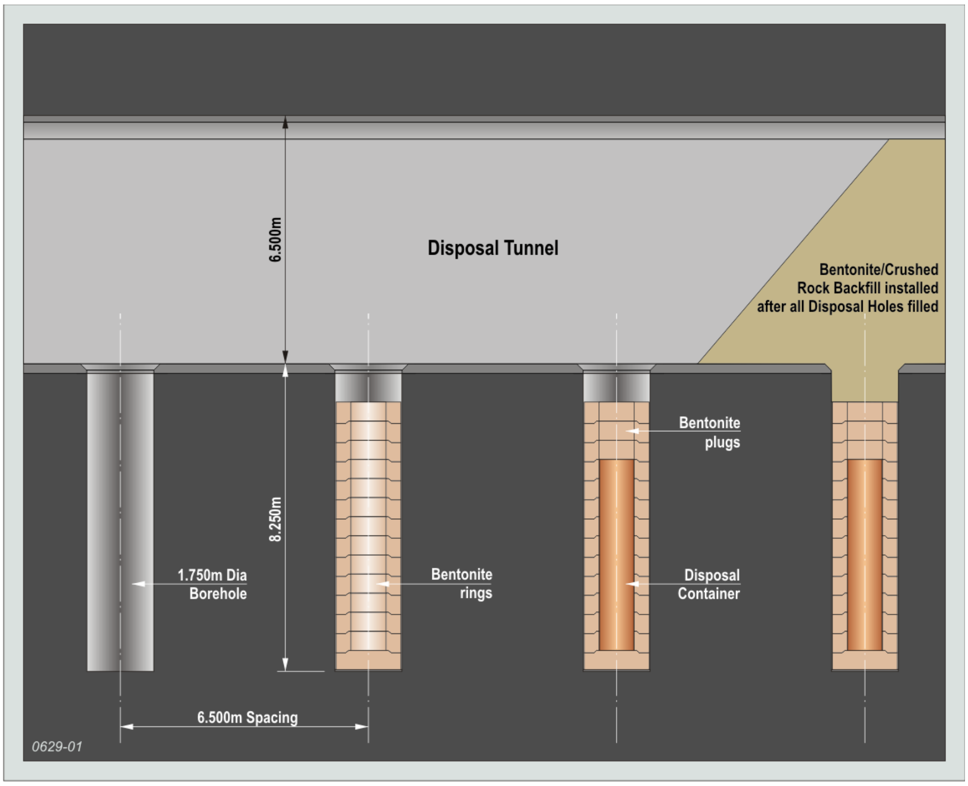


Figure B7 – Longitudinal section of a disposal tunnel in higher strength rock illustrating the deposition holes and immediate emplacement of backfill following disposal of spent fuel

B4.3 Spent Fuel Package Numbers and Characteristics

Hitachi-GE has estimated that a UK ABWR would discharge 9,600 off 50 GWd/tU spent fuel assemblies over its 60-year operational life. This corresponds to 800 disposal containers. Assuming that the lifetime heat energy coming from the reactor would be the same for the 60 GWd/tU case, 8,000 spent fuel assemblies would be discharged, which would require 667 disposal containers.

Hitachi-GE provided one-year-cooled ABWR fuel assembly inventory datasets for the 50 and 60 GWd/tU burn-up cases. These calculations were made with ORIGEN v2.2, using nuclear data libraries used for licensing in Japan. The reactor physics model used to generate the nuclear data libraries was based on a 9x9 fuel rod assembly. This assembly is considered to be a reasonable approximation to the GE14 10x10-8 assembly, because the moderator to fuel ratio, and hence the neutron spectrum should be similar in the two types of assembly.

To check that the inventories supplied by Hitachi-GE were conservative, RWM generated independent inventories using the ORIGEN-ARP inventory calculation tool and used these inventories to calculate heat output from the fuel assemblies. The independent calculations used an available cross-section library for the GE14 fuel assembly. The calculations in ORIGEN use 2D neutron transport calculations, and, therefore, the 3D nature of the UK ABWR fuel assembly (e.g. the presence of the part-length fuel rods and the difference in the physical form of the coolant which is converted to steam as it traverses the fuel rod) are accounted for in a representative manner.

The independent calculations demonstrated that the Hitachi-GE supplied inventories were conservative. For the 50 GWd/tU case, the heat output derived from the Hitachi-GE inventory exceeds that from the RWM initiated ORIGEN-ARP calculations by no more than 5.6% in the cooling time range 1-100 years. At longer cooling times (up to 260 years), the difference in the heat output between the Hitachi-GE and ORIGEN-ARP calculations increases, but still does not exceed 10.3%. The comparison for the 60 GWd/tU case is similar, although the differences in the heat output are slightly larger. At 100 years cooling, temperatures generated from the Hitachi-GE inventory are 6.2% higher than the ORIGEN-ARP inventory data, with the difference rising to 11.1% at 260 years cooling.

B4.4 Comparison of UK ABWR Spent Fuel with Sizewell B PWR Spent Fuel

Tables B7 and B8 provide comparisons, assembled by RWM, of the radionuclide inventories for the most significant post-closure radionuclides in spent fuel from a UK ABWR with radionuclide inventories for spent fuel from PWR (Sizewell B). Two comparisons are made:

- The comparison in Table B7 is based on the inventory of radionuclides estimated to be present in per tonne of uranium present in fresh fuel.
- The comparison in Table B8 is based on the inventory of radionuclides estimated to be present in a single disposal container of irradiated fuel.

The two comparisons provide different perspectives on the radionuclide inventories of UK ABWR spent fuel compared to Sizewell B spent fuel. The comparison of radionuclide inventories highlights any fundamental differences that may arise owing to, for example, the type of reactor or operating regime. The comparison of container inventories illustrates any differences that result in different packaging approaches, i.e. the quantity of spent fuel packaged in each disposal container.

The comparisons are based on two different burn-ups for each type of reactor:

- ‘Average Burn-up’ Activities: Average burn-up activities are based on the 50 GWd/tU UK ABWR inventory. The Sizewell B data are for stocks, which are assumed to have experienced a burn-up of 45 GWd/tU. The Sizewell B average burn-up data are modelled with 8 years cooling.
- High Burn-up Activities: High burn-up activities are based on the 60 GWd/tU UK ABWR inventory. The Sizewell B data are for arisings, which are assumed to have experienced a burn-up of 55 GWd/tU. The Sizewell B high burn-up data are modelled with 1 years cooling.

There is assumed to be 0.1798 tU per ABWR fuel assembly and, assuming that 12 are incorporated in a single disposal container, this corresponds to 2.158 tU per disposal container. In contrast, there are 1.834 tU assumed to be in a Sizewell B disposal container, based on 4 PWR fuel assemblies.

These comparisons demonstrate that the radionuclide inventories for the UK ABWR and Sizewell B are very similar. For the comparison of total activities per disposal container, only two radionuclides, Cl-36 and Sn-126 have activities in UK ABWR spent fuel greater than twice the activities in Sizewell B spent fuel, and only two radionuclides, Ni-59 and U-233 have activities in UK ABWR less than half of the activities in Sizewell B spent fuel. These radionuclides are highlighted in Tables B7 and B8 in orange and green respectively.

The activities of Cl-36 are approximately three times higher in the estimated inventory for the UK ABWR used in this Disposability Assessment compared to the inventory for Sizewell B spent fuel in the 2013 Derived Inventory [B11]. This is due to the differences in the assumed contamination of chlorine in the fresh spent fuel; the UK ABWR inventory was based on 25.5g of chlorine per tonne of uranium, whereas the Sizewell B inventory was based on 6.12g of chlorine per tonne of uranium.

The activities of Sn-126 are approximately three times higher in the estimated inventory for the UK ABWR used in this Disposability Assessment compared to the inventory for Sizewell B spent fuel in the 2013 Derived Inventory [B11]. This is due to the differences in the assumed precursor concentration of tin in the fresh spent fuel; the UK ABWR inventory was based on 8,030g of tin per tonne of uranium, whereas the Sizewell B inventory was based on 4,440g of tin per tonne of uranium. Tin is an alloying element in Zircaloy and Zircaloy is used for the fuel cladding and channel box in the UK ABWR but only for the fuel cladding in Sizewell B. There is therefore a significantly greater proportion of Zircaloy, and therefore tin, in the UK ABWR[5].

The activities of Ni-59 are approximately five times lower in the estimated inventory for the UK ABWR used in this Disposability Assessment compared to the inventory for Sizewell B spent fuel in the 2013 Derived Inventory [B11]. This is due to the lower quantities of Inconel, and hence nickel precursor, used in a UK ABWR fuel assembly compared to a Sizewell B fuel assembly; the UK ABWR inventory was based on 2,790g of nickel per tonne of uranium, whereas the Sizewell B inventory was based on 9,210g of nickel per tonne of uranium.

The activities of U-233 are approximately thirty times lower in the estimated inventory for the UK ABWR used in this Disposability Assessment compared to the inventory for Sizewell B spent fuel in the 2013 Derived Inventory [B11]. This is predominantly owing to the differences in the assumed precursor concentration of thorium in the fresh spent fuel; the UK ABWR inventory assumes a concentration of 10ppm of thorium in Zircaloy-2 resulting in 10g of thorium per tonne of uranium, whereas the Sizewell B inventory was based on 282g of thorium per tonne of uranium from the Earth's crustal abundance method, which assumes a minimum concentration of 1,000ppm.

[5] The UK ABWR is proposed to use Zircaloy-2 for the fuel cladding and channel boxes. Sizewell 'B' uses Zircaloy-4 for its fuel cladding. The tin levels are assumed the same for both in the above calculations.

Table B7 – Comparison of radionuclide activities for spent fuel from an UK ABWR with spent fuel from Sizewell B; total activities are presented per tonne of uranium in the fresh fuel (key radionuclides only)

	Average Burn-up SF Activity (TBq)			High Burn-up SF Activity (TBq)		
Nuclide	**ABWR**	**SZB**	**Ratio**	**ABWR**	**SZB**	**Ratio**
C-14	1.17E-01	2.14E-01	0.55	1.48E-01	2.13E-01	0.69
Cl-36	3.15E-03	9.94E-04	3.17	3.89E-03	9.94E-04	3.92
Ni-59	5.96E-02	2.91E-01	0.21	7.13E-02	2.91E-01	0.25
Se-79	1.93E-03	3.17E-03	0.61	2.20E-03	3.80E-03	0.58
Sr-90	9.10E+02	8.55E+02	1.06	6.75E+02	6.52E+02	1.04
Tc-99	7.11E-01	6.60E-01	1.08	8.14E-01	7.78E-01	1.05
Sn-126	3.82E-02	1.16E-02	3.30	4.83E-02	1.46E-02	3.30
I-129	1.78E-03	1.35E-03	1.31	2.15E-03	1.68E-03	1.28
Cs-135	2.86E-02	2.66E-02	1.08	3.39E-02	3.19E-02	1.06
Cs-137	1.43E+03	1.30E+03	1.10	1.15E+03	1.06E+03	1.09
U-233	1.43E-04	4.39E-03	0.03	1.49E-04	4.40E-03	0.03
U-234	6.74E-02	7.19E-02	0.94	8.05E-02	8.75E-02	0.92
U-235	4.47E-04	6.32E-04	0.71	2.52E-04	4.55E-04	0.55
U-236	1.30E-02	1.33E-02	0.98	1.33E-02	1.45E-02	0.92
U-238	1.15E-02	1.15E-02	1.00	1.14E-02	1.14E-02	1.00
Np-237	1.94E-02	1.97E-02	0.99	2.38E-02	2.51E-02	0.95
Pu-238	1.24E+02	1.18E+02	1.05	1.55E+02	1.47E+02	1.05
Pu-239	1.17E+01	1.37E+01	0.85	1.14E+01	1.41E+01	0.81
Pu-240	2.40E+01	2.20E+01	1.10	2.71E+01	2.53E+01	1.07
Pu-241	3.03E+02	3.20E+02	0.95	1.44E+02	1.57E+02	0.92
Pu-242	1.28E-01	1.10E-01	1.16	1.84E-01	1.55E-01	1.19
Am-241	1.76E+02	1.83E+02	0.96	1.90E+02	2.10E+02	0.90
Am-242m	2.80E-01	3.32E-01	0.85	2.82E-01	3.71E-01	0.76
Am-243	1.47E+00	1.55E+00	0.95	2.45E+00	2.45E+00	1.00

Table B8 – Comparison of radionuclide activities for spent fuel from an UK ABWR with spent fuel from Sizewell B; total activities are presented per disposal container (key radionuclides only)

	Average Burn-up SF Activity (TBq)			High Burn-up SF Activity (TBq)		
Nuclide	ABWR	SZB	Ratio	ABWR	SZB	Ratio
C-14	2.53E-01	3.92E-01	0.64	3.19E-01	3.91E-01	0.81
Cl-36	6.79E-03	1.82E-03	3.73	8.40E-03	1.82E-03	4.61
Ni-59	1.29E-01	5.33E-01	0.24	1.54E-01	5.33E-01	0.29
Se-79	4.16E-03	5.82E-03	0.72	4.75E-03	6.96E-03	0.68
Sr-90	1.96E+03	1.57E+03	1.25	1.46E+03	1.20E+03	1.22
Tc-99	1.53E+00	1.21E+00	1.27	1.76E+00	1.43E+00	1.23
Sn-126	8.24E-02	2.12E-02	3.89	1.04E-01	2.68E-02	3.89
I-129	3.84E-03	2.48E-03	1.55	4.65E-03	3.08E-03	1.51
Cs-135	6.18E-02	4.88E-02	1.27	7.31E-02	5.85E-02	1.25
Cs-137	3.09E+03	2.39E+03	1.29	2.48E+03	1.94E+03	1.28
U-233	3.08E-04	8.06E-03	0.04	3.22E-04	8.06E-03	0.04
U-234	1.45E-01	1.32E-01	1.10	1.74E-01	1.61E-01	1.08
U-235	9.65E-04	1.16E-03	0.83	5.44E-04	8.35E-04	0.65
U-236	2.81E-02	2.44E-02	1.15	2.87E-02	2.66E-02	1.08
U-238	2.49E-02	2.11E-02	1.18	2.46E-02	2.09E-02	1.18
Np-237	4.19E-02	3.61E-02	1.16	5.14E-02	4.61E-02	1.12
Pu-238	2.68E+02	2.17E+02	1.24	3.35E+02	2.70E+02	1.24
Pu-239	2.52E+01	2.52E+01	1.00	2.46E+01	2.58E+01	0.95
Pu-240	5.19E+01	4.03E+01	1.29	5.85E+01	4.64E+01	1.26
Pu-241	6.55E+02	5.88E+02	1.11	3.10E+02	2.88E+02	1.08
Pu-242	2.77E-01	2.03E-01	1.37	3.97E-01	2.84E-01	1.40
Am-241	3.79E+02	3.36E+02	1.13	4.09E+02	3.85E+02	1.06
Am-242m	6.05E-01	6.08E-01	0.99	6.09E-01	6.80E-01	0.89
Am-243	3.17E+00	2.84E+00	1.12	5.30E+00	4.49E+00	1.18

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