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Geological Disposal

Generic Design Assessment: Summary of Disposability Assessment for Wastes and Spent Fuel arising from Operation of the Westinghouse AP1000

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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. Amongst the parties requesting assessment under the GDA process is Westinghouse Electric Company LLC, which is seeking an initial endorsement of the Westinghouse Advanced Passive Pressurised Water Reactor (AP1000) design.

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 and decommissioning. Consequently, regulators have indicated that requesting parties 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 and spent fuel [3].

In accordance with regulatory guidance, Westinghouse has requested that the Radioactive Waste Management Directorate (RWMD) of NDA provide advice on the disposability of the higher activity wastes and spent fuel expected to arise from the operation and decommissioning of an AP1000. The reported assessment of the disposability of the higher activity wastes and spent fuel from the AP1000 is based on information on wastes and spent fuel, and proposals for waste packaging supplied by Westinghouse, supplemented as necessary by relevant information available to RWMD.

The principal conclusions of this GDA Disposability Assessment are presented in this Summary Report, together with the details of the wastes and their characteristics applied in the assessment. More comprehensive details of the information supplied to RWMD by Westinghouse, measures taken by RWMD to supplement this information, assessment methods and the detailed conclusions of the GDA Disposability Assessment are provided in a separate Assessment Report for the Westinghouse AP1000.

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; identification of the main outstanding uncertainties, and associated research and development needs relating to the future disposal of the wastes and spent fuel. A summary of the radionuclide inventories for ILW and spent fuel derived for the purposes of this GDA Disposability Assessment is set out in Appendix B.

It is recognised that, at this early stage in reactor licensing and development of operating regimes, packaging proposals are necessarily outline in nature, however, this Disposability Assessment has led to the production of a comprehensive and detailed data set describing the higher activity wastes and spent fuel to be generated from operation and decommissioning of an AP1000. At a later stage in the licensing process for new reactors, RWMD would expect to assess more specific and detailed proposals through the existing Letter of Compliance process for endorsing waste packaging proposals [4].

2 Nature of the Higher Activity Wastes and Spent Fuel

Westinghouse has provided information on the higher activity wastes and spent fuel expected to arise from an AP1000 operating for 60 years with a maximum fuel assembly average irradiation (burn-up) of 65 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 wastes and spent fuel are identified in this report: intermediate-level waste (ILW) arising from reactor operation, ILW arising from reactor decommissioning, and spent fuel. Westinghouse has provided information for the following three types of operational ILW:

- Primary Circuit Filters, including filters used in the Chemical and Volume Control System (CVCS), Spent Fuel pond cooling System (SFS), the Liquid Radwaste System (WLS) and the Solid Radwaste System (WSS);
- Primary Resins: including CVCS Mixed Bed Resin, CVCS Cation Bed Resin, SFS Demineralizer and Inorganic Resin from WLS;
- Secondary Resins: including Condensate Polisher Resins and Steam Generator Blowdown Material.

Westinghouse has indicated that the decommissioning ILW should be assumed to comprise the more highly activated steel components that make up the reactor vessel and its internals, and information has been assessed accordingly. In practice, decommissioning wastes will comprise a mix of ILW and LLW. 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.

As indicated above, information on spent fuel has been supplied by Westinghouse based on an assumed maximum fuel assembly average burn-up of 65 GWd/tU. It has been conservatively assumed that all spent fuel would achieve this burn-up. In practice this value will represent the maximum of a range of burn-up values for individual fuel assemblies.

3 Proposals for Packaging

Westinghouse has put forward proposals for the packaging of operational ILW based on the current practice for similar wastes in the UK. The Primary Circuit Filters would be cement grouted into RWMD standard $3m^3$ Boxes. To package the Primary and Secondary Resins, Westinghouse proposals are for cement encapsulation in UK standard $3m^3$ Drums. The $3m^3$ Boxes and Drums 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 also based on the use of UK standard waste containers consistent with RWMD standards and specifications. Westinghouse proposals are for cement encapsulation in UK standard $3m^3$ Boxes. Again, the $3m^3$ Boxes would need to be transported in a reusable shielded transport overpack to meet the requirements of the transport regulations.

The GDA Disposability Assessment has assumed that the spent fuel assemblies will be packaged in a robust disposal canister for disposal. For the purposes of this assessment, the spent fuel disposal canister is assumed to be manufactured from either copper or steel, with the fuel assemblies loaded into a cast-iron inner vessel. For consistency with previous assessments of the disposal of spent fuel undertaken by RWMD, it has been assumed that each disposal canister would contain up to four spent fuel assemblies. It is further assumed that the spent fuel would be delivered to the disposal facility packaged in the disposal canisters.

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

4 Radionuclide Inventory of ILW and Spent Fuel

The information supplied by Westinghouse on the radionuclide inventories of the identified wastes and spent fuel has been used to derive assessment inventories for the proposed ILW and spent fuel disposal packages (see Appendix B). In some cases, to ensure a full coverage of potentially significant radionuclides, it has been necessary to supplement the information supplied by Westinghouse using information available to RWMD. Further details of enhancement of the information supplied by Westinghouse are reported in the associated Assessment Report. The assessment inventories are intended to characterise the range of disposal package inventories, taking account of uncertainties and the potential variability between packages. The assessment inventory defines a best-estimate (average) and bounding (maximum) inventory for a disposal package.

The uncertainties in the inventories arise from numerous sources, for example the reactor operating regime adopted, fuel irradiation history, possible fuel cladding failures and the disposal package loadings that will be achieved in practice. The GDA Disposability Assessment has used expert judgement to bound this uncertainty and thereby provide robust, conservative conclusions. It is anticipated that information on the inventories associated with the wastes and spent fuel will be refined as the reactor operating regimes are developed further. RWMD would expect to consider such information, together with more refined packaging proposals, at an appropriate time in the future through the Letter of Compliance process.

Examples of opportunities for the refinement of data and removal of conservatisms include the assumptions relating to the incidence of fuel cladding failure (and the resultant activity associated with ILW ion exchange resin and filters), the pre-cursor concentrations for important activation products such as carbon-14 and chlorine-36 in the reactor and fuel assembly components, and the influence of the distribution of fuel burn-up.

It is particularly noted that the inventory associated with the spent fuel has been based on the conservative assumption that the maximum fuel assembly average burn-up of 65 GWd/tU applies uniformly to all fuel assemblies for disposal. In practice, the burn-up will vary with the operating history experienced by the assembly and the average burn-up of all assemblies would be less than 65 GWd/tU.

RWMD has concluded that the inventory data supplied by Westinghouse, together with measures implemented by RWMD to supplement the data, has provided a comprehensive data set sufficient to provide confidence in the conclusions of the GDA Disposability Assessment.

The GDA Disposability Assessment has shown that the principal radionuclides present in the wastes and spent fuel are the same as those present in existing UK legacy wastes and spent fuel, and in particular, with the anticipated arisings from the existing PWR at Sizewell B. This conclusion reflects both the similarity of the designs of the AP1000 and of existing PWRs, and the expectation that similar operating regimes would be applied.

The adoption of a higher burn-up for the AP1000, as compared to Sizewell B, is expected to result in increased concentrations of radionuclides in the spent fuel. Also, the longer operational life of the AP1000 (60 years as compared to 40 years anticipated for Sizewell B) increases the concentration of long-lived radionuclides in the decommissioning waste. The potential significance of such differences has been considered. The radionuclide inventory associated with the operational ILW will depend on operating decisions, for example the permitted radioactive loadings of ion exchange resins and filters, and therefore could be managed with the aim of meeting specific requirements for disposal.

5 Assessment of Proposed ILW Packages

The proposals for the packaging of ILW include outline descriptions of the means proposed for conditioning and immobilising the waste. Detailed descriptions and supporting evidence as to the performance of the proposed packages are not provided at this stage. This is consistent with expectations for the GDA Disposability Assessment. In future, RWMD would expect to work with potential reactor operators and provide assessment of fully-developed proposals through the Letter of Compliance process.

The proposal to use RWMD standard waste containers provides compliance with many aspects of the existing standards and specifications. Furthermore, the requirement for such packages to be transported in a reusable shielded transport overpack has been assessed to eliminate potential challenges to the dose-rate limits set out in the IAEA Transport Regulations.

The proposed use of cement 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 RWMD standards and specifications.

The assessment of long-term disposal system performance in the GDA Disposability Assessment has been undertaken by comparison with the assessment performed for legacy ILW. This was based on the assumed characteristics for a generic UK Geological Disposal Facility site. Since the properties of any selected site necessarily would need to be consistent with meeting the regulatory risk guidance level [5], 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 legacy ILW. The additional radionuclide inventory associated with the ILW from an AP1000 represents only a small fraction of that of the legacy 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 AP1000 in a site of the type described would be consistent with meeting the regulatory risk guidance level. The consideration of a fleet of nine reactors does not alter this conclusion.

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 ultimately the need to demonstrate the expected performance of the packages, these would represent requirements for future assessment under the Letter of Compliance process.

The number and type of new build reactors that may be constructed in the UK is currently not defined. Therefore, the GDA Disposability Assessment has evaluated the implications of a single AP1000 and, to illustrate the potential implications of constructing a fleet of such reactors, consideration also has been given to a fleet of nine AP1000 reactors. This corresponds to a generating capacity of about 10 GW(e), equivalent to the capacity of the existing nuclear reactors in the UK expected to cease operations in the next 20 years.

The potential impact of the disposal of AP1000 operational and decommissioning ILW on the size of a Geological Disposal Facility has been assessed. It has been concluded that the necessary increase in the 'footprint area' is small, corresponding to approximately 65m of vault length for each AP1000. This represents approximately 1% of the area required for the legacy ILW, per reactor, and less than 10% for the illustrative fleet of nine AP1000 reactors. This is in line with previous estimates for potential new build reactor designs [6].

6 Assessment of Spent Fuel Packages

Westinghouse has indicated that the GDA Disposability Assessment for the AP1000 should assume that the reactor would operate with uranium dioxide fuel 4.5% enriched in U-235 to achieve a maximum fuel assembly average burn-up of 65 GWd/tU. This burn-up is higher than that achieved for the existing PWR at Sizewell B.

In practice, the average burn-up for AP1000 spent fuel assemblies would be less than 65 GWd/tU and this maximum would represent the extreme of a distribution of burn-up values for individual fuel assemblies. However, in the absence of detailed information on the distribution of burn-up between fuel assemblies, for the purposes of the GDA Disposability Assessment it has been conservatively assumed that the value of 65 GWd/tU applies uniformly to them all.

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 difference is recognised as an important consideration in the assessment of spent fuel from the AP1000.

The GDA Disposability Assessment for the AP1000 has assumed that spent fuel would be overpacked for disposal. Under this concept, spent fuel would be sealed inside durable, corrosion-resistant disposal canisters manufactured from suitable materials, which would provide long-term containment for the radionuclide inventory. Although the canister material remains to be confirmed, the assessment has considered the potential performance of both copper and steel canisters. In both cases, it is assumed that cast-iron inner vessel is used to hold and locate the spent fuel assemblies, and in the case of the copper canister would provide mechanical strength as well. Overpacking of spent fuel in robust containers for disposal is a technology that is being developed in several overseas' disposal programmes.

Current RWMD generic disposal studies for spent fuel define a temperature criterion for the acceptable heat output from a disposal canister. In order to ensure that the performance of the bentonite buffer material to be placed around the canister in the disposal environment is not damaged by excessive temperatures, a temperature limit of 100°C is applied to the inner bentonite buffer surface. Based on a canister containing four AP1000 fuel assemblies, each with the maximum burn-up of 65 GWd/tU and adopting the canister spacing used in existing concept designs, it would require of order of 100 years for the activity, and hence heat output, of the AP1000 fuel to decay sufficiently to meet this temperature criterion.

It is acknowledged that the cooling period specified above is greater than would be required for existing PWR fuel to meet the same criterion and RWMD proposes to explore how this period can be reduced. This may be achieved for instance through refinement of the assessment inventory (for example by considering a more realistic distribution of burn-up), by reducing the fuel loading in a canister, or by consideration of alternative disposal concepts. The sensitivity of the cooling period to fuel burn-up has been investigated by consideration of an alternative fuel inventory based on an assembly irradiation of 50 GWd/tU. For this alternative scenario it is estimated that the cooling time required will reduce to the order of 75 years to meet the same temperature criterion.

RWMD 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 AP1000 spent fuel may influence the necessary arrangements, for example through the need for additional shielding, it is judged that sufficient flexibility exists in the current concept to allow suitable arrangements to be developed.

The GDA Disposability Assessment has considered how spent fuel packages would evolve in the very long term post-disposal, recognising that radionuclides would be released only subsequent to a breach in a disposal canister. A limited sensitivity analysis has been performed, examining two different canister materials (copper and steel) and testing the influence of the assumed corrosion properties.

Subsequent to any canister 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.

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 contact with groundwater and is influenced by the properties of the spent fuel. In the case of higher burn-up fuel, the increased irradiation of the AP1000 fuel would increase the IRF as compared to that for lower burn-up fuel. Generally available information [7] on the potential performance of higher burn-up fuel has been used to provide a suitable IRF for 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 necessarily would need to be consistent with meeting the regulatory risk guidance level, this assessment assumed the same site characteristics as assumed for the existing RWMD generic assessment. On the basis of the information provided and what are expected to be conservative calculations of canister performance, it is estimated that the spent fuel from a fleet of nine AP1000 reactors would give rise to an estimated risk below the risk guidance level based on these geological conditions and the existing safety case arguments.

The risks calculated for the disposal of spent fuel reflect the estimated performance of the proposed packaging methods. The sensitivity analysis demonstrated that while the calculated risk would be influenced by assumptions about the canister materials, for the assumed characteristics of the canisters and the disposal site, risks always remained below the regulatory guidance level, regardless of any impact that the high burn-up experienced by the fuel assemblies would have on the IRF.

RWMD recognises that the performance of disposal canisters will be an important element of a safety case for the disposal of spent fuel. Consequently, it is anticipated that RWMD will continue to develop canister designs, with the intention of substantiating current assumptions and optimising the designs.

The potential impact of the disposal of AP1000 spent fuel on the size of the Geological Disposal Facility has been assessed. The assumed operating scenario for an AP1000 (60 years operation) gives rise to an estimated 640 disposal canisters, requiring an area of approximately 0.11 km^2 for the associated disposal tunnels. A fleet of nine such reactors would require an additional area of approximately 1 km^2, excluding associated service facilities. This represents approximately 6% of the area required for legacy HLW and spent fuel per AP1000 reactor, and approximately 55% for the illustrative fleet of nine AP1000 reactors. This is in line with previous estimates for potential new build reactor designs [6].

RWMD is currently developing a Generic Disposal System Safety Case covering the Baseline Inventory of waste and wastes that may potentially arise in the future as set out in the Managing Radioactive Waste Safely White Paper [8]. RWMD is also considering an upper bound inventory reflecting the uncertainty around the Baseline Inventory, including the potential for wastes and spent fuel to arise from a new nuclear build power programme. This will provide information on the disposability of the various categories of waste in a single 'co-located' facility. It is planned that the Generic Disposal System Safety Case will be published in September 2010 to support the Geological Disposal Facility site selection and assessment process. This will provide a baseline for the ongoing provision of advice on the disposability of wastes, including for future interactions on AP1000 wastes and spent fuel.

7 Conclusions

RWMD has undertaken a GDA Disposability Assessment for the higher activity wastes and spent fuel expected to arise from the operation of an AP1000. 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 RWMD by Westinghouse. This information has been used to assess the implications of the disposal of the proposed ILW packages and spent fuel disposal packages against the waste package standards and specifications developed by RWMD and the supporting safety assessments for a Geological Disposal Facility. The safety of transport operations, handling and emplacement at a Geological Disposal Facility, 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.

RWMD has concluded that sufficient information has been provided by Westinghouse to produce valid and justifiable conclusions under the GDA Disposability Assessment. RWMD has concluded that ILW and spent fuel from operation and decommissioning of an AP1000 should be compatible with plans for transport and geological disposal of higher activity wastes and spent fuel. It is expected that these conclusions eventually would be supported and substantiated by future refinements of the assumed 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, RWMD would expect to assess, and potentially endorse, more specific and detailed proposals through the established Letter of Compliance process for assessment of waste packaging proposals.

On the basis of the GDA Disposability Assessment for the AP1000, RWMD has concluded that, compared with legacy wastes and existing spent fuel, no new issues arise that challenge the fundamental disposability of the wastes and spent fuel expected to arise from operation of such a reactor. This conclusion is supported by the similarity of the wastes to those expected to arise from the existing PWR at Sizewell B. Given a disposal site with suitable characteristics, the wastes and spent fuel from the AP1000 are expected to be disposable.

8 References

1. Meeting the Energy Challenge, *A White Paper on Nuclear Power*, Cm 7296, January 2008.

2. The Future of Nuclear Power, *The Role of Nuclear Power in a Low Carbon UK Economy*, Consultation Document, URN 07/970, May 2007.

3. Environment Agency, *Process and Information Document for Generic Assessment of Candidate Nuclear Power Plant Designs*, January 2007.

4. NDA RWMD, *Guide to the Letter of Compliance Assessment Process*, NDA Document WPS/650, March 2008.

5 Environment Agency and Northern Ireland Environment Agency, *Geological Disposal Facilities on Land for Solid Radioactive Wastes: Guidance on Requirements for Authorisation*, February 2009.

6 United Kingdom Nirex Limited, *The Gate Process: Preliminary Analysis of Radioactive Waste Implications Associated with New Build Reactors*, Nirex Technical Note Ref: 528386, February 2007.

7 Nagra Technical Report, *Estimates of the Instant Release Fraction for UO_2 and MOX fuel at t = 0*, Nagra TR 04-08, November 2004.

8 *Managing Radioactive Waste Safely: A Framework for Implementing Geological Disposal*, Cm 7386, June 2008.

Appendix A
Protocol for GDA Disposability Assessment

The GDA Disposability Assessment of the AP1000 was based on a protocol agreed with Environment Agency and the Nuclear Installations Inspectorate (NII) [A1]. It was managed as a structured project using management procedures controlled under the RWMD Management System. A Project Board was established to provide oversight and a point of reference for key decisions.

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 Westinghouse, supplemented by existing RWMD experience. In particular, knowledge of radioactive waste management at the Sizewell B pressurised water reactor (PWR) was used to add value to the GDA Disposability Assessment for the AP1000.

The Nature and Quantity of Waste evaluation was used to collate data on the operational and decommissioning ILW, and the spent fuel from the AP1000, 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, including:

- peer review of the submitted information;
- identification of any deficiencies and/or inconsistencies in the information;
- confirmation of waste volumes and 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 (GDF) and operations in a GDF, including estimation of release fractions for a range of standard impact and fire scenarios.

The Disposal Facility Design evaluation considered the implications of operation of an AP1000 on the design of the GDF, including the following:

- the footprint area needed to accommodate the wastes, in both a standalone facility and in a disposal facility also incorporating legacy wastes;
- 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 impact of any novel 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 the AP1000 with existing assessments of RWMD reference disposal concepts. The assessments provide the basis for judging the potential disposability of operational and decommissioning ILW, and spent fuel from the AP1000, including the following:

- the Transport Safety assessment considered the logistics, regulatory compliance and risk of transport operations, with specific consideration of dose, gas generation, containment and heat output under normal and accident conditions;
- the Operational Safety assessment considered dose due to accidents, effects of gas generation and criticality;
- the Post-closure Safety assessment considered potential radioactive impacts due to the groundwater and gas pathways, human intrusion and criticality, and environmental impacts due to chemotoxic species contained in the waste;
- the Consideration of Environmental Issues considered material usage in the GDF and commented on the consideration of options for waste management strategies and their implications for non-radiological environmental impacts;
- the Security Evaluation included determination of the likely security categorisation of the proposed waste packages, identification of nuclear material and commentary on proposals for accountancy and independent verification of the use of nuclear materials.

The process will conclude with the preparation of a detailed Assessment Report, describing these activities and their findings in full.

References

A1. NDA RWMD, *Disposability Assessment of Solid Waste Arisings from new Build, April 2008.*

Appendix B
AP1000 Operation, Wastes, Packaging Proposals and Package Characteristics

This Appendix provides a summary of the information used in the GDA Disposability Assessment for the AP1000. RWMD used the information supplied by Westinghouse, supplemented as necessary by information available to RWMD, to provide a comprehensive dataset of information covering waste package numbers, inventories and characteristics when conditioned and packaged.

This section contains the following information:

- summary description of an AP1000;
- assumptions regarding the operation of an AP1000;
- description of the higher activity radioactive waste streams and spent fuel that will be generated through operation and decommissioning of an AP1000 (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 AP1000 wastes in context, the expected ILW and spent fuel arisings are compared to the reported arisings from Sizewell B PWR.

B1 Summary of AP1000 Design and Operation

The AP1000 is an evolutionary PWR design with a rated thermal power of 3400 MW and an electrical power output of 1117-1154 MW(e), depending on site-specific factors.

The AP1000 evolutionary design is based on experience from operation of Light Water Reactors (LWR) worldwide, primarily those incorporating the most recent technologies. The primary system adopts the most reliable design features of both civil and naval PWRs and introduces many passive safety features that simplify the management of faults including loss of cooling events. The AP1000 design received US NRC Certification in January 2006 and four reactors are under construction in China.

In PWRs such as the AP1000, ordinary (light) water is utilised to remove the heat produced inside the reactor core by thermal nuclear fission. This water also 'thermalises' or moderates, neutrons in a manner necessary to sustain the nuclear fission reaction. The heat produced inside the reactor core is transferred to the turbine through the steam generators. Only heat is exchanged between the reactor cooling circuit (primary circuit) and the steam circuit used to feed the turbine (secondary circuit). No exchange of cooling water takes place.

The AP1000 design is furnished with a two-loop, primary circuit system composed of a reactor vessel that contains the fuel assemblies, a pressuriser including control systems to maintain system pressure, two reactor coolant pumps per loop, one steam generator per loop, one hot leg and two cold legs per loop (Figure B1).

In the reactor coolant system, the primary cooling water is pumped through the reactor core and the tubes inside the steam generators, in two parallel closed loops, by four reactor coolant pumps powered by electric motors. The reactor operating pressure and temperature are such that the cooling water does not boil in the primary circuit but remains in the liquid state, increasing its cooling effectiveness. A pressuriser, connected to one of the coolant loops is used to control the pressure in the reactor coolant system. Feed-water entering the secondary side of the steam generators absorbs the heat transferred from the primary side and evaporates to produce saturated steam. The steam is dried inside the steam generators then delivered to the turbine. After exiting the turbine, the steam is condensed and returned as feedwater to the steam generators. A schematic of the whole heat transfer and electricity production system in a PWR is provided in Figure B2.

Figure B1 – Principal primary circuit components of an AP1000. Figure reproduced from [B2].

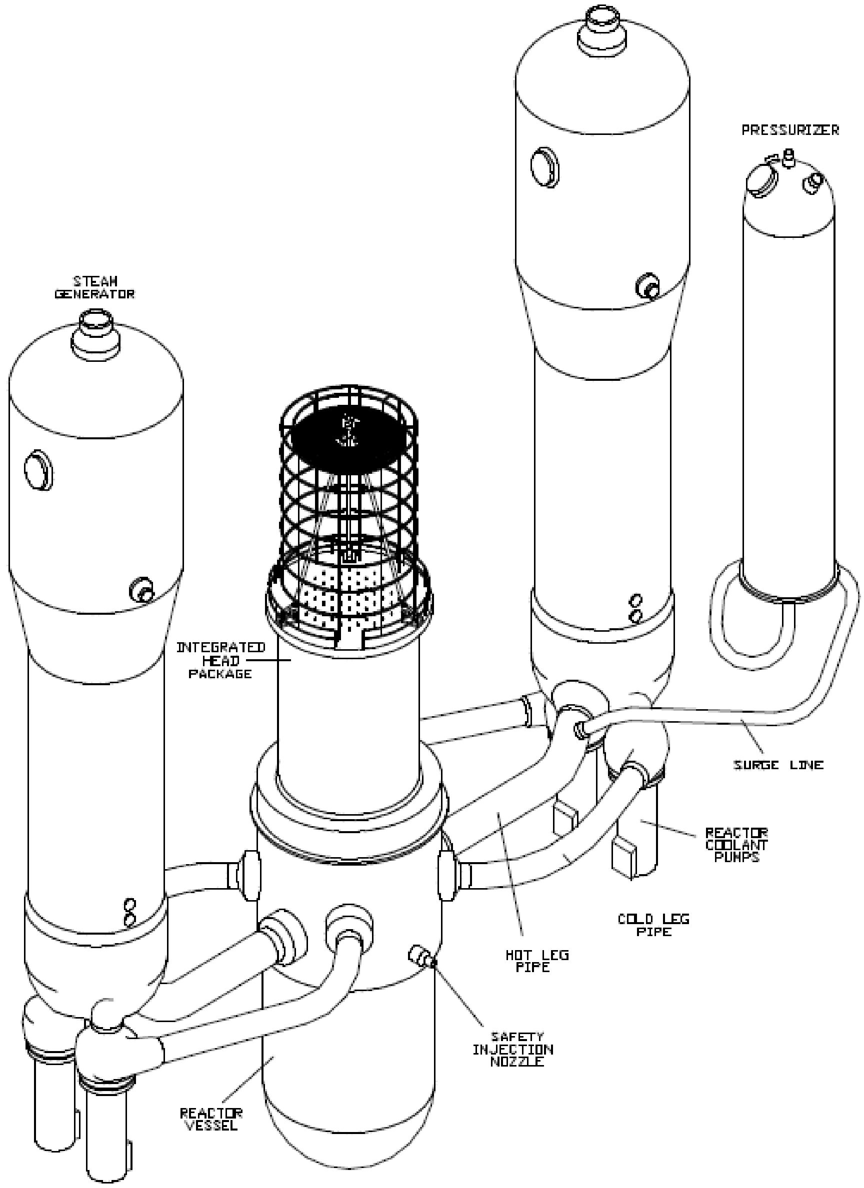
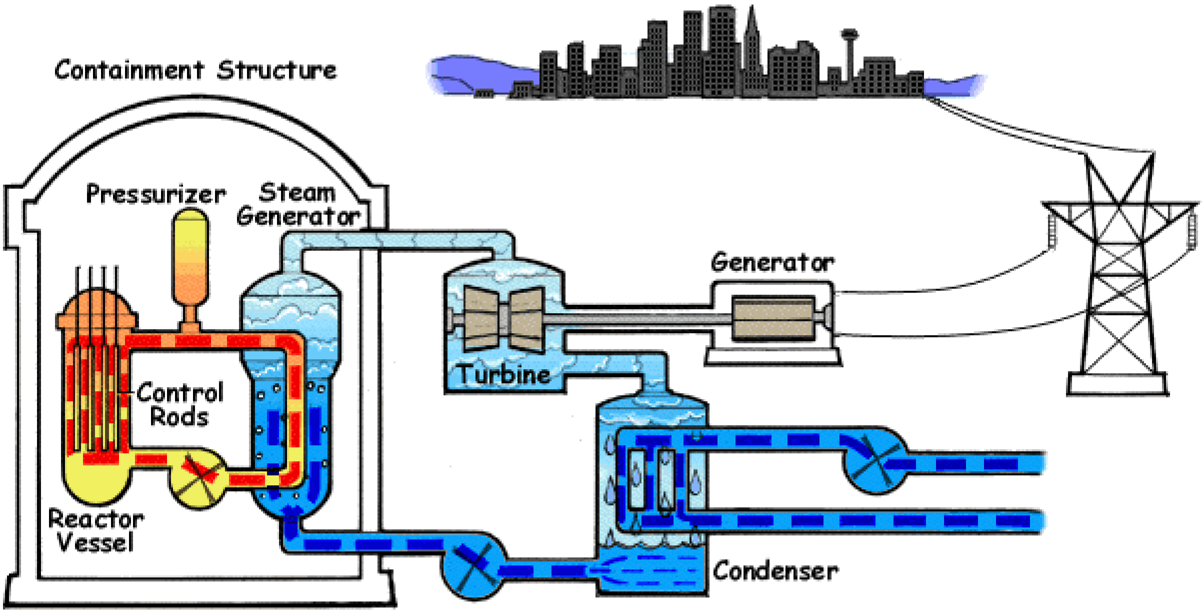


Figure B2 – Principal systems of a PWR. Figure reproduced from [B3].



B2 Assumptions

The GDA Disposability Assessment for the AP1000 was based on the following assumptions:

- The AP1000 would be operated for 60 years. During the operation of the reactor, fuel assemblies would be periodically rotated within the reactor core, and then removed and replaced with other fuel assemblies. Sixty-four spent fuel assemblies would be removed from the reactor every 18 months during planned shutdown periods and require storage.
- The date at which operation of power production from an AP1000 would commence in the UK is uncertain. In the GDA Disposability Assessment for the AP1000, estimates of time-dependent properties, e.g. those related to radioactive decay, are assessed from time of generation of the waste. In discussion of the implications for management of radioactive waste, RWMD has assumed a start date for a single reactor of 2020.
- Spent fuel characteristics have been determined on the assumption that the reactor would be operated to achieve a maximum fuel assembly irradiation (burn-up)* of 65 GWd/tU. In the absence of data to the contrary, the GDA Disposability Assessment has assumed that all fuel will be irradiated to the maximum fuel assembly burn-up. This is a conservative approach and ensures that the conclusions from the assessment are bounding for a wide range of possible operational behaviours.

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* The fuel assembly average irradiation (burn-up) represents the total irradiation associated with all the fissile material in an assembly divided by the initial mass of uranium in the assembly. It takes into account the variation in irradiation both axially along a fuel rod and the variation from one fuel rod to another. For simplicity, whenever fuel irradiation or burn-up is referred to in the remainder of the report what is meant is fuel assembly average irradiation or burn-up. Thus, the statement that the maximum fuel assembly burn-up is 65 GWd/tU means that the highest fuel assembly average burn-up will be 65 GWd/tU.

- The fuel used in the AP1000 would be manufactured from freshly mined uranium enriched to an initial U-235 content of 4.5%†.
- It is assumed that ILW and spent fuel from the AP1000 will arrive at the GDF in a packaged state, ready for disposal.

B3 ILW Streams, Packaging Assumptions, Package Numbers and Characteristics

B3.1 Operational ILW Streams and Packaging Assumptions

Westinghouse has indicated that three broad operational ILW streams would arise from normal operation of an AP1000:

- (AP01) Primary Circuit Filters, including filters used in the Chemical and Volume Control System (CVCS), Spent Fuel pond cooling System (SFS), the Liquid Radwaste System (WLS) inlet and outlet, and the Solid Radwaste System (WSS) resin fines filters;
- (AP02) Primary Resins: including CVCS Mixed Bed Resin, CVCS Cation Bed Resin, SFS Demineralizer, and Resins (organic and inorganic) from WLS
- (AP03) Secondary Resins: including Condensate Polisher Resins and Steam Generator Blowdown Material.

To package the Primary Circuit Filters, it is assumed that about 80 filters, with a raw waste volume of $0.9m^3$ would be cement grouted into a RWMD standard $3m^3$ Box. To accommodate all the filters arising from a 60 year operational lifetime for a single AP1000, 24 such waste packages would be produced. For transport, the $3m^3$ Boxes would be carried inside a Standard Waste Transport Container (SWTC) which is being developed by RWMD 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 $3m^3$ Boxes would need to be transported in a SWTC-285 to meet the IAEA Transport Regulation dose rate requirements.

To package the Primary and Secondary Resins, Westinghouse proposals are for cement encapsulation in $3m^3$ Drums. Westinghouse indicates that on the basis of grouting trials, an adequate wasteform may be generated if the resins occupy 25% of the wasteform by volume. To accommodate all the Primary and Secondary Organic Resin arising from a 60 year operational lifetime for a single AP1000: 1020 (for Primary Resins) and 190 (for Secondary Resins) waste packages would be produced. The $3m^3$ Drums would need to be transported in a SWTC-285 to meet the IAEA Transport Regulation dose rate requirements.

Both the $3m^3$ Box and $3m^3$ Drum are standard RWMD waste packages and are illustrated in Figure B3.

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. With such a delay, Westinghouse has assumed that even the highest specific activity bioshield concrete will have decayed to LLW, that any resins from a final decontamination of the primary circuit will also be LLW, and that these materials will be suitable for disposal to a LLW repository.

† Freshly-mined uranium may be contrasted with reprocessed uranium. The latter potentially contains significant quantities of U-236, which is a pre-cursor to Pu-238 and therefore can adversely affect the heat output of spent fuel. It is currently assumed that reprocessed uranium would not be used for manufacturing AP1000 fuel. Any change to this assumption would require further assessment.

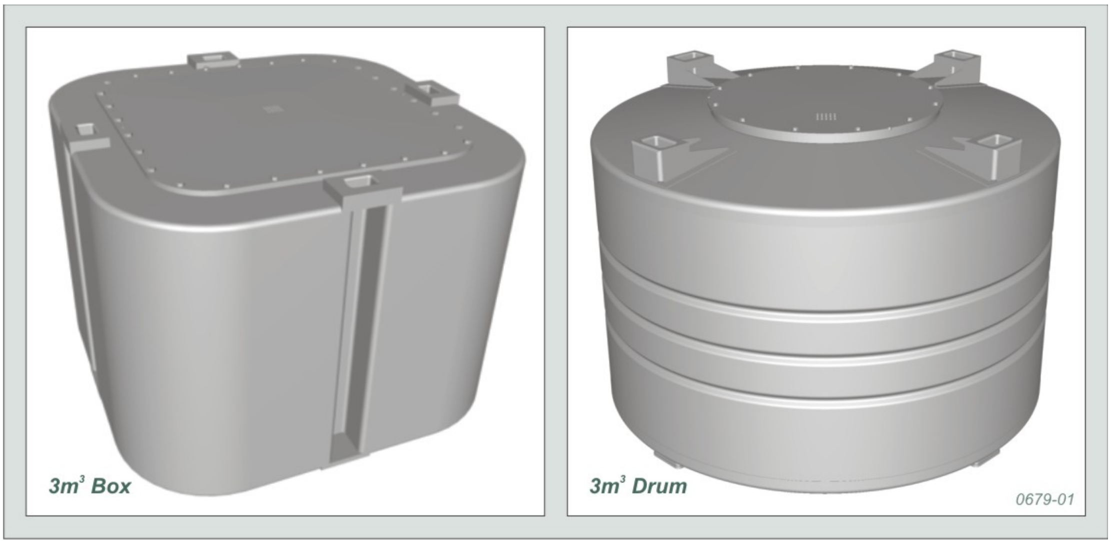
Although it is asserted that all concrete would be LLW after 40 years storage, this remains to be proven. Nevertheless, given the compact nature of an AP1000, RWMD estimates that the volume of any such ILW is unlikely to exceed 100m^3, and would be unlikely, therefore, to cause significant concern for disposability.

All other ILW produced prior to Stage 3 decommissioning would be managed as operational ILW and, for the purposes of this assessment, has been assumed to be encompassed by the operational ILW described above. This would include any wastes generated during early decommissioning, i.e. immediately after the reactor shut-down, and prior to Care and Maintenance (Stage 2).

Decommissioning ILW has been defined in two broad waste streams as follows:

- AP04 (ILW Steel), which consists of the stainless steel associated with pressure vessel internals including: Radial shield Baffle, Barrel, Neutron Pads and Formers; Upper and Lower Axial Shield, Loop pipes, Radial shield insulation and Liner. These steels are expected to have plate-like structures with a thickness of the order of 0.01m. The raw waste volume for this waste stream is 20 m^3. Westinghouse proposals are for cement encapsulation of this waste in 3m^3 Boxes (about 20 packages being required to accommodate the whole waste stream). The 3m^3 Boxes would need to be transported in a SWTC-285 to meet the IAEA Transport Regulation dose rate requirements.
- AP05 (Pressure Vessel), which consists of ferritic steel, associated with the mid-height section of the pressure vessel and from the internal vessel cladding. The pressure vessel steel will be in the form of thick (~0.2m) curved steel plate, possibly with its stainless steel cladding, typically a few mm thickness, still attached. The raw waste volume for this waste stream is 39 m^3. Westinghouse proposals are for cement encapsulation of this waste in 3m^3 Boxes (about 40 packages being required to accommodate the whole waste stream). The 3m^3 Boxes should be transportable in an SWTC-70 and still satisfy the IAEA Transport Regulation dose rate requirements.

Figure B3 – Illustration of a 3m^3 Box and 3m^3 Drum as proposed for packaging of Operational and Decommissioning ILW from the AP1000



B3.3 ILW Package Numbers and Characteristics

The information supplied by Westinghouse on the radionuclide inventories of the identified wastes 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 Westinghouse with information available to RWMD. 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 defined:

- 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 is particularly relevant to the post-closure assessment and some aspects of operational safety assessment;
- bounding (maximum) waste package inventory. This is used for transport safety and certain aspects of the operational safety assessment where individual waste packages are considered.

A comparison of the raw waste specific activity of the AP1000 resins with those quoted for the comparable Sizewell B wastes in the UK National Inventory [B5] indicates significantly higher activities in the AP1000 resins. This is explained by Westinghouse's conservative design basis assumption of a 0.25% fuel cladding failure rate. Such fuel cladding failure rates are believed to be conservative, but lower values have not been provided. The average Cs-137 inventory of the resin waste is an order of magnitude higher than that reported for Sizewell B. Furthermore, since Cs-137 is used as the reference radionuclide from which other, difficult to measure fission products are determined, the conservative approach will extend to many other radionuclides. Overall it seems likely that the radionuclide content declared for the AP1000 resin wastes contains significant conservatisms.

Although Westinghouse was able to supply separate volume data for the Primary and Secondary resins, and radionuclide data for the Primary resins, reliable radionuclide data for the Secondary resins were not available. Since the Secondary resins are expected to be less active than the Primary resins, for assessment purposes it was conservatively assumed that the radionuclide concentrations in the Secondary and Primary resins were the same.

Estimates of the quantities and characteristics of decommissioning ILW were developed based on modelling of the neutron flux, power history and material composition data for the region immediately surrounding the core of an AP1000 reactor. For the ILW Steel waste stream (AP04) account was taken of the variation in neutron flux through the material in the derivation of the total waste stream inventory and the maximum and average waste package inventory.

The inventory of C-14 associated with decommissioning ILW has been estimated through activation calculations based on an assumed concentration of the relevant pre-cursor species (primarily nitrogen). Westinghouse proposed that the nitrogen content of the stainless steels be taken as 1000ppm. In the absence of other data this is thought to be a conservative assumption.

The AP1000 ILW waste package radionuclide-related parameters and waste quantities (package numbers and total packaged volume) are given in Table B1. 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). In the absence of specific information on interim storage plans for operational waste, the conservative assumption of prompt dispatch to the GDF was adopted. The fissile content of waste is not included in the summary tables as it is estimated to be well below the 15g fissile exception level for non-fissile transport packages.

Table B1 – AP1000 Operational and Decommissioning ILW Waste Stream Data (1) (2) (3)

Waste Stream (4)	Package Type	Number of Packages	Total Packaged Waste Volume (m^3)	Average Package Alpha Activity (TBq)	Average Package Beta/ Gamma Activity (TBq)	Average Package A_2 Content	Average Package Heat Output (Watts)	Average Package Dose Rate at 1m from Transport Container (mSv/hr)
AP01	3m^3 Box	24	78.5	3.95E-06	2.02E+00	5.62E+00	4.21E-01	8.52E-05
AP02	3m^3 Drum	1020	2661.0	1.75E-05	7.30E-01	1.07E+00	1.16E-01	6.55E-05
AP03	3m^3 Drum	191	498.3	1.75E-05	7.30E-01	1.07E+00	1.16E-01	6.55E-05
AP04	3m^3 Box	22	71.4	1.47E-02	1.51E+03	9.14E+01	8.30E+00	3.10E-03
AP05	3m^3 Box	43	140.7	5.48E-06	1.04E+00	7.05E-02	7.75E-03	3.56E-06
TOTALS		13001300	3449.9					

Notes:

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

(2) Radionuclide data for the maximum package may be obtained as M times the average package data where approximately M=10 for AP01, M≤20 for AP02 & AP03, M ≤9 for AP04, M=2 for AP05.

(3) Dose rate refers to that 1m outside and SWTC-285 in the case of AP01, AP02, AP03 & AP04 and 1m outside an SWTC-70 in case of AP05.

(4) See Section B3.1 for description of AP01 to AP03 waste streams, and Section B3.2 for description of AP04 and AP05 waste streams .

B3.4 Comparison of AP1000 ILW with Sizewell B ILW

In order to place the information on the radioactivity of the ILW that would arise from an AP1000 in context, a comparison has been made with ILW from Sizewell B, which is the pressurised water reactor operated in the UK by British Energy. The Sizewell B design net electrical power output is 1,188 MW(e) [B4] and an assumed operating life of 40 years, whereas the AP1000's electrical power output is 1,117 MW(e) for an assumed operating life of 60 years. Information on the Sizewell B ILW inventory has been taken from the 2007 National radioactive Waste Inventory [B5]

Decommissioning ILW is the dominant source of many radionuclides in the estimated inventory for AP1000, with most of this activity being concentrated in the stainless steel waste stream AP04. The radionuclide with the highest total activity in both operational and decommissioning ILW (from AP1000) is Ni-63 and it is estimated that there is approximately 2,000 times more of this radionuclide in the decommissioning waste than in the operational waste. Similar (slightly larger) factors apply to Ni-59 and Co-60. The C-14 content of the AP1000 decommissioning waste at 199 TBq is about 400 times that in the operational waste.

The activity of AP1000 stainless steel decommissioning ILW (stream AP04) is compared with the activity of the equivalent Sizewell B PWR waste [B5] (2007 National Inventory stream 3S306) in Table B2. The basis for Table B2 is as follows:

- radionuclide activities have been estimated for 40 years after reactor shutdown;
- the activity data have been normalised to the total electrical output of the two reactors (Sizewell B – 1.18 GW(e) for 40 years; AP1000 1.117 GW(e) for 60 years); this allows a like-for-like comparison of the radionuclide inventories between the two types of reactors, and highlights any differences that would result from the design of the reactor or the operational practices (e.g. intensity of neutron flux);
- the radionuclides considered in Table B2 are the top 10 most active in the AP1000 wastes for which estimates were also available for the Sizewell B PWR wastes;

- the cell colouration displayed in the sixth column of Table B2 is used to indicate the closeness of the agreement that presents the ratio of AP1000 to Sizewell B normalised activities as follows: green 0.33 to 3, yellow 0.1 to 0.33 & 3 to 10, pink <0.1 & > 10.

Table B2 – Comparison of radionuclide activities for Stainless Steel decommissioning ILW from an AP1000 with Equivalent ILW stream from Sizewell B PWR (3S306)

Nuclide	Sizewell B 3S306 (TBq)	AP1000 St_Steel (TBq)	Sizewell B 3S306 (TBq per GW(e).yr)	AP1000 St Steel (TBq per GW(e).yr)	{AP1000 St Steel} / {3S306}
Ni-63	3.35E+04	3.12E+04	7.09E-01	4.66E-01	6.57E-01
H-3	8.77E+01	1.06E+03	1.86E-03	1.58E-02	8.48E+00
Nb-93m	3.84E+02	3.30E+02	8.13E-03	4.92E-03	6.06E-01
Ni-59	3.23E+02	2.40E+02	6.85E-03	3.58E-03	5.22E-01
Co-60	8.04E+02	2.13E+02	1.70E-02	3.18E-03	1.87E-01
C-14	1.21E+02	1.99E+02	2.56E-03	2.96E-03	1.16E+00
Mo-93	1.21E+00	4.49E+01	2.56E-05	6.70E-04	2.62E+01
Fe-55	1.64E+02	1.66E+01	3.48E-03	2.47E-04	7.10E-02
Nb-94	4.04E+00	4.58E+00	8.56E-05	6.83E-05	7.98E-01
Tc-99	1.21E-01	1.14E+00	2.57E-06	1.70E-05	6.62E+00

As can be seen from Table B2, with the exception of H-3 and Co-60, the activities of the six radionuclides with the highest activities are similar (within a factor of three). Like H-3 the total activity of Mo-93 and Tc-99 is considerably higher in the AP1000 stainless steel wastes than that from Sizewell B. This can be explained by the application of conservative upper bound trace element concentrations in the RWMD inventory enhancement work.

The practices used in operating an AP1000 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 estimates at this stage. For ILW, the most active waste streams are those from decommissioning, and estimates of decommissioning ILW from an AP1000 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 AP1000 ILW 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 the AP1000 decommissioning 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 AP1000 fuel design is based on the 17x17 XL (14 foot) design used successfully at plants in the US and Europe. The core of an AP1000 consists of 157 fuel assemblies providing a controlled fission reaction and a heat source for electrical power production. Each fuel assembly is formed by a 17×17 array of Zirlo tubes, made up of 264 fuel rods, 24 control rod guide thimbles and a central instrument thimble, as illustrated in Figure B4. Zirlo is an advanced alloy of zirconium with a typical major element composition by mass of Zr – 97.4%, Nb – 1.2%, Sn – 1.1% and trace iron and oxygen. Zirlo is a development of Zircaloy-4, which has been used previously for fuel rod cladding; the new alloy provides for greater radiation and chemical stability (i.e. corrosion-resistance in reactor water) to allow for higher burn-up in the reactor.

The rods are held in bundles by 10 spacer grids distributed at roughly uniform intervals up the 4.6m free height of the rods (5 additional grids consisting of 4 intermediate flow mixing grids and one so-called 'P-Grid' are also part of the fuel assembly). The rods are fixed top and bottom into stainless steel nozzles that provide both structural integrity and direct coolant flow up the assembly. The total height of the assembly excluding the upper hold-down springs is 4.795m. The 25 guide thimbles are joined to the grids and the top and bottom nozzles. Twenty four of the guide thimbles are the locations for the rod cluster control assemblies (RCCAs – the control rods) or burnable poison rods[‡]. The remaining central thimble may contain neutron source rods, or in-core instrumentation. Guide thimbles that do not contain one of these components are fitted with plugs to limit the bypass flow. The grid assemblies consist of an 'egg-crate' arrangement of interlocked straps. The eight spacer grids and four intermediate flow mixing grids distributed along the fuelled section of the assembly are made from low neutron capture Zirlo, whereas the top and bottom spacer grids and P grid are made from the nickel alloy Inconel 718.

The AP1000 fuel assembly and fuel rod are illustrated in Figure B4 and some additional dimensional information is provided in Table B3.

The fuel rods consist of uranium dioxide (UO_2) pellets, typically 4.5% enriched in U-235, stacked in a Zirlo cladding tube plugged and seal welded to encapsulate the fuel. The stack of UO_2 pellets extends over a height of 4.267m known as the active height of the fuel. Above and below the UO_2 stack are the upper and lower fission gas plenums designed to accommodate any volatile fission products released during the irradiation process. An Inconel (believed to be Grade 718) spring is present in the upper plenum to maintain the dimensional integrity of the UO_2 stack, at the bottom of which is placed a thermal insulation pellet (believed to be made from alumina, Al_2O_3).

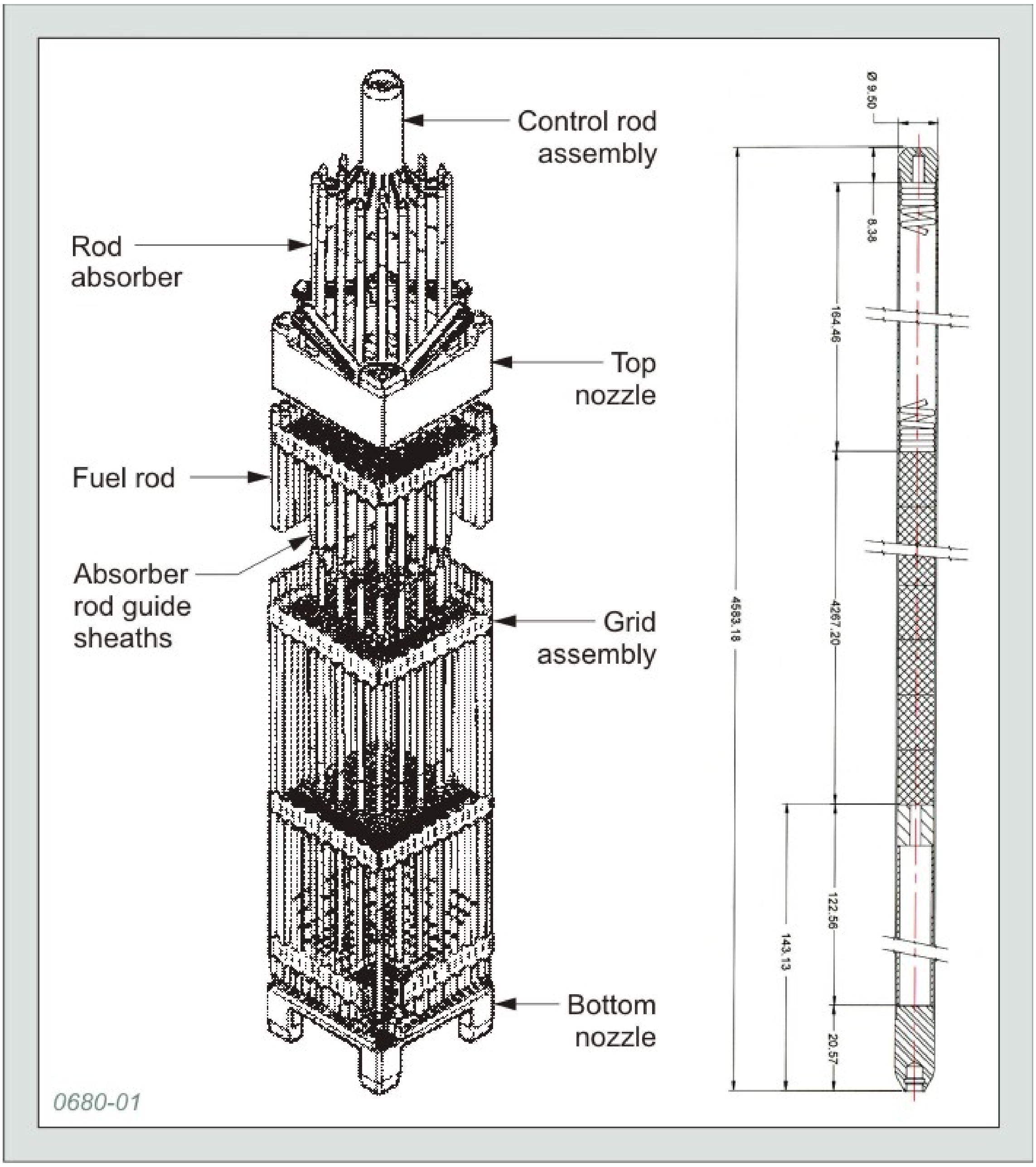
In some fuel rods, consumable neutron absorber ("burnable poison"), in which the fuel pellets are coated with neutron absorbing boron compound or gadolinium oxide (Gd_2O_3), is used to control excess reactivity during the fuel cycle.

Table B3 – Dimensional information for AP1000 fuel assemblies and rods

Fuel Assembly	
External maximum section (mm x mm)	214 × 214
Maximum length (mm)	4795
Active length (mm) (Average, at 20 °C)	4267
Fuel Rod	
Number of fuel rods	264
Fuel rod outer diameter (mm)	9.5
Cladding thickness (mm)	0.57
Pin pitch (mm)	12.6

‡ The RCCAs are not included within the initial disposal inventory supplied by Westinghouse and therefore are not considered in the GDA Disposability Assessment.

Figure B4 – Components of an AP1000 fuel assembly and separate control rod assembly (left) and a single AP1000 fuel rod (right)



B4.2 Spent Fuel Packaging Assumptions

The packaging assumptions for AP1000 spent fuel are based on concepts developed by RWMD to date [B6]. Under these concepts, spent fuel would be overpacked into durable, corrosion-resistant disposal canisters manufactured from suitable materials, which would provide long-term containment for the radionuclides contained within the spent fuel (Figure B5). Although the canister material remains to be confirmed, the assessment has considered the potential performance of copper and steel canisters. In both cases, it is assumed that an additional cast-iron inner vessel is used to hold and locate the spent fuel assemblies, and in the case of the copper canister would provide mechanical strength as well. These canisters would be emplaced in disposal holes lined with a buffer made from compacted bentonite, which swells following contact with water (Figure B6). The concept is based on the KBS-3V concept developed by SKB for disposal of spent fuel in Sweden [B7].

Figure B5 – Illustration of an AP1000 spent fuel disposal canister

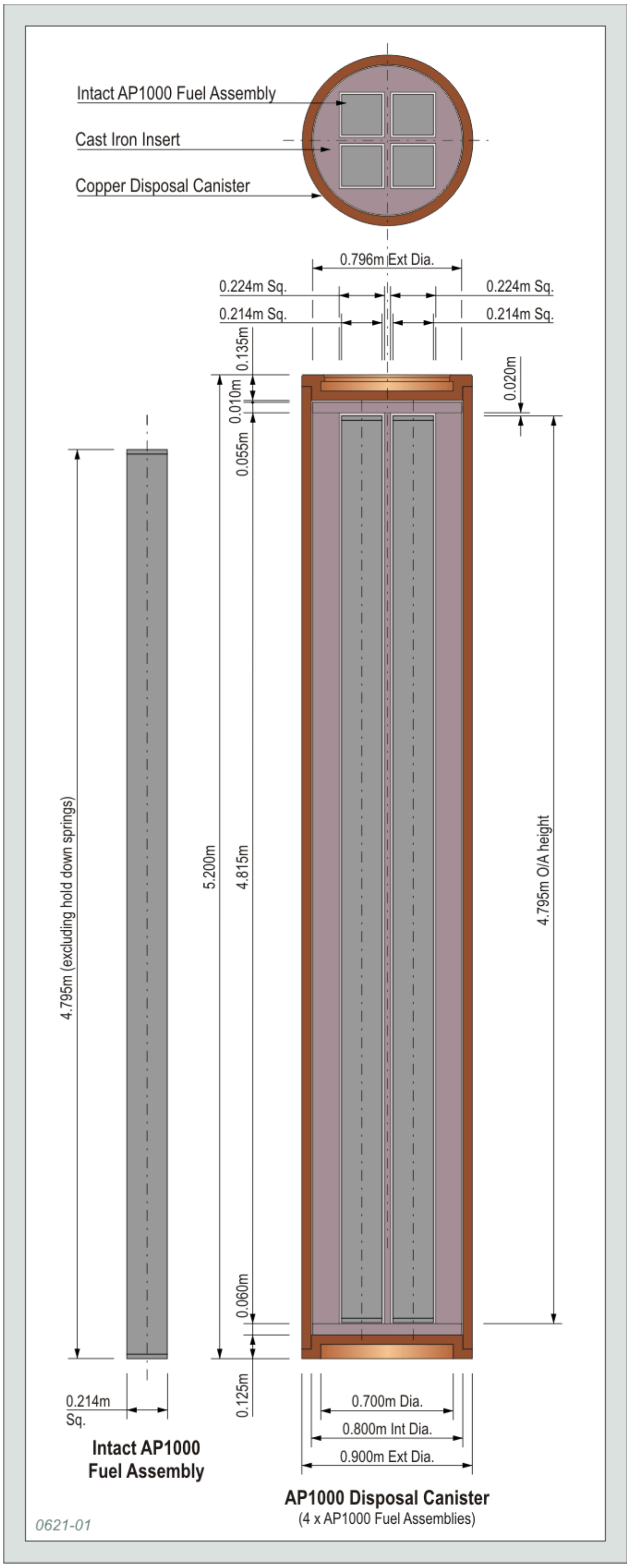
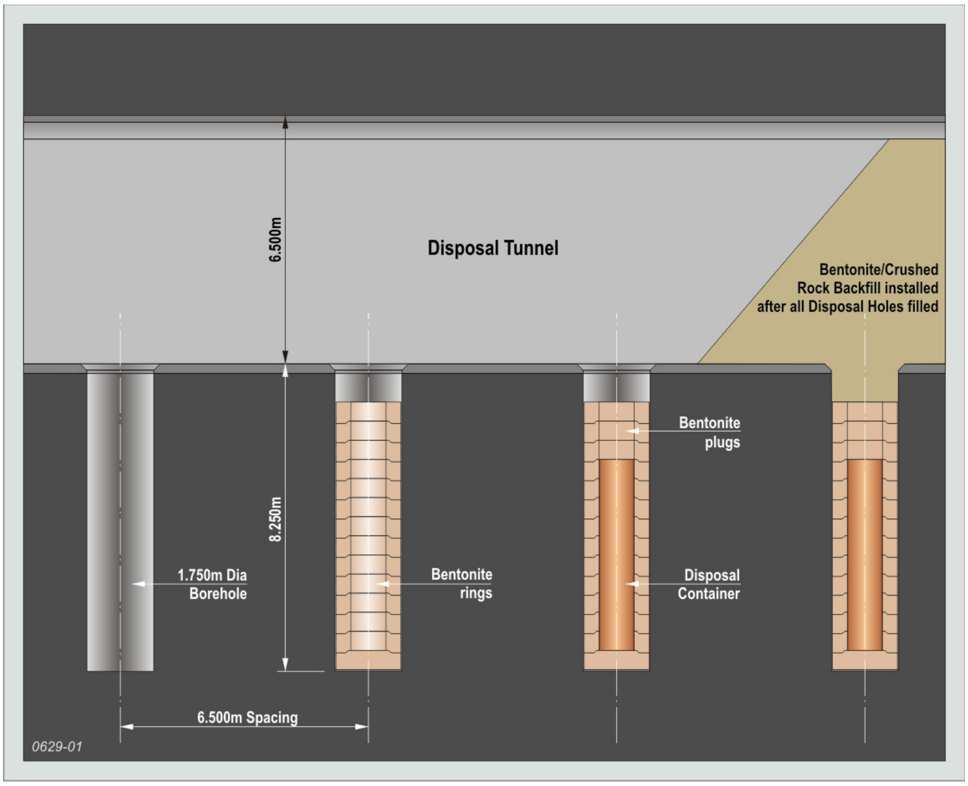


Figure B6 – Longitudinal section of a disposal tunnel illustrating the disposal holes and immediate emplacement of backfill following disposal of spent fuel



The disposal concept for spent fuel assumes that fuel assemblies will be loaded into a robust disposal canister with a length of 5.2 m (Figure B5). This is a development of the canister envisaged for legacy fuel from Sizewell B PWR and is approximately 0.6 m longer. The reference assumption is for four spent fuel assemblies to be packaged in each canister.

It is assumed that spent fuel will be packaged for disposal (sometimes referred to as encapsulation) before being dispatched to the GDF. For transport the packaged spent fuel would need to be shielded and contained in a reusable shielded transport overpack. For the purposes of assessment, this is assumed to be accomplished by use of a Disposal Canister Transport Container (DCTC) which has been developed to a preliminary design stage by RWMD. The DCTC provides two layers of shielding material:

- immediately adjacent to the canister is a stainless steel gamma shield with thicknesses of 140mm in the radial direction and 50mm at the ends of the canister;
- surrounding the stainless steel gamma shield is a 50mm thick neutron shield made of the high neutron capture material such as 'Kobesh'.

Although the quantitative analyses conducted in the GDA Disposability Assessment for the AP1000 are based on certain disposal concept assumptions, the implications of alternative disposal concepts also have been considered.

B4.3 Spent Fuel Package Numbers and Characteristics

The GDA Disposability Assessment for the AP1000 assumes that 64 fuel assemblies will be generated every 18 months of reactor operation, which, for an assumption of 60 years operation, results in a total of 2,560 assemblies requiring disposal, i.e. 640 canisters.

The RCCAs described in Section B4.1 were not included in the initial disposal inventory supplied by Westinghouse. Although these wastes may have high specific activity, they will not be of large volume, and, therefore, are not expected to affect disposability of wastes from an AP1000. These components could be managed as either ILW or, given their dimensions, packaged as a complete unit with their associated fuel assembly. The RCCAs are longer than the spent fuel, but can be reduced in size by removing the end supports. In any future submission under the LoC process, the operator should provide further information on proposals for the management of RCCAs.

The dimensions of one fuel assembly are 0.214m x 0.214m x 4.795m (Figure B5), so the raw waste volume associated with 2,560 fuel assemblies is 562m^3. Regarding packaged volume, the envelope volume of a canister capable of accommodating four fuel assemblies is 3.33m^3, and the packaged volume of the waste consisting of 640 canisters is therefore 2,131m^3.

Westinghouse proposed that the concentration of chlorine impurities in the fuel was 5ppm for UO_2 and 20ppm for Zirlo. Both concentrations are considered to represent conservative assumptions.

The component mass estimates for an AP1000 fuel assembly are provided in Table B4. Table B5 presents the mass data for each fuel assembly and per disposal canister, summed for each material type.

Package radionuclide related data for the spent fuel waste are summarised in Table B6.

Table B4 – Estimates of component mass for an AP1000 fuel assembly

Component	**Material**	**Mass per Assembly (kg)**
UO_2	UO_2	6.125E+02
Cladding	Zirlo	1.246E+02
Zirlo Grids & Guide Tubes etc	Zirlo	2.930E+01
Inconel Grids	Inconel 718	2.070E+00
Nozzles Springs	Inconel 718	1.290E+00
Nozzles Steel	St Steel Type 304	1.457E+01
Lower Plenum standoff tube	Zirlo	2.310E+00
Plenum Springs	Inconel 718	1.820E+00
Alumina Insulating Pellets	Al_2O_3	5.650E-01
Total - whole fuel Assembly		**7.890E+02**

Table B5 – Material mass breakdown for an AP1000 fuel assembly and for a canister (assuming four assemblies per canister)

Material	Mass per Assembly (kg)	Mass per Canister (kg)
UO_2	6.13E+02	2.450E+03
Zirlo	1.56E+02	6.25E+02
St Steel Type 304	1.5E+01	5.8E+01
Inconel 718	5E+00	2.1E+01
Al_2O_3	6E-01	2E+00
Total	**7.89E+02**	**3.156E+03**

Table B6 – AP1000 Waste Stream Data: Spent Fuel(1)

Waste Stream	Package Type	Number of Packages	Total Packaged Waste Volume (m^3)	Maximum Package Alpha Activity (TBq)	Maximum Package Total Beta/ Gamma Activity (TBq)	Maximum Package A_2 Content	Maximum Package Heat Output (Watts)	Maximum Package Dose Rate at 1 m from Transport Container (mSv/hr)	Maximum Package Total Fissile Content (g) {U233+ U235+ Pu239+ Pu241}
Spent Fuel	Disposal Canister	640	2131.00	1.06E+03	3.39E+03	1.05E+06	1.43E+03	1.18E-01	2.24E+04

Notes:

(1) The values are for maximum waste package inventories (a single set of pessimistic assumptions were used to derive the inventory data so average package data are not available) after 90 years cooling.

Although Westinghouse is designing and planning for a burn-up of fuel to 65 GWd/tU, this is the maximum burn-up that a fuel assembly would experience. The lifetime thermal energy production for an AP1000 at a load factor of 93% would be 6.93E+04 GWd. These 2,560 AP1000 fuel assemblies would contain 1,383 tU. Therefore, assuming that 2,560 fuel assemblies are generated over the lifetime of a reactor implies that the average burn-up of the assemblies is 50.1 GWd/tU. In calculating the total spent fuel inventory for the post-closure performance assessments, it was assumed that all 2,560 spent fuel assemblies had been irradiated to 65 GWd/tU, rather than 50.1 GWd/tU. This is clearly conservative although the conservatism only amounts to about a factor of 1.3 for most of the post-closure significant radionuclides.

B4.4 Comparison of AP1000 Spent Fuel with Sizewell B PWR Spent Fuel

Fuel used to generate heat in an AP1000 would be expected to experience higher burn-ups than existing commercial reactors in the UK, for example the PWR at Sizewell B. Higher burn-up results in efficiency savings for the operator. For a similar quantity of electricity produced an AP1000 would create a smaller volume of spent fuel.

For example, an AP1000 operating for 60 years at 1.117 GW(e) would produce 2,560 spent fuel assemblies, which is equivalent to 38.2 spent fuel assemblies for every GW(e) year. In comparison, assuming the PWR at Sizewell B operates for 40 years at 1.188 GW(e) and produces 2,228 spent fuel assemblies [B8], 46.9 spent fuel assemblies would be produced for every GW(e) year. Thus the efficiency gains can be seen, but this does lead to a higher concentration of activity in AP1000 spent fuel assemblies in comparison to Sizewell B PWR assemblies.

Table B7 provides a comparison of the radionuclide inventories for the most significant post-closure radionuclides in spent fuel from an AP1000 with radionuclide inventories for spent fuel from the Sizewell B PWR. The comparison is based on the inventory of radionuclides estimated to be present in one spent fuel canister at 90 years cooling[§] The data for the Sizewell B PWR are derived from the Low Burn-up PWR data presented in [B9], the fission product and actinide data from which were used in a previous assessment of the implications associated with new build reactors undertaken by Nirex [B10].

Table B7 – Comparison of radionuclide activities for spent fuel from an AP1000 with spent fuel from Sizewell B

Nuclide	Sizewell B SF TBq per Canister	AP1000 SF TBq per Canister	Ratio AP1000 : SXB
C-14	6.45E-02	3.30E-01	5.1
Cl-36	8.31E-04	3.63E-03	4.4
Ni-59	9.08E-04	1.55E-01	171
Se-79	3.18E-02	1.08E-02	0.34
Sr-90	6.75E+02	1.16E+03	1.7
Tc-99	1.03E+00	1.92E+00	1.9
Sn-126	5.67E-02	8.79E-02	1.5
I-129	2.39E-03	4.33E-03	1.8
Cs-135	3.02E-02	8.08E-02	2.7
Cs-137	1.02E+03	1.98E+03	1.9
U-233	1.23E-05	5.16E-05	4.2
U-234	1.33E-01	1.70E-01	1.3
U-235	1.53E-03	7.36E-04	0.48
U-236	2.15E-02	3.25E-02	1.5
U-238	2.46E-02	2.44E-02	1.0
Np-237	3.28E-02	6.50E-02	2.0
Pu-238	9.09E+01	4.16E+02	4.6
Pu-239	2.50E+01	3.03E+01	1.2
Pu-240	3.61E+01	6.39E+01	1.8
Pu-241	1.23E+02	2.03E+02	1.6
Pu-242	1.24E-01	4.34E-01	3.5
Am-241	2.83E+02	4.92E+02	1.7
Am-242m	7.32E-01	1.89E+00	2.6
Am-243	1.14E+00	7.25E+00	6.3

The only comparison of AP1000 and Sizewell B spent fuel inventories that could readily be made involves AP1000's maximum fuel assembly average burn-up inventory with the batch average fuel burn-up inventory associated with Sizewell B, as reported in [B4]. It is recognised that it would have been more appropriate to compare either the two maximum fuel assembly average burn-up cases or two batch average fuel burn-up inventories. However, relevant information was not available for such comparison at the time of this assessment. Since the burn-up assumed for AP1000 spent fuel is about twice that assumed for the Sizewell B spent fuel, for many radionuclides the ratio of AP1000 to Sizewell B fuel activities is about two, as shown in Table B7. Ratios a little below and above two reflect non-linearity effects that arise from, for example, the higher proportion of fissions coming from Pu-239 in the higher burn-up fuel. A few of the activity ratios are outside the range that

[§] 90 years was selected at the outset of this assessment to provide a reasonable approximation of the amount of cooling time expected before disposal.

might be expected from the different burn-ups and these, perhaps unexpected differences are attributable to five separate causes which are discussed below. Yellow, pink, blue, green and orange shadings have been used in Table B7 to identify the causes of the apparently anomalous activity ratios.

Yellow cells: C-14, Cl-36 and Ni-59. These radionuclides arise mainly as activation products of trace impurities or in the case of Ni-59, from trace impurities and the small amount of a nickel alloy (Inconel 718) used for top and bottom grids. The stable elements responsible for these activation products are: nitrogen for C-14; chlorine for Cl-36; nickel for Ni-59. In general, Westinghouse adopted more conservative specification limit values for the trace impurities in their spent fuel inventory calculations than has been adopted by RWMD in previous studies of PWR fuel. This has led to AP1000 inventories that are more than the factor of two greater than those coming from the Sizewell B calculations (identical impurity levels would have resulted in AP1000 inventories being about twice the Sizewell B inventories because of the two-fold higher irradiation). For example, for the calculations Westinghouse indicated that chlorine concentrations of approximately 5ppm and 20ppm for the UO_2 and Zirlo cladding respectively, whilst the Sizewell B calculations used approximately 5ppm chlorine for the UO_2 and neglected the chlorine content of the cladding. Based on an extensive Cl-36 research project conducted by Nirex in the 1990's the chlorine concentrations adopted for the Sizewell B calculations are considered more justifiable (i.e. the upper bound chlorine concentration for LWR UO_2 and Zircaloy were assessed to be approximately 5ppm and 1.7ppm respectively [B11],[B12]).

The large (factor of 171) activity ratio calculated for Ni-59 arises from the extra activity induced in the nickel rich Inconel 718 top and bottom grids of the AP1000 assembly. The calculations performed for the Sizewell B fuel did not include any Inconel fuel structural components.

Pink cells: Se-79. Differences in the estimated activities of Se-79 are associated with changes to data on the fission yield and half-life of this radionuclide, and these parameters have been revised in recently published nuclear data libraries. For a given fission yield in terms of number of atoms, the associated activity is inversely proportional to half-life. The estimated activity of Se-79 for an AP1000 used a half-life for the radionuclide of about 2.95E+05 years. However, the Sizewell B estimates used a Se-79 half-life of 6.5E+04 years, and the difference in Se-79 activity presented in Table 12 is in accord with the difference in half-lives and burn-ups associated with the two spent fuel calculations used to develop the estimates.

Blue cells: U-235. The lower activity of U-235 present in the AP1000 spent fuel is merely a feature of the higher burn-up experienced by the AP1000 spent fuel. Since U-235 is the main fissile isotope in the fuel, to achieve a higher burn-up, more U-235 must be consumed. Fission of Pu-239 and Pu-241 complicates the detailed fissile mass balance but extra consumption of U-235 in high burn-up fuels is expected.

Green cells: Pu-238, Pu-242 and Am-243. A number of higher mass actinides are produced by multi-step activation reactions. A characteristic of such reactions is that they produce an increase in activity above the linear dependence found for most fission products and low mass actinides. For example, Pu-238 is produced by the activation of Np-237 which in turn is produced from the irradiation of both U-236 and U-238. This is an example of a simple two step activation reaction for which the activity of the product (Pu-238) increases as the second power of burn-up. Thus a two-fold increase in burn-up results in a four-fold increase in Pu-238 activity. In other actinide build-up chains, such as those involving Pu-239, Pu-240 and Pu-241, saturation and decay effects complicate the position. Hence, the increase in Pu-242 and Am-243 activity is not as fast as would be anticipated by the number of activation steps required for their production. However, the above-linear increase of Pu-242 and Am-243 activity with burn-up is still fundamentally down to the fact that they are produced by multi-step activation reactions.

Orange cell: U-233. When the typical mix of uranium isotopes in PWR fuel is irradiated, U-233 arises predominantly from the decay of Np-237 which has been produced by neutron capture in U-235 and U-238. The long half-life of Np-237 (~2E+6 yrs) means that on the timescale of 90 years cooling only a small fraction of the Np-237 inventory decays to U-233 so the inventory of U-233 is quite small. If Th-232 is present as an impurity in the fuel materials then U-233 may also arise directly by neutron capture in this thorium isotope. Because the rate of production of U-233 from Th-232 activation is relatively high, even trace amount of Th-232 in the fuel materials can lead to a substantial increase in the arisings of U-233. In the case of the AP1000 spent fuel calculations the Zirlo and Inconel 718 cladding and fuel structural materials were assumed to contain 2.6ppm and 6.1ppm thorium respectively. However, the Sizewell B fuel inventory calculations did not consider the presence of thorium impurities. The combination of the higher fuel burn-up and the extra U-233 production from Th-232 impurities explain why the U-233 inventory for the AP1000 spent fuel is about four times larger than that for the Sizewell B spent fuel.

Given the pessimisms associated with the per canister inventories, it can be concluded that the characteristics of spent fuel from an AP1000 are consistent with those from Sizewell B PWR.

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