

| <b>DOCUMENT RELEASE AND CHANGE FORM</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |  |                                                                                                                |                     | <b>Release Stamp</b>                                                                                                                                                                                                                                                                                                                                                                          |  |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--|----------------------------------------------------------------------------------------------------------------|---------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--|
| Prepared For the U.S. Department of Energy, Assistant Secretary for Environmental Management<br>By Washington River Protection Solutions, LLC., PO Box 850, Richland, WA 99352<br>Contractor For U.S. Department of Energy, Office of River Protection, under Contract DE-AC27-08RV14800<br><br>TRADEMARK DISCLAIMER: Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof or its contractors or subcontractors. Printed in the United States of America. |  |                                                                                                                |                     | <div style="border: 2px solid red; padding: 10px; display: inline-block;"> <b style="color: red; font-size: 1.2em;">DATE:</b><br/> <b style="color: red; font-size: 1.2em;">May 08, 2017</b> </div> <div style="border: 1px solid red; padding: 10px; display: inline-block; margin-left: 20px; text-align: center;"> <b style="color: red; font-size: 0.8em;">HANFORD<br/>RELEASE</b> </div> |  |
| 1. <b>Doc No:</b> RPP-RPT-60027 <b>Rev.</b> 00                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |  |                                                                                                                |                     |                                                                                                                                                                                                                                                                                                                                                                                               |  |
| 2. <b>Title:</b><br>Benchmarking of DFLAW Solid Secondary Wastes and Processes with UK/Europe Counterparts                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |  |                                                                                                                |                     |                                                                                                                                                                                                                                                                                                                                                                                               |  |
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| <b>7. Approvals</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |  |                                                                                                                |                     |                                                                                                                                                                                                                                                                                                                                                                                               |  |
| <b>Title</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |  | <b>Name</b>                                                                                                    |                     | <b>Signature</b>                                                                                                                                                                                                                                                                                                                                                                              |  |
| Checker                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |  | SWANBERG, DAVID J                                                                                              |                     | SWANBERG, DAVID J                                                                                                                                                                                                                                                                                                                                                                             |  |
| Clearance Review                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |  | AARDAL, JANIS D                                                                                                |                     | AARDAL, JANIS D                                                                                                                                                                                                                                                                                                                                                                               |  |
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| Originator                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |  | BROWN, ELVIE E                                                                                                 |                     | BROWN, ELVIE E                                                                                                                                                                                                                                                                                                                                                                                |  |
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| Responsible Manager                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |  | SWANBERG, DAVID J                                                                                              |                     | SWANBERG, DAVID J                                                                                                                                                                                                                                                                                                                                                                             |  |
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| This report, produced by DBD, a WRPS subcontractor, presents the benchmarking of Hanford solid secondary wasteform (SSW) to the UK/Europe waste counterparts. This benchmarking will provide reference and guidance in the development and testing of Hanford SSW.                                                                                                                                                                                                                                                                                                                                                                                                              |  |                                                                                                                |                     |                                                                                                                                                                                                                                                                                                                                                                                               |  |
| 9. <b>TBDs or Holds</b> <span style="float: right;"><input checked="" type="checkbox"/> N/A</span>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |  |                                                                                                                |                     |                                                                                                                                                                                                                                                                                                                                                                                               |  |
| <b>10. Related Structures, Systems, and Components</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |  |                                                                                                                |                     |                                                                                                                                                                                                                                                                                                                                                                                               |  |
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| <b>11. Impacted Documents – Engineering</b> <span style="float: right;"><input checked="" type="checkbox"/> N/A</span>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |  |                                                                                                                |                     |                                                                                                                                                                                                                                                                                                                                                                                               |  |
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| <b>12. Impacted Documents (Outside SPF):</b><br>N/A                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |  |                                                                                                                |                     |                                                                                                                                                                                                                                                                                                                                                                                               |  |
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| <b>14. Distribution</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |  |                                                                                                                |                     |                                                                                                                                                                                                                                                                                                                                                                                               |  |
| <b>Name</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |  |                                                                                                                | <b>Organization</b> |                                                                                                                                                                                                                                                                                                                                                                                               |  |
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## INFORMATION CLEARANCE REVIEW AND RELEASE APPROVAL

### Part I: Background Information

|                                                                                                        |                                                                                                                                                                                                                                                                                                                                                                        |
|--------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Title: <b>Benchmarking of DFLAW Solid Secondary Wastes and Processes with UK / Europe Counterparts</b> | Information Category:<br><input type="checkbox"/> Abstract <input type="checkbox"/> Journal Article <input type="checkbox"/> Summary<br><input type="checkbox"/> Internet <input type="checkbox"/> Visual Aid <input type="checkbox"/> Software<br><input type="checkbox"/> Full Paper <input checked="" type="checkbox"/> Report <input type="checkbox"/> Other _____ |
| Publish to OSTI? <input checked="" type="checkbox"/> Yes <input type="checkbox"/> No                   |                                                                                                                                                                                                                                                                                                                                                                        |
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| Document Number: <b>RPP-RPT-60027 Revision 0</b>                                                       |                                                                                                                                                                                                                                                                                                                                                                        |
| Date: <b>April 2017</b>                                                                                |                                                                                                                                                                                                                                                                                                                                                                        |
| Author: <b>Brown, Elvie E</b>                                                                          |                                                                                                                                                                                                                                                                                                                                                                        |

### Part II: External/Public Presentation Information

|                                                                                                  |                                                                                                                                                                             |
|--------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Conference Name:                                                                                 |                                                                                                                                                                             |
| Sponsoring Organization(s): <b>WRPS</b>                                                          |                                                                                                                                                                             |
| Date of Conference:                                                                              | Conference Location:                                                                                                                                                        |
| Will Material be Handed Out? <input type="checkbox"/> Yes <input checked="" type="checkbox"/> No | Will Information be Published? <input type="checkbox"/> Yes <input checked="" type="checkbox"/> No <i>(If Yes, attach copy of Conference format instructions/guidance.)</i> |

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| Description                                                                    | Yes                      | N/A                                 | Print/Sign/Date |
|--------------------------------------------------------------------------------|--------------------------|-------------------------------------|-----------------|
| Information Product meets requirements in TFC-BSM-AD-C-01?                     | <input type="checkbox"/> | <input checked="" type="checkbox"/> |                 |
| Document Release Criteria in TFC-ENG-DESIGN-C-25 completed? (Attach checklist) | <input type="checkbox"/> | <input checked="" type="checkbox"/> |                 |
| If product contains pictures, safety review completed?                         | <input type="checkbox"/> | <input checked="" type="checkbox"/> |                 |

### Part IV: WRPS Internal Review

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|-----------------------|--------------|-------------------|----------------------------------------------|
| Subject Matter Expert | <b>WRPS</b>  | <b>05/04/2017</b> | <b>Brown, Elvie E</b> IDMS Data File att.    |
| Responsible Manager   | <b>WRPS</b>  | <b>03/30/2017</b> | <b>Swanberg, David J</b> IDMS Data File att. |
| Other:                |              |                   |                                              |

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| WRPS External Affairs                   | <input checked="" type="checkbox"/> | <input type="checkbox"/> | IDMS Data File att.  | Holloway, Jerry N   |
| WRPS Office of Chief Counsel            | <input checked="" type="checkbox"/> | <input type="checkbox"/> | IDMS Data File att.  | Cherry, Stephen B   |
| DOE – ORP Public Affairs/Communications | <input checked="" type="checkbox"/> | <input type="checkbox"/> | IDMS Data File att.  | Marshall, Richard A |
| Other: ORP SME                          | <input checked="" type="checkbox"/> | <input type="checkbox"/> | IDMS Data File att.  | Pyles, Gary L       |
| Other: DOE OCC                          | <input checked="" type="checkbox"/> | <input type="checkbox"/> | IDMS Data File att.  | O'Hagan, Michael D  |

Comments Required for WRPS-Indicate Purpose of Document:

This report, produced by DBD, a WRPS subcontractor, presents the benchmarking of Hanford solid secondary wasteform (SSW) to the UK/Europe waste counterparts. This benchmarking will provide reference and guidance in the development and testing of Hanford SSW.

**APPROVED**

By Janis Aardal at 3:17 pm, May 04, 2017

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RPP-RPT-60027, Rev. 0

# Benchmarking of DFLAW Solid Secondary Wastes and Processes with UK / Europe Counterparts

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**Key Words:** Hanford solid secondary wastes, US-UK/Europe LLW counterparts, grout wasteform, low level waste

**Abstract:** This report provides information and background on UK solid wastes and waste processes that are similar to those which will be generated by the Direct-Feed Low Activity Waste (DFLAW) facilities at Hanford. The aim is to further improve the design case for stabilizing and immobilizing of solid secondary wastes, establish international benchmarking and review possibilities for innovation.

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**APPROVED***By Janis Aardal at 9:20 am, May 08, 2017*

Release Approval

Date

**DATE:**  
**May 08, 2017****HANFORD  
RELEASE**

Release Stamp

**Approved For Public Release**

# Benchmarking of DFLAW Solid Secondary Wastes and Processes with UK / Europe Counterparts

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Document No: DBD/4909/PRJ/RP/001

Revision No: B



## Executive Summary

This report has been written for Washington River Protection Solutions LLC (WRPS) to support the Direct Feed project for Low-Activity Waste treatment (DFLAW). The aim of the DFLAW project is to accelerate processing of LAW from the waste tanks at Hanford, Washington State. For this project, facilities are currently being designed and constructed, including a Waste Treatment and Immobilization Plant (WTP) to treat the wastes generated.

DBD Inc. have been contracted by WRPS to undertake a package of work to assist in a waste form development program to address the performance requirements and waste form characteristics for the solid secondary wastes (SSW) specifically. The SSW are expected to include used process equipment, contaminated tools and instruments, decontamination wastes, high-efficiency particulate air filters, carbon absorption beds, silver mordenite sorbent, and spent ion exchange resin.

This work will support waste treatment operations and eventual disposal of the wastes at Hanford's Integrated Disposal Facility (IDF). This report provides an initial evaluation to determine how comparable the Hanford SSW types are to equivalents generated within the UK, and provides an overview of the waste conditioning, storage and disposal methods used within the UK (and Europe where appropriate).

The intent of this exercise is to compare waste practices in the UK and Europe to those wastes arising at the Hanford site, with a view to:

- Provide additional information to assist the design and planning for the new plants and waste facilities for the treatment of solid secondary wastes at Hanford.
- Introduce relevant UK and Europe best practice and possible innovations which can be brought to the site, building on lessons learned from experience.

This report is the first technical deliverable (Task 1) under this contract.

- Aims:
  - Outline the US and UK activity thresholds for solid waste classifications (Sections 4.1 and 4.2 respectively) and provide a high level comparison (Section 4.3).
  - Initial review of the Hanford solid secondary wastes (Section 5.1) and how they fit within the US and UK waste classifications (Section 5.2).
  - Review of equivalent SSWs within the UK and Europe (where appropriate), and where they are generated (Section 6.1).
  - Outline the methods used within the UK and Europe (where appropriate) to condition equivalent SSWs (Section 6.2).
  - Outline the waste storage and disposal facilities within the UK and Europe (where appropriate) for equivalent SSWs (Section 6.4).

**Benchmarking of DFLAW Solid Secondary Wastes  
and Processes with UK / Europe Counterparts  
Document No: DBD/4909/PRJ/RP/001  
Revision No: B**



- Summary of results:
  - The basis behind the US and UK waste classification regulations are similar in that they consider activity concentrations and thresholds for key radionuclides.
  - The US and UK categories are not directly comparable, but in general terms it appears that for the majority of cases US Class A is the equivalent of UK Low-Level Waste (LLW), US Class C is the equivalent of UK Intermediate-Level Waste (ILW) and US Class B fits across both UK LLW and UK ILW categories.
  - A summary level review of average activity concentrations across each of the DFLAW waste streams indicates that the non-debris wastes are likely to be (US) Class A / (UK) LLW and debris wastes are likely to be a combination of (US) Class A, Class B, Class C / (UK) LLW, ILW. It should be noted however that this is based on average arising for each waste type, and there are some specific instances of SSW's appearing to fall within Class C / ILW due to the presence of specific isotopes.
  - Section 6 outlines the relevant facilities and methods used within the UK for LLW and ILW wastes and the conditioning, storage and disposal for each. There are many possible examples from which learning and best practice can be assessed. This section gives an overall view for the UK (and a comparison with France to show a different perspective from a European view). It is intended that more detailed work can be undertaken on areas of interest arising from this study.
  - A key point to note is that this is a summary level assessment. Further work would also need to be undertaken to underpin any formal decisions regarding waste processing and disposal.
  - Of particular interest may be the modelling and performance data for LLW disposal, which is covered in Section 6.4.1.5.

DBD have presented this information for review by WRPS, and have suggested possible areas of work for future detailed investigation (in Section 8), pending further discussion and agreement with WRPS.

**Benchmarking of DFLAW Solid Secondary Wastes  
and Processes with UK / Europe Counterparts**  
Document No: DBD/4909/PRJ/RP/001  
Revision No: B



## Approvals

|          | Name        | Signature                                                                         | Role                       | Date       |
|----------|-------------|-----------------------------------------------------------------------------------|----------------------------|------------|
| Authors  | J. Surman   |  | Technical Officer          | 22/07/2016 |
|          | R. Kay      |  | Technical Officer          |            |
|          | K. Williams |  | Process Engineer           |            |
| Checked  | D. Shete    |  | Senior Process Engineer    | 22/07/2016 |
| Approved | I. Jones    |  | Principal Process Engineer | 22/07/2016 |

## Revision History

| Rev | Date       | Summary of Changes                              | Authors                            | Checked                 | Approved |
|-----|------------|-------------------------------------------------|------------------------------------|-------------------------|----------|
| A   | 21/06/2016 | First Approved Issue                            | J. Surman<br>R. Kay<br>K. Williams | M. Johnson <sup>1</sup> | I. Jones |
| B   | 22/07/2016 | Incorporates Review<br>Comments (RCR) from WRPS | R. Kay                             | D. Shete                | I. Jones |
|     |            |                                                 |                                    |                         |          |

<sup>1</sup> It should be noted, that because this document is reporting the findings from a summary level assessment, Sections 4 and 5 have been subject to a Level 2 check whilst the remainder of the document has been checked to Level 1.





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## Abbreviations, Acronyms and Definitions

|       |                                                                                                                                                                    |
|-------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| AGR   | Advanced Gas-cooled Reactor                                                                                                                                        |
| AgZ   | Silver mordenite (type of other non-debris SSW, SSW waste stream at Hanford)                                                                                       |
| ALARA | As Low As Reasonably Achievable                                                                                                                                    |
| BAT   | Best Available Techniques (UK terminology for requirement under the environmental regulations with in the UK for operations)                                       |
| BEP   | Box Encapsulation Plant (a proposed large scale encapsulation plant of large items ILW in grout at Sellafield)                                                     |
| BFS   | Blast Furnace Slag (component of grout used for immobilization of waste)                                                                                           |
| Bq    | Becquerels (SI unit generally used with the UK for measurement of the level of activity in radioactive material)                                                   |
| CfA   | Conditions for Acceptance (UK terminology, restrictions on waste conditions accepted at facilities. Also known as (a.k.a.) Waste Acceptance Criteria)              |
| CFR   | Code of Federal Regulations (US regulations)                                                                                                                       |
| Ci    | Curies (unit used with the US for measurement of the level of activity in radioactive material)                                                                    |
| CORWM | Committee on Radioactive Waste Management (UK terminology)                                                                                                         |
| CSFMA | Centre de l'Aube Disposal Facility for LIL Waste (French disposal facility)                                                                                        |
| CSTFA | Centre de l'Aube Disposal Facility for VLL Waste (French disposal facility)                                                                                        |
| CTO   | Centraco Processing and Conditioning Plant (Centre de traitement et de conditionnement), operated by SOCODEI (EDF subsidiary) (French waste conditioning facility) |
| DCP   | Dounreay Cementation Plant (facility at Dounreay for cementing ILW)                                                                                                |
| DFLAW | Direct Feed Low Activity Waste (a project at Hanford site to bypass the PT facility within the WTP)                                                                |
| DIF   | Drum Inspection Facility (at Harwell, UK for ILW waste drums)                                                                                                      |
| DIL   | Discrete Item Limit (UK terminology for classification of discrete items)                                                                                          |
| DOE   | Department of Energy (US government body)                                                                                                                          |
| DSRL  | Dounreay Site Restoration Limited (Site license company responsible for the closure program at the UK's former center of fast reactor research and development)    |

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|          |                                                                                                                 |
|----------|-----------------------------------------------------------------------------------------------------------------|
| EARP     | Enhanced Actinide Removal Plant (liquid effluent treatment facility at Sellafield, UK)                          |
| Eh       | Electrical conductivity unit                                                                                    |
| EIS      | Environmental Impact Statement                                                                                  |
| EPR      | European Pressurized Reactor (type of operating nuclear power plant)                                            |
| EPR-2010 | Environmental Permitting Regulations (2010)                                                                     |
| ETF      | Effluent Treatment Facility (processing facility on Hanford site for treating liquid-effluent secondary wastes) |
| g        | weight unit = grams                                                                                             |
| G        | (units prefix) Giga = $\times 10^9$                                                                             |
| GAC      | Granular Activated Carbon (from carbon adsorber beds, a SSW stream at Hanford)                                  |
| GDF      | Geological Disposal Facility (deep disposal option for radioactive waste)                                       |
| GRM      | Generalized Repository Model (for UK LLWR, used for assessing biogeochemical evolution of the LLWR)             |
| GTCC     | Greater than Class C (within the US waste classification)                                                       |
| GWPS     | Generic Waste Package Specifications (requirements for waste disposal within GDF in the UK)                     |
| HEPA     | High-Efficiency Particle Arrestance air filter (US SSW stream)                                                  |
| HIC      | High Integrity Container (non-standard disposal package used for spent ion exchange resin in US)                |
| HL       | High-Level waste (French waste category)                                                                        |
| HLW      | High-Level Waste (UK and US waste class for those with highest levels of radioactivity)                         |
| HLWF     | High-Level Waste facility (processing facility within WTP on Hanford site)                                      |
| HTWOS    | Hanford Tank Waste Operations Simulator model                                                                   |
| IDF      | Integrated Disposal Facility (US landfill facility for final disposal of solid wastes from WTP)                 |
| IL-LL    | Intermediate-Level Long-Lived waste (French waste category)                                                     |
| ILAW     | Immobilized Low-Activity Waste (US terminology for the vitrified product from the LAW vitrification facility)   |
| ILW      | Intermediate-Level Waste (UK waste class)                                                                       |

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|        |                                                                                                                                 |
|--------|---------------------------------------------------------------------------------------------------------------------------------|
| ISO    | International Standards Organization freights / shipping containers (used for the disposal of LLW within the UK)                |
| IX     | Ion Exchange (one of the US waste streams is spent resin from ion exchange columns)                                             |
| JET    | Joint European Torus (fusion facility in the UK)                                                                                |
| k      | (units prefix) Kilo = $\times 10^3$                                                                                             |
| LAW    | Low-Activity Waste (US waste class)                                                                                             |
| LAWPS  | Low-Activity Waste Pretreatment System                                                                                          |
| LDR    | Land Disposal Restrictions                                                                                                      |
| LIL-SL | Low-Level and Intermediate-Level Short-Lived waste (French waste category)                                                      |
| LL-LL  | Low-Level Long-Lived waste (French waste category)                                                                              |
| LLW    | Low-Level Waste (UK waste class)                                                                                                |
| LLRW   | Low-Level Radioactive Waste (US waste category)                                                                                 |
| LLWR   | Low-Level Waste Repository (waste disposal in the UK)                                                                           |
| LoC    | Letter of Compliance (UK terminology, for the approval of a waste form for disposal)                                            |
| M      | (units prefix) Mega = $\times 10^6$                                                                                             |
| mAOD   | meters Above Ordnance Datum                                                                                                     |
| MEB    | Multi-Element Bottle (cylindrical containers used for transporting and storing LWR fuel at Sellafield site, UK)                 |
| MEP    | Magnox Encapsulation Plant (processing facility on Sellafield site for treating ILW from Magnox reprocessing at Sellafield, UK) |
| MOX    | Mixed Oxide Fuel (UK terminology)                                                                                               |
| MTR    | Materials Testing Reactor (present at Dounreay site, UK)                                                                        |
| n      | (units prefix) Nano = $\times 10^{-9}$                                                                                          |
| NDA    | Nuclear Decommissioning Authority (UK government body which owns all of the nuclear sites undergoing decommissioning in the UK) |
| NPP    | Nuclear Power Plant                                                                                                             |
| NRC    | Nuclear Regulatory Commission (US nuclear regulator)                                                                            |

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|         |                                                                                                                     |
|---------|---------------------------------------------------------------------------------------------------------------------|
| OPC     | Ordinary Portland Cement (component of grout used for immobilization of waste)                                      |
| PA      | Performance Assessment (US terminology)                                                                             |
| PCM     | Plutonium Contaminated Material (UK waste designation)                                                              |
| PEG     | Potentially Exposed Group (exposure modes from assessing LLWR biosphere model)                                      |
| PFA     | Pulverized Fuel Ash (a.k.a. fly ash, component of grout used for immobilization of waste)                           |
| PTF     | Pre-Treatment Facility (within WTP at Hanford WRPS site)                                                            |
| PPE     | Personal Protective Equipment (can form LLW after used)                                                             |
| PWR     | Pressurized Water Reactor (type of operating nuclear power plant)                                                   |
| Q       | Total activity symbol                                                                                               |
| R&D     | Research and Development                                                                                            |
| RSRL    | Research Sites Restoration Limited (UK nuclear facility, at Harwell, within NDA estate, undergoing decommissioning) |
| RWI     | Radioactive Waste Inventory (UK inventory of all existing radioactive wastes)                                       |
| RWM Ltd | Radioactive Waste Management Ltd (UK)                                                                               |
| SOW     | Statement of Work                                                                                                   |
| SSW     | Solid Secondary Waste (US Hanford site waste streams that are being assessed here)                                  |
| Stores  | Storage facilities for conditioned waste packages within the UK                                                     |
| SWEF    | Solid Waste Export Facility (receives specific containers at Sellafield site from waste treatment facilities)       |
| TBC     | To be confirmed                                                                                                     |
| te      | metric tonne = 1000 kilograms = $10^6$ grams                                                                        |
| ThORP   | Thermal Oxide Reprocessing Plant (processing facility at Sellafield reprocessing spent fuel)                        |
| UK      | United Kingdom                                                                                                      |
| UKAEA   | UK Atomic Energy Authority (set up the UK LLWR in 1957)                                                             |
| US      | United States                                                                                                       |



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|       |                                                                                                                                                  |
|-------|--------------------------------------------------------------------------------------------------------------------------------------------------|
| VLL   | Very-Low-Level waste (French waste category)                                                                                                     |
| VLLW  | Very-Low-Level Waste (UK waste class)                                                                                                            |
| WAC   | Waste Acceptance Criteria (US & UK terminology for the requirements for packaging, receipt, conditioning and disposal of radiological wastes)    |
| WAGR  | Windscale Advanced Gas-cooled Reactor (a partially decommissioned prototype reactor at Sellafield site in the UK).                               |
| WEP   | Waste Encapsulation Plant (processing facility on Sellafield site for treating ILW from oxide reprocessing)                                      |
| WIPP  | Waste Isolation Pilot Plant (US deep geological facility)                                                                                        |
| WIR   | Waste Incidental to Reprocessing (US waste category)                                                                                             |
| WPEP  | Waste Packaging and Encapsulation Plant (processing facility on Sellafield site for treating ILW from the EARP)                                  |
| WRACS | Waste Receipt Assay Characterization and Supercompaction facility (for processing LLW at Dounreay site, UK)                                      |
| WRPS  | Washington River Protection Solutions, LLC                                                                                                       |
| WTC   | Waste Treatment Complex (processing facility at Sellafield for treating PCM)                                                                     |
| WTP   | Waste Treatment and Immobilization Plant (processing facility on Hanford WRPS site for treating waste from HLW and LAW vitrification facilities) |





## 1. Introduction

DBD Inc. has been contracted by Washington River Protection Solutions, LLC (WRPS) to assist in a waste form development program to address performance requirements and waste form characteristics for solid secondary wastes expected to be generated during the Hanford tank waste treatment mission. A key driver for conducting this assessment is the responsibility of WRPS to perform a Performance Assessment (PA) for the proposed Integrated Disposal Facility (IDF).

As part of this contract, this document has been written to support the Direct Feed Low Activity Waste (DFLAW) project at the Hanford site in Washington State, USA.

The Hanford site has approximately 56 million gallons of radioactive and chemical wastes stored in 177 underground tanks (tank farms) located on Hanford's Central Plateau. A specific mission of the site is to immobilize this waste, and allow the ultimate closure of the tanks and decommissioning of the treatment facilities.

The tank waste is currently stored in aging single-shell (SST) and double-shell tanks (DST); containing liquors / sludges that require immobilization. Immobilization will occur in the Waste Treatment and Immobilization Plant (WTP). The WTP is a highly complex nuclear and chemical processing facility with many 'first-of-a-kind' technology applications. The complexity of both the waste itself, as well as the WTP facilities has resulted in difficult, technical issues for the portions of the facility (primarily the Pretreatment [PT] Facility and High-Level Waste [HLW] Facility) that will process the solid portions of the waste.

Because the current design of WTP anticipates that all waste (both higher and lower activities) will be processed through the PT Facility, immobilization of any waste cannot occur until the technical issues involving the PT Facility are resolved. Therefore, an alternative approach for immobilizing waste as soon as practicable, while simultaneously resolving the remaining technical challenges, was identified, i.e. 'Direct Feed' of low active wastes (DFLAW), bypassing the PT facility.

Operation of this DFLAW option will generate several types of solid secondary wastes. These wastes (and how they compare to UK / Europe waste arisings and processes) are the subject of this report.



## 2. Purpose

DBD is undertaking a package of project work to assist WRPS with the underpinning of the design and strategy for the DFLAW facilities on the Hanford site. The stated aim of the overall project is to provide information and background on UK solid wastes and waste processes that are similar to those which will be generated by the DFLAW facilities at Hanford. The aim is to further improve the design case for processing of these solids, establish international benchmarking and review possibilities for innovation.

This report is the first technical deliverable of this contract. This document has been produced to undertake the following activities:

- Review solid secondary waste designations, activity thresholds and other relevant information in the US and UK. This is to provide a baseline for any subsequent work (e.g. “Does the term ‘Low-Level Waste’ mean the same in the US that it does in the UK?”).
- Review the specific solid secondary wastes expected to arise from DFLAW operations on the Hanford site, and how these compare to UK equivalents.
- Review (at a summary level) the range of equivalent solid waste arisings, processing routes and disposal options used in the UK and to a lesser degree, Europe.
- Act as a basis for identifying possible areas of specific interest to WRPS from waste processing in the UK, and from there to recommend more detailed work to assess these areas.

A primary objective for WRPS is to collect information to underpin assumptions for the IDF performance assessment (PA) on how secondary solid waste from DFLAW facilities are to be treated / packaged for disposal and how those waste forms are expected to perform in the disposal facility in retaining contaminants and isolating them from the environment. The overall intent of this benchmarking exercise is to provide relevant, targeted, innovation / learning from the UK and Europe to Washington River Protection Solutions, LLC (WRPS).



### 3. Background and Approach

The DFLAW SSW wastes comprise of both 'debris waste' (> 60 mm diameter) and 'non-debris waste' (< 60 mm diameter).

- The debris SSW includes used process equipment, contaminated tools and instruments, decontamination wastes and spent HEPA filters (as well as other debris wastes).
- The non-debris SSW includes spent carbon absorption beds, spent silver mordenite sorbent beds and spent ion exchange resin (as well as other non-debris wastes).

Many of these wastes are similar to those produced in the UK (as detailed in Section 6.1). The conditioning and disposal routes for Low-Level Waste (LLW) within the UK are mature and have been in operation for many years (as described in more detail in Sections 6.2 and 6.4). At the moment, the UK is currently conditioning and holding Intermediate-Level Waste (ILW) and High-Level Waste (HLW) at the sites where it is generated and the UK is developing the strategy for long term disposal routes for these wastes (as described in more detail in Sections 6.2 and 6.4).

In general, radioactive waste is any material that is either radioactive itself or is contaminated by radioactivity, for which no further use is envisaged. The term 'radioactive waste' therefore covers a wide variety of material, ranging from wastes that can be put into a landfill, to items that need remote handling, heavy shielding and cooling to be managed safely.

The aim of this benchmarking report is to provide an understanding of the DFLAW SSW in a UK context and then to identify and focus on counterpart wastes in the UK (and Europe where appropriate), including how they are conditioned, managed and stored / disposed of.

- Section 4 describes and clarifies the differences in terminology between the US and the UK. The intent is to ensure that there is no ambiguity or confusion in the use of the same or different terms in the US / UK.
- Section 5 provides a brief summary of the situation with regards to plans for the management of current and future SSW from WTP DFLAW at the Hanford site, in the US. An assessment of Hanford site generated SSW, against US and UK radioactive waste classifications, has also been undertaken to ensure equivalent wastes could be identified in the UK.
- Section 6 outlines the situation with regards to radioactive waste generation and processing in the UK (and to a lesser extent in Europe) - what the sources, types and inventories of SSW equivalent wastes are, where they originate from and how they are (or will be) conditioned, stored and managed. Section 6 thus focuses on how the UK manages 'counterpart' SSW wastes that are of relevance to the Hanford DFLAW project.

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- Section 7 compares the radioactive waste situation at the Hanford site with the situation in the UK / Europe. The relevance and applicability of different UK / European SSW streams and management practices and procedures is mapped out.
- Section 8 suggests a number of areas where possible future work packages could be focused to assist WRPS in their requirements relating to DFLAW SSW's.

The overall aim of this benchmarking document is to provide WRPS with a background on the UK situation and help identify areas of similarities / differences between the UK and Hanford. It should be noted that this document only represents an overview comparison (based on publically available information and tacit knowledge), and further detailed work will likely be required to develop specific areas of interest for WRPS.



## 4. US / UK Radioactive Waste Terminology

To allow a comparison of approaches to waste processes and types in the US and UK, it is first necessary to fully understand any differences between the two. To facilitate this, a general comparison of UK and US activity limits and regulations have been carried out including:

- An overview of the US NRC (Nuclear Regulatory Commission) approach to waste categorizations (Section 4.1), (i.e. US / Hanford approach to waste classification);
- An introduction to UK waste categorization (LLW, ILW, HLW) in terms of radioactivity concentration, heat generation etc. (Section 4.2); and
- A comparison of the two approaches and categorizations (Section 4.3).

Similar designation and approaches have also been identified in both countries. Whilst the focus for the DFLAW project is Low-Level Radioactive Waste (LLRW), a summary of all waste categories is presented for completeness.

With regard to the likely designations for solid secondary wastes there is not a firm link between US and UK approaches, and the situation is different for individual isotope. However, on the basis of the summary level review carried out in this Section, the following can be seen:

- US Class A appear to fall within the bounds of UK LLW;
- US Class B appear to border UK LLW and ILW;
- US Class C waste appear to fall within the bounds of UK ILW;
- US GTCC wastes appear to correspond to UK ILW.

Further analysis and discussion on these points (including a specific assessment of solid secondary wastes and how they compare with US and UK classifications) is carried out in Section 5 of this document. The results from the analysis of data from Ref 19 on the Hanford SSWs are provided with general categorizations (against US and UK limits) have been provided for each waste stream type.





## 4.1. US Classification of Radioactive Waste

The US classifications of radioactive waste for commercial waste disposal sites are defined by the NRC (Ref 4). The use of US NRC waste categorizations, as a published, recognizable categorization system, provides a standardized platform for comparison between Hanford and UK / Europe waste streams.

The following sub-sections give a brief overview of some of the main NRC classifications:

- High-Level Waste;
- Uranium Mill Tailings;
- Waste Incident to Reprocessing;
- Transuranic wastes; and
- Low-Level Radioactive Waste.

### 4.1.1. High-Level Waste (HLW)

HLW is the highly radioactive material produced as a by-product of the nuclear reactor operations. High-level wastes can take one of two forms:

- Spent reactor fuel designated for disposal; or
- Radioactive waste generated following reprocessing operations.

Spent nuclear fuel is used fuel from a reactor that is no longer efficient in creating electricity, because its fission process has slowed. However, it is still thermally hot, highly radioactive, and potentially harmful. Until a permanent disposal repository for spent nuclear fuel is built, licensees must safely store this fuel at their reactors (Ref 6). Note also that used nuclear fuel, although presenting similar hazards as HLW, is regulated separately by US DOE, which has a waste determination process by which certain streams can be reclassified as 'Waste Incidental to Reprocessing (WIR) and subsequently managed as LLW.

Aside from the spent nuclear fuel rods arising from the various reactors across the US, the majority of the USA's high-level waste inventory is generated at sites such as Hanford and Savannah River (Ref 6).

Parallels can be derived with waste generated from sites such as Sellafield and Dounreay in the UK, where the (heat generating) highly active liquids and solids derived from reprocessing are classed as HLW (see Section 4.2.5).

HLW is not suitable for near-surface disposal, and is instead ultimately destined for a geological disposal facility (GDF), such as the proposed Yucca Mountain facility (although it is recognized this facility is currently on hold).

HLW is not a focus of this report and will not be discussed further (except for discussing the thresholds and differences between HLW and Low-Level Radioactive Waste, see Section 4.1).



#### 4.1.2. Uranium Mill Tailings

Uranium milling produces very large amounts of waste material known as 'tailings' that contain radioactive uranium decay products and heavy metals (Ref 7). Although there are some uranium ore deposits in the UK, they are small and uneconomic to mine. Consequently the UK does not mine its own uranium ore, therefore there is no direct comparison with this particular US waste type, and will not be discussed further in this report.

#### 4.1.3. Transuranic Waste

Material contaminated with transuranic elements (such as neptunium, plutonium, or americium). Transuranic waste is primarily produced from recycling spent fuel or using plutonium to fabricate nuclear weapons. Within the US, such materials are routed to a deep geological facility such as the Waste Isolation Pilot Plant (WIPP) as defined in Part 61 of Title 10 of the Code of Federal Regulations (CFR) (Ref 291).

Transuranic waste is not a focus of this report and will not be discussed further, apart from to briefly note equivalent streams in the UK.

#### 4.1.4. Low-Level Radioactive Waste (LLRW)

LLRW encompasses a wide ranging class of waste, split into several sub divisions.

As per 61.55 Title 10 of the CFR, US LLRW wastes are designated as Class A, Class B, Class C or Greater Than Class C (GTCC) (Ref 5).

Classes A - C are suitable for near-surface disposal, Class C waste must meet more rigorous requirements on waste form to ensure stability, and require additional measures at the disposal facility to protect against inadvertent intrusion. GTCC wastes are not generally acceptable for near-surface disposal and (in the absence of other arrangements being made) are likely to be routed to a GDF (Ref 5). Determination of the sub-classification of radioactive waste involves two considerations:

1. The concentration of long-lived nuclides (and shorter-lived precursors) whose hazard will persist long after such precautions as institutional controls and deeper disposal have ceased to be effective; and
2. The concentration of shorter-lived radionuclides for which requirements on institutional controls, waste form, and disposal methods are effective.

If radioactive waste contains only radionuclides listed in Table 1, the classification shall be determined as follows:-

- Class A: The concentration does not exceed 0.1 times the value in Table 1
- Class C: The concentration exceeds 0.1 times the value in Table 1 but does not exceed the Class C limits presented in Table 2.
- GTCC: The concentration exceeds the value in Table 1 (and the waste is not generally acceptable for near-surface disposal).



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- For wastes containing mixtures of radionuclides, the assessment will use the 'sum of fractions' rule<sup>2</sup>:

*Table 1. US-NRC Long-lived Nuclides Concentration Limits.*

| Long-lived Radionuclides                                                | Concentration          |
|-------------------------------------------------------------------------|------------------------|
| C-14                                                                    | 8 Ci/m <sup>3</sup>    |
| C-14 in activated metal                                                 | 80 Ci/m <sup>3</sup>   |
| Ni-59 in activated metal                                                | 220 Ci/m <sup>3</sup>  |
| Nb-94 in activated metal                                                | 0.2 Ci/m <sup>3</sup>  |
| Tc-99                                                                   | 3 Ci/m <sup>3</sup>    |
| I-129                                                                   | 0.08 Ci/m <sup>3</sup> |
| Alpha emitting transuranic nuclides with half-life greater than 5 years | 100 nCi/g              |
| Pu-241                                                                  | 3,500 nCi/g            |
| Cm-242                                                                  | 20,000 nCi/g           |

If radioactive waste does not contain any of the long-lived radionuclides listed in Table 1, classification is determined based on the short-lived isotope concentrations shown in Table 2. If radioactive waste does not contain any nuclides listed in either Table 1 or Table 2, it is Class A. (Ref 5).

- Class A: The concentration does not exceed the value in Column 1 in Table 2.
- Class B: The concentration exceeds the value in Column 1 in Table 2, but does not exceed the value in Column 2 in Table 2.
- Class C: The concentration exceeds the value in Column 2 in Table 2, but does not exceed the value in Column 3 in Table 2.
- GTCC: The concentration exceeds the value in Column 3 in Table 2 and the waste is not generally acceptable for near-surface disposal.
- For wastes containing mixtures of radionuclides, the assessment will use the 'sum of fractions' rule.

<sup>2</sup> The 'sum of fractions' rule is used to determine class of waste that contains a mixture of different radionuclides, i.e. determine the sum of fractions by dividing each nuclide's concentration by the appropriate limit and adding the resulting values. The sum of the fractions for the column must be less than 1.0 if the waste class is to be determined by that column (Ref 5).

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*Table 2. US-NRC Short-lived Nuclides Concentration Limits.*

| Short-lived Radionuclides                             | Class A Limits Concentration (Ci/m <sup>3</sup> ) | Class B Limits Concentration (Ci/m <sup>3</sup> ) | Class C Limits Concentration (Ci/m <sup>3</sup> ) |
|-------------------------------------------------------|---------------------------------------------------|---------------------------------------------------|---------------------------------------------------|
| Total of all nuclides with less than 5 year half-life | 700                                               |                                                   |                                                   |
| H-3                                                   | 40                                                |                                                   |                                                   |
| Co-60                                                 | 700                                               |                                                   |                                                   |
| Ni-63                                                 | 3.5                                               | 70                                                | 700                                               |
| Ni-63 in activated metal                              | 35                                                | 700                                               | 7000                                              |
| Sr-90                                                 | 0.04                                              | 150                                               | 7000                                              |
| Cs-137                                                | 1                                                 | 44                                                | 4600                                              |

Class A waste contains the lowest concentrations of short lived and long lived radionuclides. The major components of Class A wastes include: personal protective clothing, instruments, tools, and medical wastes (Ref 8).

Class B waste contains short-lived radionuclides exclusively, that do not exceed Class B concentration limits or a mixture of short lived and long lived radionuclides, in which the long lived concentration is less than 10 % of the Class C limit, examples include reactor components, sealed radioactive sources, filters and resins from nuclear power plants (Ref 8).

Class C waste contains long-lived or short-lived radionuclides or a combination of both, that do not exceed the NRC concentration limits for shallow near-surface disposal, examples include ion exchange resins and filter materials used to treat reactor cooling water, and activated metals (Ref 8).

Class A wastes generally do not require stabilization prior to disposal while Class B and C waste generally do. Class A, B and C wastes are candidates for near-surface disposal. Class A and B wastes are buried no greater than 30 meters depth, while Class C wastes will be required to be buried deeper, to prevent an intruder from disturbing the waste after institutional controls have lapsed (Ref 8).

Greater than Class C GTCC is waste generally not acceptable for near-surface disposal. The combination of high concentration long-lived and short-lived radionuclides do not comply with acceptance criteria for near-surface disposals. GTCC wastes include irradiated metal components from reactors such as core shrouds, support plates, and core barrels, as well as filters and resins from reactor operations and decommissioning activities (Ref 5 and Ref 8).

It is the understanding of DBD that there is currently no formal disposal path way for GTCC waste, however a number of disposal options were considered by the DOE as part of the final GTCC Environmental Impact Statement (EIS). These options included borehole

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disposal, enhanced near-surface trench disposal, and above-ground vault disposal facilities. However from the EIS statement the preferred option for GTCC waste, is disposal at the Waste Isolation Pilot Plant (WIPP) deep geologic repository in New Mexico (Ref 288).

A summary of US Low-Level waste forms is given in (Ref 8), and is shown in Table 3.

*Table 3. Forms of US LLW.*

| LLW<br>Classification | Class A                                                                      | Class B                                                                                       | Class C                                 | GTCC                                                                 |
|-----------------------|------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------|-----------------------------------------|----------------------------------------------------------------------|
| Form                  | Soil, rubble, depleted uranium, minimal contaminated equipment and clothing. | Reactor components, sealed radioactive sources, filters and resins from nuclear power plants. | Same as Class B but higher in activity. | Reactor components, filters and resins from reactor decommissioning. |

#### 4.1.5. Contact and Remote Handled Wastes

Further sub-divisions of US LLW are Contact and Remote handled wastes. Contact handled (CH) wastes are defined as materials or packages with a surface exposure rate of less than 200 mrem/h (<2 mSv/hr) that may be handled without shielding for radiation workers. Remote handled (RH) wastes are materials or packages that exceed the surface exposure rate of 200 mrem/h (>2 mSv/hr) and therefore must be handled remotely to ensure protection of radiation workers (Ref 290). An equivalent set of surface threshold limits exist at LLW facilities in the UK for LLW waste packages, see Section 4.2.3.



## 4.2. UK Classification of Radioactive Waste

In the UK, general alpha and beta / gamma radioactive wastes are classified according to the type and quantity of radioactivity they contain and how much heat that this radioactivity produces. There are three categories of UK waste classification:

- Low-Level Waste (LLW);
- Intermediate-Level Waste (ILW); and
- High-Level Waste (HLW).

It should also be noted that there are some more specific waste categories that do not fit fully within these general designations, such as Plutonium Contaminated Material (PCM). These are not the focus of this report, but are discussed later in Section 4.2.7.

### 4.2.1. Low-Level Radioactive Waste (LLW)

LLW can come from a variety of operational activities, for instance lightly contaminated miscellaneous waste, including plastics, paper and metal. Examples of LLW arising from decommissioning activities would be soils, construction materials, metals, and equipment. Where practicable, LLW material is re-used or recycled. Also, additional techniques, such as compaction and incineration (for solid wastes) and evaporation and filtration (for liquid wastes), are used to reduce the volume of waste in final disposal.

The UK environment agencies (Environment Agency<sup>3</sup>, Scottish Environment Protection Agency, and the Northern Ireland Environment Agency) have set requirements for authorization of near-surface disposal facilities on land of solid radioactive wastes (Ref 286). Within this statutory guidance, the upper bound for the LLW category is defined as radioactive waste having a radioactive content not exceeding (Ref 288):

- 4 GBq/te (gigabecquerels per tonne) ( $1.08 \times 10^{-4}$  Ci/kg) for all alpha emissions;
- 12 GBq/te ( $3.24 \times 10^{-4}$  Ci/kg) for beta/gamma emissions.

All near-surface disposal facilities within the UK must meet these limits. Approved near-surface disposal facilities currently within the UK include the national Low-Level Waste Repository facility (LLWR) near Drigg in Cumbria, and the Dounreay Low-Level Waste facility in Caithness, Scotland (further details on the conditioning processes and disposal methods for these sites is detailed in Sections 6.2 and 6.4). Each facility, however, has other restrictions influenced by site specific factors (such as coastal erosion predictions and current inventories). Hence there are specific Conditions for Acceptance (CfA, a.k.a. Waste Acceptance Criteria [WAC]) for each site, which represent the full requirements for packaging, receipt, grouting and disposal of LLW for each near-surface disposal facility.

It should be noted that it is a legal requirement of operations in the UK that waste consigners are required to show Best Available Techniques (BAT) in their operations, which

<sup>3</sup> The Environment Agency's area of responsibility covered both England and Wales when the statutory guidance (Ref 286) was issued in 2009. After April 2013, it was split so that the Environment Agency covers only England and Natural Resources Wales covers Wales.

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includes the principle of Eliminate > Re-use > Reduce > Recycle. The UK has more finite resources (e.g. available land area) than the US and a different regulatory system, and demonstration of BAT and 'As Low as Reasonably Practicable' risks (ALARP) are key requirements in the UK. Practically, this means that as part of the authorization / permits to operate a nuclear facility, the operator would have to demonstrate to the regulator that all reasonable / practicable steps have been taken to minimize the final volume of wastes being routed for disposal.

The LLWR facility controls and dis-incentivizes the consignment of wastes containing certain radionuclides via activity surcharges, in order to preserve the radiological capacity of the site. Typically this is for radionuclides which have a low "activity limit" within the Environmental Safety Case (see Refs 262 - 269) and / or are particularly long-lived. This is charged on a £/MBq basis. This can restrict the use of the facility for certain types of waste (e.g. carbon-14 contaminated materials) and encourages site operators to minimize the radioactivity of wastes as much as possible before disposal.

The WAC for the LLWR facility specifies that only solid, radioactively contaminated or activated, waste will be accepted for disposal. An example of the typical WAC considering physical and chemical properties of wastes for LLWR facility, is shown in Table 4.



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*Table 4. Physical And Chemical Waste Acceptance Criteria For National Low-Level Waste Repository Facility (LLWR), Near Drigg In Cumbria (Ref 9).*

| Examples of Chemical Waste Acceptance Criteria at LLWR | Description                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |
|--------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Explosive materials</b>                             | LLW shall not contain any explosive materials.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |
| <b>Liquids</b>                                         | <p>Waste shall not contain any Free Liquid or liquids with flashpoint less than 21 °C absorbed on solid materials. In addition the following conditions must be met:</p> <ul style="list-style-type: none"> <li>Any liquid shall, prior to consignment, must be fixed in a suitable solid matrix that will not result in release of liquid under applied loads of up to 400 kN/m<sup>2</sup>; and</li> <li>The non-aqueous content of any liquid in the waste shall be conditioned, prior to consignment, such that no visible oil or grease will be released by leaching as demonstrated using a leach test agreed with LLW Repository Ltd.</li> </ul> |
| <b>Strong oxidizing agents</b>                         | Waste shall not contain strong oxidizing agents.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
| <b>Chemical complexing or chelating agents</b>         | Waste shall not contain chemical complexing agents or chelating agents.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |
| <b>Ion exchange media</b>                              | Waste shall not contain Ion Exchange Material unless conditioned using a method approved in advance by LLWR                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |
| <b>Soluble Solids</b>                                  | <p>Soluble Solids that present as bulk chemical compounds greater than 1 kg mass in a waste consignment may be accepted for disposal but only on approval of a waste consignment variation form with suitable supporting justification by LLW Repository Ltd.</p> <p>Such materials shall be fixed, prior to consignment, in a suitable solid matrix that will not readily release that component as demonstrated using a leach test agreed with LLW Repository Ltd.</p>                                                                                                                                                                                |
| <b>Other Wastes</b>                                    | Waste contaminated with uranium.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |

As a general rule, waste in the UK is classed as LLW if the overall specific activity of the waste consignment does not exceed the total specific alpha and beta limits (as denoted at the start of this section). However certain waste consignments may include volumes of wastes or *individual* discrete items that may exceed these limits. Therefore the activity of these discrete items, are limited based on the activity of specific radionuclides. This approach is similar in concept to the US-NRC LLW classification.



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Activities and Specific Activities of individual Discrete Items must comply with the following sum of fractions:

$$Q_A/DIL_A + Q_{B1}/DIL_{B1} + Q_{B2}/DIL_{B2} + Q_C/DIL_C \leq 1$$

where  $Q_N$  is the total Activity or Specific Activity of group N radionuclides and  $DIL_N$  is the discrete item limit for that group, depending on the mass of the Discrete Item, as shown in Table 5.

*Table 5. UK Radionuclide Groups For Discrete Item Limits at LLWR (Ref 9).*

| Groups   | Radionuclides                                                                                                                       | Mass 1 kg or less                       | Mass between 1 and 100 kg                        | Mass 100 kg or greater                |
|----------|-------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------|--------------------------------------------------|---------------------------------------|
| Group A  | Nb-94, Ag-108m, Sn-126, Ra-226, Th-229, Th-230, Th-232, Pa-231, Np-237, Am-243, Cm-247, Cm-248, Cf-251                              | 0.001 GBq<br>( $2.7 \times 10^{-5}$ Ci) | 1 GBq per te<br>( $2.7 \times 10^{-5}$ Ci/kg)    | 0.1 GBq<br>( $2.7 \times 10^{-3}$ Ci) |
| Group B1 | I-129, Pu-238, Pu-239, Pu-240, Pu-242, Am-241, Am-242m, U-235, U-238, U-natural, U-enriched, Cm-245, Cm-246                         | 0.01 GBq<br>( $2.7 \times 10^{-4}$ Ci)  | 10 GBq per te<br>( $2.7 \times 10^{-4}$ Ci/kg)   | 1 GBq<br>( $2.7 \times 10^{-2}$ Ci)   |
| Group B2 | C-14, Cl-36, Ca-41, Sr-90, Zr-93, Mo-93, Tc-99, Cs-135, Cs-137, Pb-210, Ac-227, U-233, U-234, U-236, Pu-241, Cm-243, Cm-244, Cf-250 | 0.1 GBq<br>( $2.7 \times 10^{-3}$ Ci)   | 100 GBq per te<br>( $2.7 \times 10^{-3}$ Ci/kg)  | 10 GBq<br>(0.27 Ci)                   |
| Group C  | H-3, Co-60, Ni-59, Ni-63, Nb-93m, Sm-151, Eu-152                                                                                    | 1 GBq<br>( $2.7 \times 10^{-2}$ Ci)     | 1000 GBq per te<br>( $2.7 \times 10^{-2}$ Ci/kg) | 100 GBq<br>(2.70 Ci)                  |

Some examples of discrete items which could fall in into the LLW designation include:

- Hand tools, engineered items and equipment of durable materials;
- Grouted drums of waste; and
- Large metal items, e.g. steel beams and plates, pipework, shielding, heavy equipment and flasks (but not general scrap metal).

LLW can only be disposed of at facilities which have a radioactive waste permit under Environmental Permitting Regulations 2010 (EPR-2010)<sup>4</sup>.

<sup>4</sup> The EPR were originally introduced in 2007, as a means of achieving a streamlined permitting and compliance regime within in England and Wales. The EPR combined aspects of the Pollution Prevention and Control (England and Wales) Regulations 2000, the system of waste management licensing in Part II of the Environmental Protection Act 1990 and the Waste Management Licensing Regulations 1994. The regulations were extended in 2010 to cover waste discharge consents, groundwater permits and radioactive substances regulations.



#### 4.2.2. Very Low-Level Wastes

A further subcategory at the lower end of the LLW spectrum is Very Low-Level waste (VLLW) (Ref 10) and this is divided into the following:

- Low-Volume VLLW ('dustbin' loads) - small volumes of waste that can be safely disposed of with municipal, commercial or industrial waste at any landfill site. This has specific activity limits expressed in terms of volume based concentration of:
  - For solid radioactive waste:
    - < 400 kBq ( $1.08 \times 10^{-5}$  Ci) of total activity for every 0.1 m<sup>3</sup> of material; and
    - < 40 kBq ( $1.08 \times 10^{-6}$  Ci) of total activity for single items; and
    - < 200 MBq ( $5.4 \times 10^{-3}$  Ci) to be disposed per calendar year.
  - For solid radioactive wastes containing carbon-14 or hydrogen-3 (tritium):
    - < 4000 kBq ( $1.08 \times 10^{-4}$  Ci) for carbon-14 and tritium activity taken together, for every 0.1m<sup>3</sup> of material; and
    - < 400 kBq ( $1.08 \times 10^{-5}$  Ci) for carbon-14 and tritium activity taken together, for single items; and
    - < 2 GBq ( $5.4 \times 10^{-2}$  Ci) to be disposed per calendar year.
- High-Volume VLLW (bulk disposals) - higher volumes of waste that can be safely disposed of with municipal, commercial or industrial waste, but only at specified landfill sites. This has specific activity limits of:
  - Maximum of 4 MBq ( $1.08 \times 10^{-4}$  Ci) of total activity per tonne of material; and
  - For wastes containing tritium, the concentration limit for tritium is 40 MBq/te ( $1.08 \times 10^{-6}$  Ci/kg).

In general most high-volume VLLW is produced at nuclear sites, while low-volume VLLW is generated principally by small users such as academic and medical institutions (Ref 11). Figure 1 shows the volumes of raw VLLW arisings in the UK (as of 2011). The majority of VLLW is structural materials (principally concrete, cement, sand, asbestos and soil) from decommissioning of nuclear facilities such as Sellafield (Ref 12).

Currently in the UK a greater focus on putting effort into exemption of wastes and "down categorizing" LLW into the VLLW category, has been achieved by increased monitoring and characterisation methods. Where waste cannot be "down categorised" it is diverted to non-disposal routes where ever practicable.

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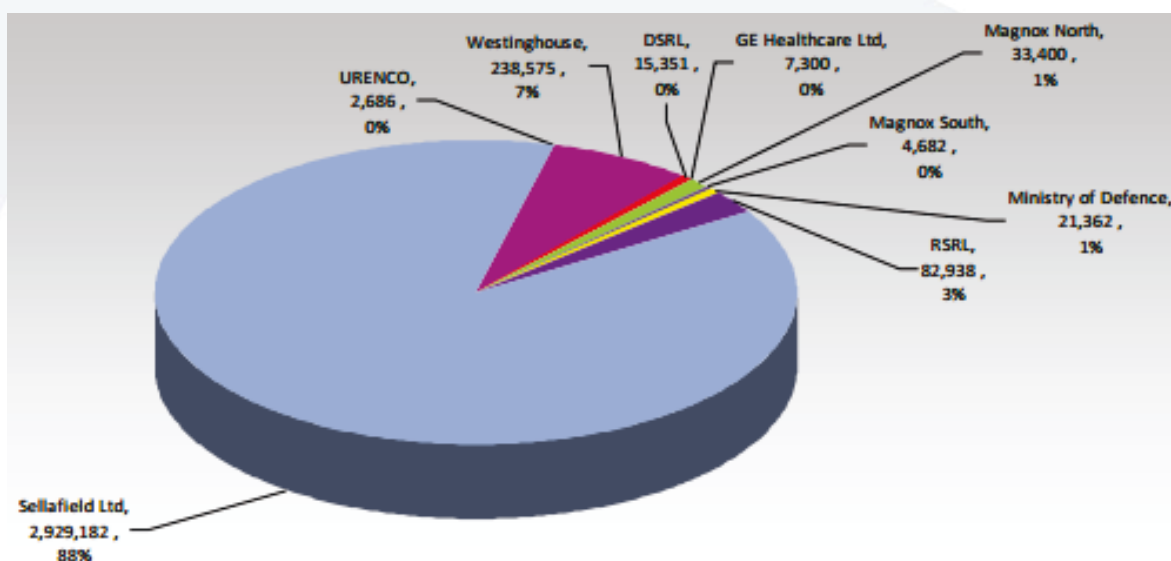


Figure 1. Arisings of UK VLLW, As Of 2011, By Producer In Cubic Meters (Total = 3,335,476 m³) (Ref 12).

#### 4.2.3. External Surface Radiation Limits

In the UK, facilities such as, LLWR impose external surface radiation limits for LLW containers. In the case of LLWR these limits shall not exceed 2 mSv/hr (Ref 9) and 100 µSv/h at a distance of 2 metres. This is equivalent to US contact handled waste subdivisions. For VLLW packages this threshold limit is significantly lower at <5 µSv/h (Ref 10).

#### 4.2.4. Intermediate-Level Radioactive Waste (ILW)

ILW generally has a radioactive content exceeding the upper UK limit for LLW (4 GBq/te of alpha or 12 GBq/te of beta / gamma activity). ILW exceeds the upper boundary limits for UK LLW but does not emit enough decay heat to significantly affect its own temperature or the temperature of its surroundings. Therefore levels of decay heat do not need be taken into account when designing ILW storage or disposal facilities in the UK. This threshold for the thermal power output of ILW is < 2 kW/m³ (Ref 289).

ILW arises mainly from (1) reactor site operations and (2) the reprocessing of spent fuel, and (3) from general operations and maintenance of radioactive facilities. Typical examples include:

- Fuel rod cladding materials;
- 'Fines' / insoluble fission products from spent fuel processing;
- Contaminated filters or other maintainable/replaceable items, that are too heavily contaminated (through fault condition or otherwise) to dispose of as LLW; and
- Reactor components (activated through neutron flux).

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Generally in the UK, conditioned ILW comprises various types of waste immobilized in cement in stainless steel containers, and wastes immobilized in polymer in mild steel containers.

UK- ILW is generally interim stored in above-ground storage facilities pending ultimate disposal in a deep geological disposal facility (GDF) (see Section 6.4.4).

#### 4.2.5. High-Level Radioactive Waste (HLW)

High-level radioactive waste is radioactive enough for the decay heat it produces to significantly affect the temperature of the waste itself and the surrounding environment. Typically characteristics of HLW are a radioactive content exceeding 4 GBq/te of alpha or 12 GBq/te of beta/gamma, and a decay heat exceeding 2 kW/m<sup>3</sup>.

In the UK, HLW waste includes:

1. Nitric acid based liquid residue from reprocessing facilities, a waste stream(s) containing the majority of fission products from reprocessed fuel (this is an interim waste form, pending conversion to 2 below);
2. Solid waste form produced from the vitrification of the aforementioned liquid residue; and
3. Un-reprocessed spent fuel rods currently stored in ponds, which are not planned to be reprocessed.

All of the above are ultimately destined for disposal in a GDF (see Section 6.4.4).

#### 4.2.6. UK General Waste Classification Summary

Table 6 below shows the bounding limits in terms of activity level and decay heat for the various classifications of radioactive waste in the UK.

*Table 6. Classification Bounding Limits In The UK For Radioactive Waste In Terms of Activity Level And Decay Heat (Ref 289).*

| Waste Classification     | Alpha activity (GBq/te) | Beta/gamma activity (GBq/te) | Decay heat (kW/m <sup>3</sup> ) |
|--------------------------|-------------------------|------------------------------|---------------------------------|
| Low-Level Waste          | ≤ 4                     | ≤ 12                         | n/a                             |
| Intermediate-Level Waste | > 4                     | > 12                         | < 2                             |
| High-Level Waste         | > 4                     | > 12                         | > 2                             |

In generalized terms, the UK follows the following set of disposal routes for its waste:

- HLW: at present, fuel is reprocessed and the resulting HLW is vitrified and stored ready for long term deep geological disposal. Long term, un-reprocessed fuel will be stored intact in the GDF.
- ILW: is immobilized by concrete (or other agents such as Vinyl Ester resins used at Trawsfynydd - see Section 6.3.3.2) within stainless steel packages. It is held in



temporary above-surface ground facilities, ready for long term deep geological disposal (when the GDF opens).

- LLW: is grouted in metal containers before being stacked in concrete lined, highly-engineered vaults, and disposed of at facilities such as the Low-Level Waste Repository (LLWR), in Cumbria or the Dounreay LLW Vaults in Scotland (which only accepts waste arising from the Dounreay site). However, it should be noted that not all LLW will be sent for disposal to near-surface waste repositories. There are various other routes of recycling / disposal for LLW waste, such as:
  - Diversion as VLLW (very Low-Level waste) to landfill (e.g. Clifton Marsh);
  - Metal Recycling (e.g. Lillyhall, Cumbria); and
  - Incineration or supercompaction (e.g. Fawley / Ellesmere Port or WAMAC / Winfrith).

#### 4.2.7. Other Notable UK Waste Designations

##### 4.2.7.1. Plutonium Contaminated Waste (PCM)

PCM is generated when equipment comes into contact with and is contaminated by plutonium. Treatment of some categories of PCM generated from reprocessing and decommissioning activities, at Sellafield, is treated at the site's Waste Treatment Complex (WTC). For a detailed description of the treatment processes used see Section 6.3.1.6. As an overview, PCM wastes are contained in 200 liter drums and subject to high force compaction to reduce their waste volume. The resulting waste pucks are placed in 500 liter drums and grouted. There are however significant volumes of PCM at Sellafield are unsuitable for treatment at WTC. These waste packages are temporarily stored at Sellafield and designated for deep geological disposal in the future (Ref 13).

Similar waste at other UK sites include:

- Contact Handled ILW (a combination of PCM and low activity ILW) from former UKAEA sites<sup>5</sup>; and
- From the LLWR site, where a series of bunkers stored plutonium residues. The decommissioning of these facilities has generated PCM waste.

##### 4.2.7.2. Plutonium / Plutonium Product Material

Currently in the UK, Plutonium / Plutonium product material is not classed as waste. In December 2011, the Government proposed a preliminary policy to pursue re-use of plutonium as Mixed Oxide fuel (MOX), converting the UK civil separated plutonium into fuel for use in civil nuclear reactors, however given the relatively uncertainties surrounding the UK new build program, the desire for developers to include MOx fuel as part of their development options remains unclear. Any remaining plutonium that is deemed unsuitable for re-use as MOx would be immobilized and treated as a waste for

<sup>5</sup> The former UKAEA consists of a group of sites which included Dounreay (now DSRL), Culham, Harwell and Winfrith (now collectively known as RSRL), and Windscale (now part of the Sellafield Site).





disposal. However at present the UK approach is the safe and secure storage of plutonium in above-ground storage facilities, such as the Sellafield Product and Residue Store (Ref 14).

#### 4.2.7.3. Uranic Materials

As with plutonium, uranic materials in the UK are not currently classed as wastes (Ref 15). Given the diverse nature of the uranic inventory, a number of credible options for management of uranic materials have been considered these include:-

- The continued safe and secure storage of uranic materials;
- Recycling and reuse of uranic materials; and
- Conditioning of uranic materials into appropriate form for long-term disposal in a deep geological disposal facility.

The NDA is factoring in the possible inclusion of uranics into the design and development of the geological disposal facility (GDF). The ultimate disposal route for these materials has yet to be developed. The ultimate disposal route for these materials has yet to be determined.

As an example uranic material residues can be found at the Westinghouse Springfields Fuels Ltd site, arising from fuel manufacturing (legacy and current). Where possible, the uranium from these residues is recovered in residue processing plants on site and reintroduced to the fuel cycle (Ref 15).

### 4.3. French Classification of Radioactive Waste

To offer a European comparison, the basis for assessment of waste classifications is similar for the French as it is for the US and UK.

The categories include (Ref 243):

- Very short half-life (<100 days) waste;
- Very-Low-Level (VLL) wastes;
- Low and Intermediate Level, Short half-Life (LIL-SL) wastes;
- Low-Level, Long half-Life (LL-LL) wastes;
- Intermediate-Level, Long half-Life (IL-LL) wastes; and
- High-Level (HL) wastes.

A summary of the types of wastes that fit in these categories, as well as the conditioning and final disposal of these waste types are summarized in Sections 6.1.3, 6.3.3.3 and 6.4.5 respectively.





#### 4.4. Initial Comparison between US and UK Classifications

It should be noted that US threshold designations are per unit volume, whereas UK ones are per unit mass of waste, making an immediate comparison difficult. However, if an average waste package density range is assumed, these can be compared to the US designations more easily. The mean density of an overall package is unknown, but if a range from 500 - 10,000 kg/m<sup>3</sup> is taken (note that waste streams such as compacted PPE would be near the lower end, grouted wastes would be around 2000 kg/m<sup>3</sup> and compacted metal wastes near the upper end of the range) then a high-level assessment can be made. An example of such an assessment can be found below:

*Table 7. Conversion of UK Consignment Limits from 'Per Tonne' To 'Per m<sup>3</sup>'.*

| Assumed Waste Density (kg/m <sup>3</sup> ) | Alpha Limit (GBq/te) | Alpha Limit (Ci/kg) | Alpha Limit (Ci/m <sup>3</sup> ) | Beta Gamma Limit (GBq/te) | Beta Gamma Limit (Ci/kg) | Beta/Gamma Limit (Ci/m <sup>3</sup> ) |
|--------------------------------------------|----------------------|---------------------|----------------------------------|---------------------------|--------------------------|---------------------------------------|
| 500                                        | 4                    | 1.08E-04            | 0.054                            | 12                        | 3.24E-04                 | 0.162                                 |
| 1000                                       | 4                    | 1.08E-04            | 0.108                            | 12                        | 3.24E-04                 | 0.324                                 |
| 2000                                       | 4                    | 1.08E-04            | 0.216                            | 12                        | 3.24E-04                 | 0.649                                 |
| 3000                                       | 4                    | 1.08E-04            | 0.324                            | 12                        | 3.24E-04                 | 0.973                                 |
| 4000                                       | 4                    | 1.08E-04            | 0.432                            | 12                        | 3.24E-04                 | 1.30                                  |
| 5000                                       | 4                    | 1.08E-04            | 0.541                            | 12                        | 3.24E-04                 | 1.62                                  |
| 6000                                       | 4                    | 1.08E-04            | 0.649                            | 12                        | 3.24E-04                 | 1.95                                  |
| 7000                                       | 4                    | 1.08E-04            | 0.757                            | 12                        | 3.24E-04                 | 2.27                                  |
| 8000                                       | 4                    | 1.08E-04            | 0.865                            | 12                        | 3.24E-04                 | 2.59                                  |
| 9000                                       | 4                    | 1.08E-04            | 0.973                            | 12                        | 3.24E-04                 | 2.92                                  |
| 10000                                      | 4                    | 1.08E-04            | 1.08                             | 12                        | 3.24E-04                 | 3.24                                  |

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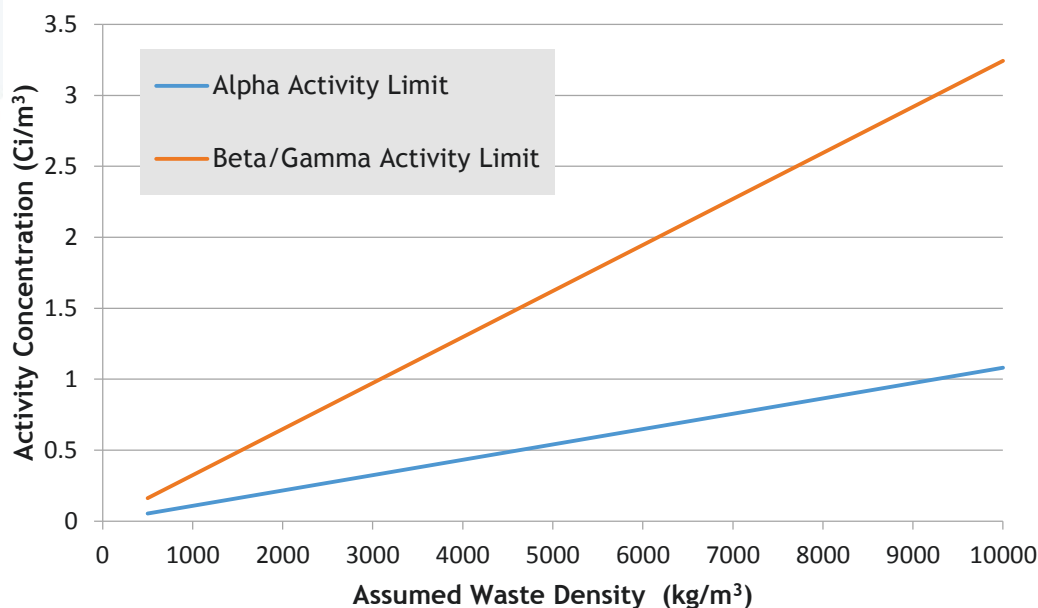


Figure 2. UK LLW - Activity Acceptance Limits (Converted From Activity Per Mass To Activity Per Volume).

To compare this data to US classifications, depending on the specific radionuclide assessed, the concentrations within each class are as follows (a summary of Table 1 & Table 2 from Ref 8): Class A - Near background to 700 Ci/m<sup>3</sup>, Class B - 0.04 to 700 Ci/m<sup>3</sup>, Class C - 44 to 7,000 Ci/m<sup>3</sup>. When these are considered against Figure 2, it can be seen that at first sight the US figures look to be well above these UK consignment limits for LLW. However, certain radionuclides are expected to be present in relatively low concentrations in the Hanford DFLAW processing scheme.

Therefore, a more appropriate comparison which can be carried out is on the individual isotopic limits. For ease of calculation, examples will be shown based upon single item limits rather than combinations of isotopes.

#### Short-lived isotope - Cs-137 (~30y half-life)

| US Category: | <u>Class A</u>            | <u>Class B</u>                     | <u>Class C</u>                        |
|--------------|---------------------------|------------------------------------|---------------------------------------|
| Cs-137       | up to 1 Ci/m <sup>3</sup> | between 1 and 44 Ci/m <sup>3</sup> | between 44 and 4600 Ci/m <sup>3</sup> |

UK designations state Cs-137 is a 'Group B2' material, having a 100GBq/te (0.0027 Ci/kg) designated for a mass of waste between 1kg and 100kg limit. If a range of waste densities is assessed, the following can be seen:

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*Table 8. UK Activity Limits for Cs-137 for a Range of Assumed Densities.*

| Assumed Mean Density (kg/m <sup>3</sup> ) | Converted UK activity limit (Ci/m <sup>3</sup> ) |
|-------------------------------------------|--------------------------------------------------|
| 500                                       | 1.35                                             |
| 1000                                      | 2.70                                             |
| 2000                                      | 5.41                                             |
| 3000                                      | 8.11                                             |
| 4000                                      | 10.81                                            |
| 6000                                      | 16.22                                            |
| 8000                                      | 21.62                                            |

It can be seen that the expected UK activity limit for Cs-137 (in the range of 1.35 to 21.6 Ci/m<sup>3</sup>, for a waste density range of 500 to 8000 kg/m<sup>3</sup>) in LLW is of the same order of magnitude as that for a range crossing Class B and Class C waste categories in the US.

Longer lived isotope - I-129 (~1.57x10<sup>7</sup> year half-life)

| US Category:                          | <u>Class A</u>                | <u>Class B</u> | <u>Class C</u>                           |
|---------------------------------------|-------------------------------|----------------|------------------------------------------|
| I-129                                 | up to 0.008 Ci/m <sup>3</sup> | -              | between 0.008 and 0.08 Ci/m <sup>3</sup> |
| (No intermediate Class B designation) |                               |                |                                          |

*Table 9. UK Activity Limits for I-129 for a Range of Assumed Densities.*

| Assumed Mean Density (kg/m <sup>3</sup> ) | Converted UK activity limit (Ci/m <sup>3</sup> ) |
|-------------------------------------------|--------------------------------------------------|
| 500                                       | 0.14                                             |
| 1000                                      | 0.27                                             |
| 2000                                      | 0.54                                             |
| 3000                                      | 0.81                                             |
| 4000                                      | 1.08                                             |
| 6000                                      | 1.62                                             |
| 8000                                      | 2.16                                             |

In the UK, I-129 is also a Class B1 material, having a 10 GBq/te (or 0.00027 Ci/kg) activity limit (for a mass of waste between 1 kg and 100 kg), which in US units (waste per unit volume) the expected UK activity limit would be in the range of 0.135 - 2.16 Ci/m<sup>3</sup> (for a waste density of 500 - 8000 kg/m<sup>3</sup>), for I-129. It can be seen that the UK limits for I-129 for LLW / near-surface disposal appear to be significantly higher (~ order of magnitude) than those limiting Class C wastes in the US.

Long-lived isotope - Nb-94 (~24000y half-life)

| US Category:                          | <u>Class A</u>               | <u>Class B</u> | <u>Class C</u>                         |
|---------------------------------------|------------------------------|----------------|----------------------------------------|
| Nb-94                                 | up to 0.02 Ci/m <sup>3</sup> | -              | between 0.02 and 0.2 Ci/m <sup>3</sup> |
| (No intermediate Class B designation) |                              |                |                                        |



In the UK, Nb-94 is a Class A material, giving a designated limit of 1 GBq/te for a mass of waste between 1kg and 100kg. Using the same approach as for Cs-137, the following Table 10 can be drawn.

*Table 10. UK Activity Limits for Nb-94 for a Range of Assumed Densities.*

| Assumed Mean Density (kg/m <sup>3</sup> ) | Converted UK activity limit (Ci/m <sup>3</sup> ) |
|-------------------------------------------|--------------------------------------------------|
| 500                                       | 0.014                                            |
| 1000                                      | 0.027                                            |
| 2000                                      | 0.054                                            |
| 3000                                      | 0.081                                            |
| 4000                                      | 0.108                                            |
| 6000                                      | 0.162                                            |
| 8000                                      | 0.216                                            |

It can be seen that the UK LLW / near-surface disposal limit for Nb-94 is broadly similar (similar order of magnitude) to the acceptance limit for Class C wastes in the US.

It should be noted however that this assessment is on the basis of an assessment of single isotopes only. When several isotopes are aggregated over a single waste consignment, then this may change the complexion of this assessment (based upon the 'sum of fractions' rule).

## 4.5. Summary of Comparison of US / UK Waste Terminologies

The previous sections have compared US and UK waste thresholds and designations. The following points can be noted:

- There are generally similar terms and approaches used ('High-Level waste' appears very similar in both US / UK for example);
- Similar outline approach in near-surface disposal for lower activity wastes vs geological disposal for higher activity/hazard wastes;
- For 'Low-Level Wastes', a similar approach in the US and UK is used for determining whether the various isotopes making up a waste consignment are suitable for near-surface disposal; and
- The UK has a general activity limit for LLW per overall consignment of 4 GBq/te ( $1.08 \times 10^{-4}$  Ci/kg) (alpha) and 12 GBq/te ( $3.24 \times 10^{-4}$  Ci/kg) (beta / gamma) - no equivalent consignment limit has been noted for US designations.

Based upon the comparisons made in Section 4.4, the following conclusions can be drawn:

- For individual isotopes in a waste package, the boundary between UK LLW/ILW and US Class A / B / C appears to be in the range around US Class B / C (as depicted in Figure 4).
- C-14 appears to offer an anomaly in that the UK threshold for LLW / near surface disposal is above that seen in US classifications. No explanation has been found for this, but it could be a point for future investigation.

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- A summary level qualitative assessment of the UK LLW / ILW and US Low-Level waste, based on waste composition, is illustrated in Figure 3, showing where the similarities overlap between the types of items typically found in each category.

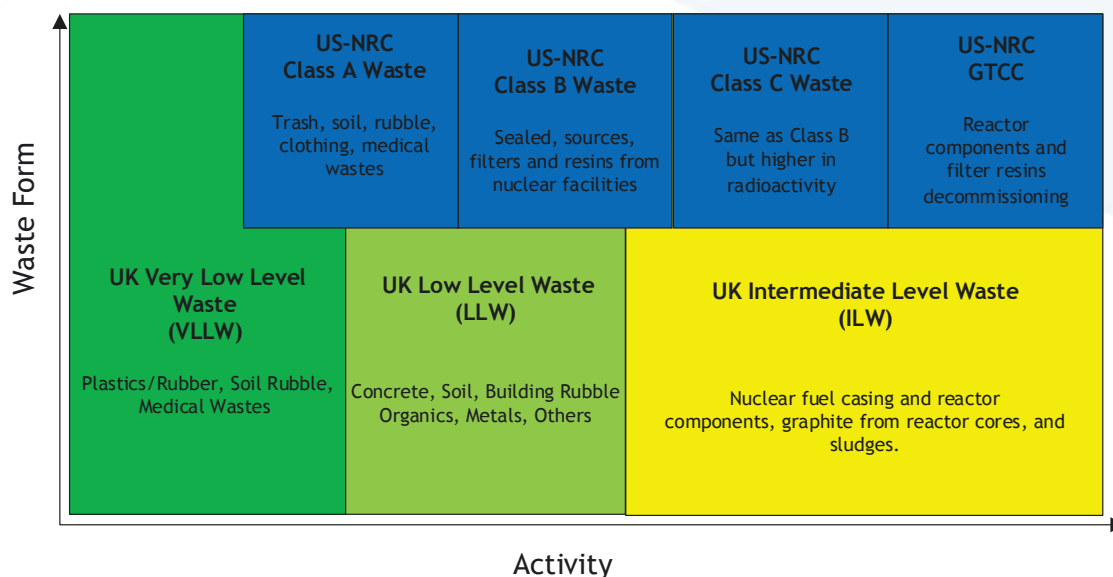


Figure 3. Qualitative Assessment Between UK and US Waste Types Based on Composition.

In summary, the following can be determined, which is also depicted in Figure 4:

- US Class A wastes are expected to be broadly equivalent to UK LLW.
- US Class C wastes are expected to be broadly equivalent to UK ILW.
- US Class B wastes can fall in both UK LLW and UK ILW categories.

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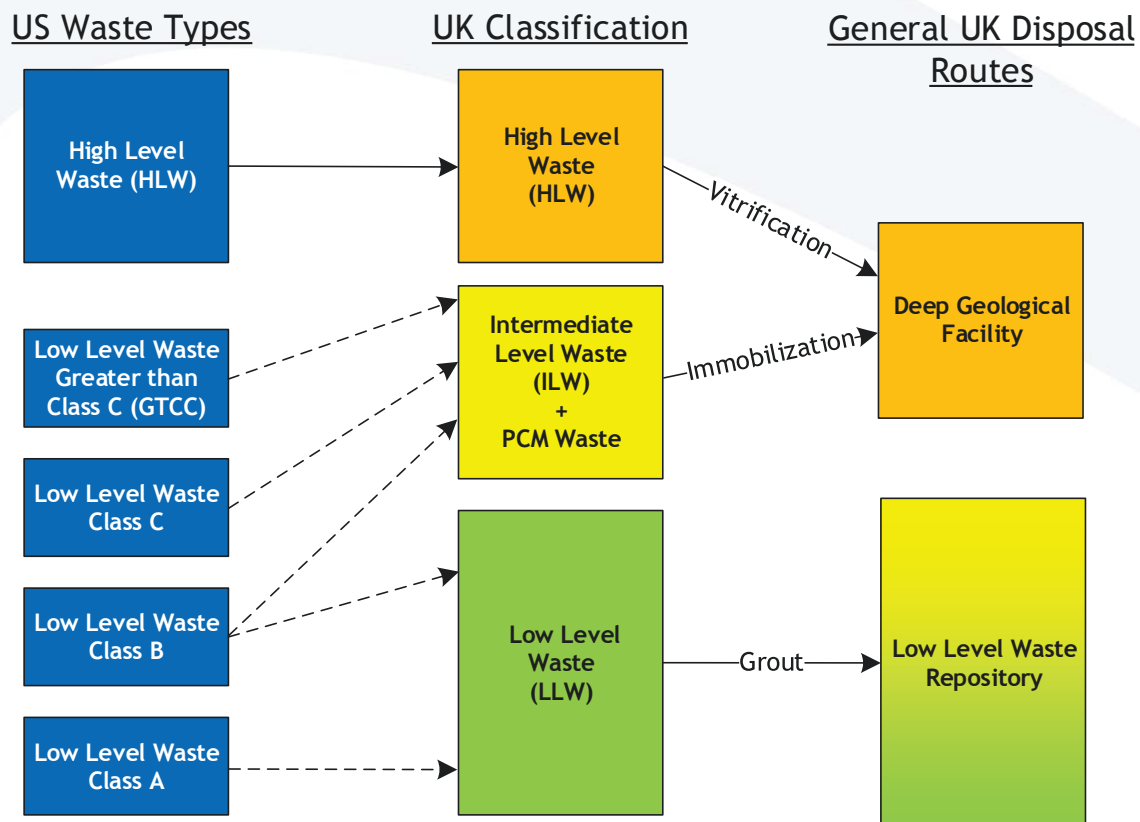


Figure 4. Comparison US Waste Types and Equivalent UK Waste Classification and Disposal Routes.





## 5. DFLAW Solid Secondary Wastes

This section briefly summarizes the situation at the Hanford site (LAWPS, DFLAW and solid secondary wastes etc.) from documentation provided by WRPS, ensuring that DBD have sufficient information and an adequate level of understanding to establish how Hanford site generated SSW would fit within a UK context. This is a key enabling step to allow the identification of equivalent UK SSW (and processing / disposal methods) in Section 6.

The Hanford site has 56 million gallons of radioactive and chemically hazardous wastes stored in 177 underground tanks. The aim is to retrieve and treat Hanford's tank waste and close its tank farms.

To achieve this, a Waste Treatment and Immobilization Plant (WTP) is under construction to treat and immobilize both High-Level (HLW) and low activity waste (LAW), into a form suitable for disposal.

LAW or ILAW (immobilized LAW), is High-Level waste where the highly radioactive components are removed, (principally Cs-137). LAW or ILAW has to demonstrate to the NRC most of the highly active constituents have been removed to allow workers to work near the waste. DBD understands that LAW is to be disposed in shallow-surface burial at Hanford.

The LAW stream will be sent to the LAW Vitrification facility, which initially is fed from the tank farms via a separate LAW pre-treatment system (LAWPS). This initiative is referred to as Direct Feed LAW (DFLAW). The DFLAW is expected to be operational for the first 10 years of the tank waste treatment mission (Ref 2).

During DFLAW operations, radioactive Solid Secondary Wastes (SSW) will be generated, that will need treatment and eventual disposal. Such wastes are expected to include:

- Used process equipment;
- Contaminated tools and instruments;
- Decontamination wastes;
- High-efficiency particulate in air (HEPA) filters;
- Carbon absorption beds;
- Silver mordenite sorbent beds; and
- Spent ion exchange resin.

Any liquid-effluent secondary wastes will be sent to the Effluent Treatment Facility (ETF) for further treatment and eventual disposal, either as treated liquid effluent under the ETF State Wastewater Discharge Permit or as solidified liquid effluents under the Dangerous Waste Permit. An additional solidification treatment unit has been proposed for the ETF. This new treatment unit would solidify the ETF evaporator brines into a cement-based waste form for disposal. Figure 5 shows the types of waste generated from the WTP and ETF.

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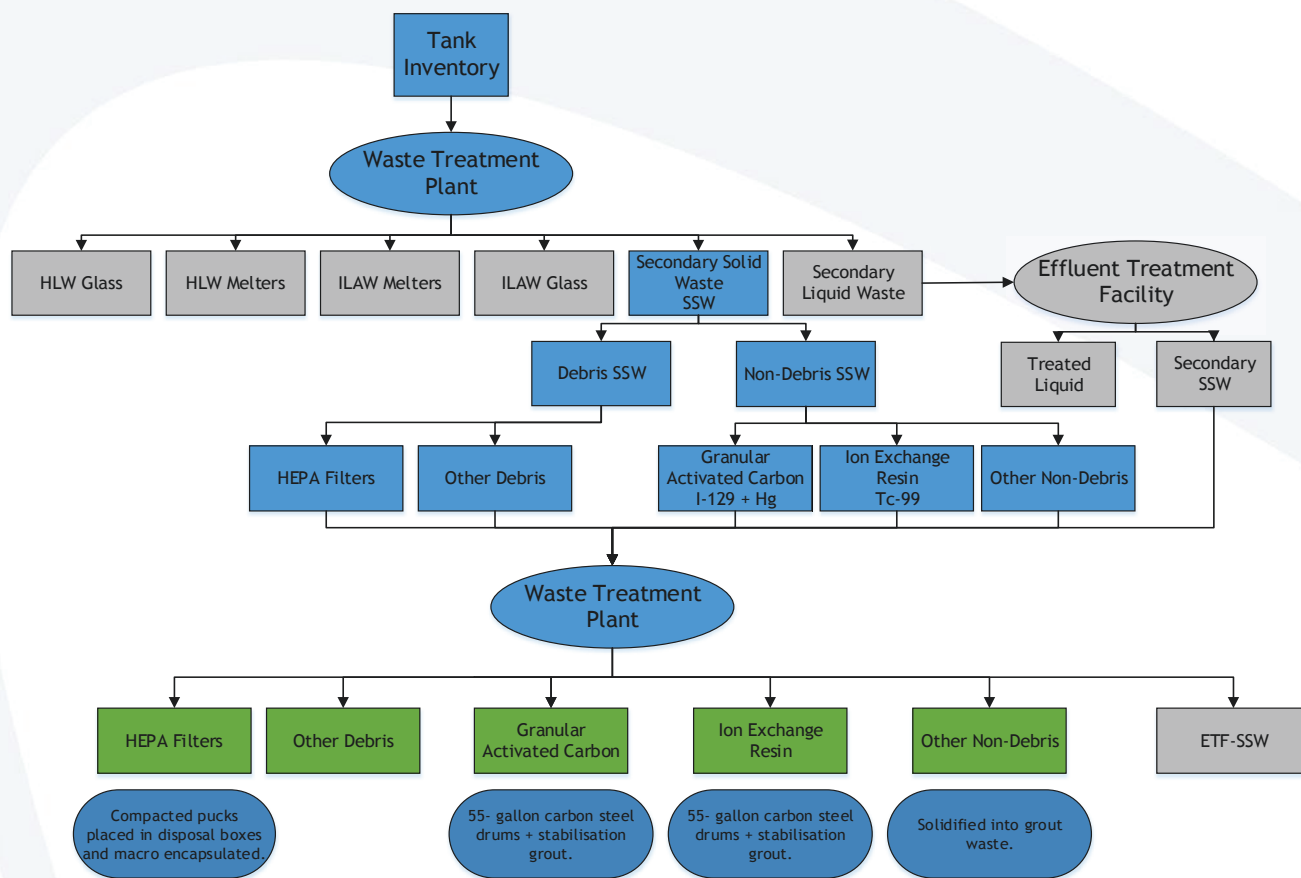


Figure 5. Types of Waste Generated From Waste Treatment Plant (WTP) and Effluent Treatment Facility (ETF). Note the secondary waste streams are shaded in blue. See Acronym List. (Ref 16).

These solid secondary wastes will be packaged and then sent to the Integrated Disposal Facility (IDF) for disposal. In addition to receiving SSW, IDF will include Immobilized Low-Activity Waste (ILAW) glass and other mixed Low-Level wastes.

A risk assessment of the disposal impacts of the proposed wastes intended for IDF, identified a number of key contaminants, which include:

- $^{99}\text{Tc}$ ,  $^{129}\text{I}$ ,  $^{137}\text{Cs}$ , and  $^{90}\text{Sr}$ ;
- Uranium isotopes; and
- Chromium, nitrate, mercury.

All solid secondary waste that is forecast to be LLRW will be packaged and grouted (or compacted) prior to disposal at IDF (Ref 16). Any glass waste forms are expected to be segregated to avoid potential issues with chemical influences of leachate from cementitious materials (Ref 16). Figure 6 shows the proposed IDF concept facility.

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Figure 6. Integrated Disposal Facility (IDF) and Example Configuration for Waste Placement (Ref 3).

The Integrated Disposal Facility (IDF) is an expandable lined landfill located near the center of the 586 square-mile Hanford site (Ref 17) and will consist of two disposal areas, cell one and cell two (Figure 6). Initially it was envisaged that one of these cells would be designed to accept mixed LLW, treated Low-Level and low activity wastes that have gone through the vitrification process at the WTP Facility. The second cell would consider storage of Low-Level waste that had not been through the WTP. However subsequent plans are considering permitting the entire facility to accept mixed LLW with relatively small volumes of LLW to be co-disposed with mixed LLW.

The waste acceptance criteria for the IDF must address a number of considerations including the need to limit potential long term waste releases to levels that are protective of human health and the environment. Any non-glass waste forms are expected to be encapsulated in a cementitious material, including solid secondary waste.



## 5.1. Solid Secondary Waste Streams

There are two generic categories of waste that encompass the DFLAW SSW streams of interest to this document: debris SSW and non-debris SSW.

Debris SSW is defined as waste with particle sizes of greater than 60 mm, this will include larger materials such as components and filters (e.g. spent HEPA filters). It is assumed this waste will be encapsulated using a standard disposal grout formulation. The exact proportions of the grout constituents are still being formalized but would include water, ordinary Portland cement, blast furnace slag (BFS), fly ash (referred to as Pulverized Fuel Ash in the UK) and / or an accompanying aggregate.

Non-debris SSW is defined as waste with particle sizes of less than or equal to 60 mm, this includes smaller materials such as ion exchange resins, and carbon adsorber beds.

Any grout formulations considered for the immobilization of non debris SSW may or may not contain BFS, this will be dependent on the primary contaminants of concern that are to be immobilized.

A more detailed description of the solid secondary waste types is given in Sections 5.1.1 - 5.1.5.

### 5.1.1. Spent HEPA Filters

HEPA filters installed across the Hanford Tank Waste Treatment and Immobilization Plant (WTP) in various locations including:

- Analytical Laboratory (Hotcell prefilter, C2 / C3 / C5 zone vents);
- Pre-Treatment Facility (PTF) (vessel vents, exhaust from power fluidic devices, C2 / C3 / C5 zone vents);
- Low-Activity Waste Vitrification Facility (LAW) (melter offgas, C2 / C3 / C5 zone vents); and
- High-Level Waste Vitrification Facility (HLW) (melter offgas, exhaust from power fluidic devices, C2 / C3 / C5 zone vents).

The HEPA filters on the vents from C2 / C3 zones and the pre-treatment facility vessel vents are expected to have very limited levels of mobile radionuclides and / or hazardous chemicals (Ref 17). On inspection of Reference 17, it is apparent that the spent HEPA filter waste stream accounts for the majority of the following radionuclides / elements in the SSW streams (total generated throughout the mission), as per Table 23 presented in Appendix A.

All HEPA filters fit within the 'Debris' category and will be transferred to an offsite treatment facility in carbon steel 55-gallon drums where they will be compacted into "pucks" at an approximated compaction ratio of 10:1 (Ref 19). Multiple pucks (~25) would be placed into disposal boxes (4ft x 4ft x 6ft) and macro-encapsulated with grout, which satisfy the Land Disposal Restrictions (LDR) requirements (Ref 19).



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### 5.1.2. Other Debris SSW

The waste stream “other debris SSW” includes all “debris” SSW except for HEPA Filters. This includes the following items from different areas of the WTP:

- **Pre-Treatment Facility (PTF)**
  - Vessel vent volatile organic compounds oxidizer
  - Spent resin collection and dewatering slurry pumps
  - Treated LAW evaporation recirculation pump
  - Vessel vent high efficiency mist eliminator
  - Ultrafiltration heat exchanger
  - Ultrafiltration recirculation pumps
  - Ultrafiltration feed pumps
  - Ultrafiltrator
  - Jumpers
  - Miscellaneous metal
  - Waste feed evaporation feed pumps
  - Waste feed evaporation concentrate pumps
  - Cesium ion exchange feed pumps
  - HLW feed receipt solution transfer pumps
  - HLW feed receipt melter feed pumps
  - LAW feed receipt transfer pumps
  - Cesium ion exchange vessel
- **Low-Activity Waste Facility (LAW)**
  - Melter offgas system submerged bed scrubber and catalytic oxidizer
  - Miscellaneous metal
  - Agitation drives
  - Discharge thermal-wells
  - LAW melter concentrate receipt and preparation ADS pumps
  - Agitator S&B
  - Vessel pumps
  - Bubblers
  - Level detectors
  - Glass debris
- **High-Level Waste Facility (HLW)**
  - Melter offgas system catalytic oxidizer and catalytic reducer
  - Melter concentrate receipt and preparation agitation drives
  - Melter concentrate receipt and preparation pump drives
  - Miscellaneous metal
  - Level detectors
  - Melter offgas high efficiency mist eliminator
  - Pool thermal-wells
  - Melter concentrate receipt and preparation ADS pumps
  - Melter concentrate receipt and preparation Agitator
  - Melter concentrate receipt and preparation feed pumps
  - Discharge thermal-wells
  - Bubblers
  - HSH L.T. Debris
  - HSH Melter Debris
- **Generic items:**
  - Vessel pump drives
  - Melter feed recirculation pump
  - Miscellaneous compactable debris (from labs, hotcells etc.)

The ‘other debris’ waste stream contains about a third of the activity within all the waste streams for  $^{137}\text{Cs}$  (1123 Ci),  $^{238}\text{Pu}$  (0.64 Ci),  $^{239}\text{Pu}$  (0.30 Ci),  $^{241}\text{Am}$  (0.86 Ci),  $^{90}\text{Sr}$  (347 Ci) (Ref 17) (where in most cases the other two-thirds come from the spent HEPA filter waste stream).

Similar to the spent HEPA filter waste stream, other debris will be size reduced with a compaction ratio varying between about 10:1 and 2.5:1 depending on the waste. The compacted waste would be placed in disposal boxes (4ft x 4ft x 6ft) and macro-



encapsulated with grout, which satisfy the Land Disposal Restrictions (LDR) requirements, as with the spent HEPA filter waste (Ref 19).

### 5.1.3. Spent Ion Exchange Resin

Spent cesium ion exchange (IX) resin is 'non-debris' and generated at the Pre-Treatment Facility (PTF) and requires remote handling (RH) (Ref 20). The fractions in the 'IDF PA Inventory' shows that IX resins contain the majority of the radionuclides / elements in the SSW streams (total generated throughout the mission) (Ref 17) as listed in Table 24 (presented in Appendix A).

This waste stream presents unique circumstances that dictate a non-standard package, in this case a High Integrity Container (HIC). After being dewatered at WTP, the resin is transported for treatment in an HIC. After treatment the IX resin is then repackaged into carbon steel 55-gallon drums with a stabilization grout (using a Hanford approved grout formulation that meets regulatory criteria) (Ref 20).

The option to consider the ion exchange resins as an encapsulated waste form, not blended in a cementitious matrix will also be assessed.

### 5.1.4. Spent Granular Activated Carbon (Carbon Adsorber Beds)

There are two sources of Granular Activated Carbon (GAC) SSW from the Hanford Tank Waste Treatment and Immobilization Plant (WTP) (Ref 20):

1. Low-Activity Waste (LAW) Facility secondary offgas / vessel vent process system (LVP) carbon bed adsorber media; and
2. High-Level Waste (HLW) Facility melter offgas treatment process system (HOP) carbon bed adsorber media.

Data from Hanford Tank Waste Operations Simulator (HTWOS) model shows that the spent adsorber beds contain about a third of the total amount of  $^{129}\text{I}$ ,  $^{14}\text{C}$  and  $^3\text{H}$  in all of the SSW streams. Also 99.997% of the Mercury within the SSW streams comes from the spent adsorber beds (Hg: 1637 kg total, 0.59 kg/m<sup>3</sup> average concentration) (Ref 19). The primary purpose of the GAC is to remove mercury (Hg), halide (F) and  $^{129}\text{I}$  from the facility's offgas streams (Ref 20).

Carbon adsorber beds are considered 'non-debris' mixed low-level radioactive waste (MLLW), but require treatment to effectively reduce the levels of Mercury, organic constituents (e.g. 2,4-dinitrotoluene, benzene, nitrobenzene) to meet the Hanford site Solid (HSS) Waste Acceptance Criteria (WAC) and Integrated Disposal Facility (IDF) WAC for land disposal. Thermal treatment could effectively eliminate organics. It is proposed that the beds would be repackaged into carbon steel 55-gallon drums and immobilization of mobile radionuclides and Mercury would occur through grouting (Ref 20).

In addition the option to consider the carbon adsorber beds as an encapsulated waste form and not blended in a cementitious matrix will also be assessed.



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#### 5.1.5. Other Non-debris SSW / Spent Silver Mordenite Media

It has been established that the only “other non-debris SSW” material is spent silver mordenite media. Silver mordenite (AgZ) is used to extract halides ( $^{129}\text{I}$ , HCl, HF etc.) from the HLW melter offgas stream.

AgZ media contains approximately 18%wt silver and even though typically high concentrations of precious metals would be extracted and recycled, it is not practical to do this because the waste material also contains mobile radionuclides (Ref 20). This waste stream accounts for approximately two thirds of the  $^{129}\text{I}$  contamination from all of the SSW waste streams (7.56 Ci total, 0.049 Ci/m<sup>3</sup> average concentration in final waste form) (Ref 21). It also contains about a third of the total  $^{14}\text{C}$  contamination (0.59 Ci) (Ref 19).

The anticipated treatment method for this waste is to transfer the spent AgZ media into carbon steel 55-gallon drums and immobilize the radionuclides using an approved Hanford grout formulation (Ref 20).



## 5.2. Hanford SSW Assessment

As part of this benchmarking exercise, WRPS have provided DBD with a copy of the IDF Performance Assessment Inventory (Ref 19). DBD have analyzed this inventory spreadsheet against the US and UK regulatory limitations (described in Sections 4.1 and 4.2 respectively) in order to establish the average US and UK radioactive waste classifications of the different SSW streams in general.

In order to obtain the results calculations have been completed based on the information provided within Reference 19, specifically using what is referred to as the '10-10 SSW fractions worksheet' which lists the contaminant inventories (radioactive in Curies and chemical in kilograms) for each SSW component over its designated run time for the WTP mission duration.

In order to obtain the results summarized in Table 11, the calculations involved the following:

- The total activities (in Curies) for each radionuclide within each SSW stream was added together (for streams that contained more than one component).
- The total volumes of SSW produced over the entire mission and the final state of the waste (i.e. compacted, grouted) was taken in to consideration (information obtained from Ref 19) to calculate the average concentration of each waste stream ( $\text{Ci}/\text{m}^3$ ). The resulting concentration values calculated are shown in Appendix B in Table 25.
- Specific radionuclides in each waste stream were assessed against the US waste classification limits (in line with the method outlined in Section 4.1), in order to classify the waste stream as Class A, Class B or Class C.
- The concentration values were then converted to UK units ( $\text{GBq}/\text{te}$ ). This was by using the Curies to Becquerel conversion factor ( $3.7 \times 10^{10}$ ) and by considering the final form of the waste (i.e. whether it is compacted, grouted) to calculate approximate densities of each waste stream. The resulting concentration values calculated are shown in Appendix B in Table 26.
- Each waste stream was then assessed against the overall UK waste classification limits (as described in Section 4.2) to classify the waste as LLW or ILW (please note that a discrete item assessment against specific radionuclides was not conducted at this stage, only an assessment against the total alpha and total beta / gamma activities within the streams). In order to assess if the waste is HLW, it would be necessary to assess the decay heat, which was not provided, however, because of the types of wastes considered here, the decay heat would not be large enough to constitute it as HLW anyway.

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*Table 11. Assignment of US and UK Waste Classifications for Hanford SSW Streams for Disposal in the IDF (for Average Concentration across the Whole Waste Stream).\**

| Waste Stream                                        | Type       | US Waste Classification | UK Waste Classification  |
|-----------------------------------------------------|------------|-------------------------|--------------------------|
| High-Efficiency Particulate Air (HEPA) Filters      | Debris     | Class B                 | Intermediate-Level Waste |
| Other Debris                                        | Debris     | Class B                 | Low-Level Waste          |
| Ion Exchange Resin                                  | Non Debris | Class A                 | Low-Level Waste          |
| Low-Activity Waste and High-Level Waste Carbon Beds | Non Debris | Class A                 | Low-Level Waste          |
| High-Level Waste Silver Mordenite Absorbent         | Non Debris | Class A                 | Low-Level Waste          |

\*The information in this table has been derived from the methodology and concentrations listed in in Appendix B.

Note that it is also necessary to consider the amount of uranium radionuclide and chemical contaminants in the potential final waste forms, as this might affect disposal in the US, which is outlined in Appendix B.

The DBD assessment of the Hanford SSW for IDF disposal shows that, based on the average activity for the entire disposal streams, most SSWs would be classified as LLW in the UK, apart from HEPA filters which would be classified as ILW.

Using the same method as for assessing the classification of the overall SSW streams, an indicative assessment was conducted on individual waste components to review the range of classification types to be expected for each component within the SSW streams. This was based on the assumption that the volume of waste in each stream is split equally across each component, since detailed information was not available on the volumes of each component to be produced. The results are presented in Appendix B in Table 27.

In terms of the spread of each type of waste classification, the indicative assessment of components shows that:

- Most of the SSW components are thought to fall in the US Class A category (52 of the 72 - that's 72% of the components). Few are thought to fall in the US Class C category (4 of the 72, that's 6% of the components). The rest are US Class B (16 of the 72, that's 22% of the components).
- For the components listed, all of those classified as US Class A, were found to be equivalent to the UK LLW category.
- The majority of the wastes categorized as Class C (75%) were equivalent to the UK ILW category (with the other being LLW). This is based on the sum of the activity of the radionuclides present.
- Of the wastes categorized as Class B, some were found to be equivalent to the UK LLW category (56%) and some equivalent to the UK ILW category (44%).

This matches the results of summary level comparison of US and UK waste classifications presented in Section 4.4.



In terms of the waste classifications predicted for each SSW stream, the indicative assessment of components shows that:

- All non-debris wastes are expected fall within US Class A and UK LLW categories
- The spent HEPA filters are expected to fall within each US and UK waste categories, depending on the component.
  - 11 of the 20 (55%) spent HEPA filter types are expected to fall within the US Class A and UK LLW categories.
  - Five of the spent HEPA filter types (25%) are expected to fall within the US Class B category but only one of those would be equivalent to UK LLW, with the other four expecting to be equivalent to UK ILW.
  - Four of the spent HEPA filter types (20%) are expected to fall within the US Class C category, but only one of those would be equivalent to UK LLW, with the other three expecting to be equivalent to UK ILW.
- The other debris items are expected to be either US Class A or US Class B:
  - 37 of the 48 (77%) of the other debris items are expected to fall within the US Class A and UK LLW categories.
  - Eleven of the other debris items (23%) are expected to fall within the US Class B category, but eight of those would be equivalent to UK LLW and the other three to UK ILW.

This is an indicative assessment, based on the information DBD have received at present, and major assumptions on the split of waste volumes and general final waste forms across the SSW streams. This is by no means a final determination of the waste classifications for each SSW component. A further detailed assessment can be made in the future if required and if an adequate amount of information is provided/assumptions agreed. These findings enable Section 6 to focus on identifying UK counterpart SSW wastes which are truly representative of Hanford SSW destined for the IDF.

### 5.3. Processing / Disposal Routes Identified for WTP Wastes

For the Hanford solid secondary wastes identified, the following waste routes have currently been identified (in Ref 19):

- Drums compacted to pucks followed by macro-encapsulation in disposal boxes - For spent HEPA filters and other debris. Note: for large equipment items it is as yet unknown whether compaction into pucks is an applicable waste route.
- Grout stabilization within drums - For spent granular activated carbon material, spent ion exchange resins and spent silver mordenite material.

Section 6 discusses, in general, the approaches used in the UK for processing of equivalent wastes.



## 6. Review of UK and European Situation

### 6.1. Radioactive Waste Generation

The majority of nuclear waste generated in the UK is from sites involved in the following activities (see Figure 7):

- Nuclear fuel manufacturing and enrichment;
- Operating nuclear power stations;
- Shutdown nuclear power stations;
- Nuclear reprocessing;
- Nuclear research and development; and
- Defense activities.



Figure 7 UK Sites That Generate Radioactive Waste. Note that small producers are not shown (Ref 22).



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UK sites that generate radioactive waste are shown in Figure 7. The Low-Level Waste Repository (LLWR) is also indicated on Figure 7. The purpose of the LLWR is for disposal of LLW from across the country. The only other major LLW disposal facility in the UK is the Dounreay site LLW Vault facility, which is dedicated to disposing of LLW from Dounreay and the adjoining Vulcan site only. These disposal sites (specifically the methods used for waste conditioning and disposal) are described in more detail in Sections 6.2 and 6.4.

Appendix D provides some detail on the various UK sites where wastes are generated, including fuel fabrication facilities, nuclear power plants (operating and shutdown), nuclear reprocessing facilities, nuclear R&D facilities and defense facilities.

For each type of nuclear site, the radioactive waste inventory data has been analyzed and wastes that are equivalent to Hanford site SSW have been identified. The SSW waste compositions and UK waste classifications are detailed. Brief descriptions are given for each waste, with information on waste composition, radiological and chemical contaminants and waste conditioning methodologies.

To identify equivalent waste types to Hanford site SSW types, an analysis of the UK Radioactive Waste Inventory (UK RWI), and relevant data sheets within this, has been undertaken (Refs 22 - 242). The SSW equivalents are documented in a series of tables (Table 12 to Table 18). Each table lists the sources for each of the Hanford SSW equivalents and shows the associated UK waste classifications.

Note - These lists (and the full list in Appendix C) offer a detailed summary of the major items in each category, but may not be fully exhaustive.

#### 6.1.1. Summary of Non-debris Wastes within the UK

*Table 12. Equivalent Granular Activated Carbon wastes generated within the UK.*

| Activity                           | LLW | ILW | Comments                                                                                                                                                           |
|------------------------------------|-----|-----|--------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Sellafield Site                    | ✗   | ✗   | Not listed as a major arising in datasheets however Likely to be generated from offgas sampling for volatiles (small volumes) based on Sellafield Site Experience. |
| Fuel Manufacturing and Enrichment  | ✓   | ✗   | Contaminated with U and hydrogen fluoride                                                                                                                          |
| Nuclear Power Stations Operational | ✓   | ✓   | For gaseous iodine abatement. Potential fission product contamination.                                                                                             |



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*Table 13. Equivalent Spent Ion Exchange Resin wastes generated within the UK.*

| Activity                           | LLW | ILW | Comments                                                                                                                                                                                                                                                                                                                                                                                                                             |
|------------------------------------|-----|-----|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Nuclear Power Stations Operational | ✓   | ✓   | Proprietary ion exchange materials (some of which organic in nature), mixed with sludge, sand and water. Includes both anion and cation exchange resins. Some resins for cement encapsulation, others for dry draining and storage in ductile cast iron casks (dependent on waste stream). Contaminated with activation products, fission products and actinides.                                                                    |
| Nuclear Power Station Shutdown     | ✗   | ✓   | Proprietary ion exchange materials (both organic and inorganic) mixed with iron shot, sand and cement paste/grout. Some polymer encapsulated. Mainly contaminated with fission products. Some actinide and activation product contamination.                                                                                                                                                                                         |
| Sellafield Site                    | ✗   | ✓   | Ion exchange material generated from the site ion exchange effluent treatment plant and from cleaning pond water. Clinoptilolite and sand, also zeolite (as proprietary ion exchange materials). Also a range of further proprietary ion exchange materials. For encapsulation in grout, assessment for polymer encapsulation for some ion exchange material to take place. Mainly contaminated with fission products and actinides. |
| Nuclear Research Sites             | ✓   | ✓   | LLW: Inorganic ion exchange resins. Cement encapsulation. Activation products, fission products and actinides.<br><br>ILW: Inorganic ion exchange columns. Polymer immobilization of ion exchange material in columns, then cement encapsulation. Contaminated with Cs-137 and Sr-90.                                                                                                                                                |
| Defence Activities                 | ✓   | ✓   | LLW: Proprietary organic ion exchange materials. Cement encapsulation (some processed first). Contamination with activation products, fission products and tritium.<br><br>ILW: Proprietary organic ion exchange materials. Cement encapsulation (some processed first). Contamination with activation products, fission products and tritium.                                                                                       |

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*Table 14. Equivalent Other Non-Debris wastes generated within the UK.*

| Activity                           | LLW | ILW | Comments                                                                                                                                                                                                                                                                                                                                                                                                                              |
|------------------------------------|-----|-----|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Defence Activities                 | ✓   | ✗   | Tritium molecular sieve desiccant. Cement encapsulation.                                                                                                                                                                                                                                                                                                                                                                              |
| Nuclear Research Sites             | ✗   | ✓   | ILW: Crushed graphite spheres. For immobilization using either polymer or cement. Contaminated with actinides.                                                                                                                                                                                                                                                                                                                        |
| Sellafield Site                    | ✗   | ✓   | (1) Fuel cladding and swarf (magnesium alloys, aluminum, stainless steel and zircaloy). Cement encapsulation. Activation products, fission products and actinides.<br>(2) Hydrocyclone solids (sands, grits and fine particles) from effluent treatment. For encapsulation. Activation products, fission products and actinides.<br>(3) Centrifuge cake. Encapsulated in cement. Activation products, fission products and actinides. |
| Nuclear Power Station Shutdown     | ✗   | ✓   | (1) Granular exhaust desiccant (activated alumina and molecular sieve sodium aluminum silicates). For cement encapsulation. Tritium is main contaminant<br>(2) Sand pressure filters (sand, gravel and sludge). For encapsulation.                                                                                                                                                                                                    |
| Nuclear Power Stations Operational | ✓   | ✗   | (1) Silica gel exhaust gas desiccant. For encapsulation. Tritium is major contaminant.<br>(2) Alumina-platinum catalyst granules. For encapsulation. Tritium and activation products are major contaminants.                                                                                                                                                                                                                          |

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### 6.1.2. Summary of Debris Wastes within the UK

*Table 15. Equivalent Debris (Contaminated Tools & Instruments) wastes generated within the UK.*

| Activity                           | LLW | ILW | Comments                                                                                                                                                                                                                                                                             |
|------------------------------------|-----|-----|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Nuclear Power Stations Operational | ✓   | ✓   | Contaminated metal plant items. Mixture of stainless and mild steel. For encapsulation. Mainly activation products.                                                                                                                                                                  |
| Nuclear Power Station Shutdown     | ✓   | ✗   | Irradiated steel from fuel handling and pond operations up to 1 meter in diameter. For encapsulation. Activation products, fission products and actinides.                                                                                                                           |
| Sellafield Site                    | ✓   | ✓   | A wide range of contaminated tools and instruments, both surface contaminated and activated. For cement encapsulation. Contaminated with activation products, fission products and actinides.                                                                                        |
| Nuclear Research Sites             | ✓   | ✓   | LLW: Contaminated tools (stainless steel, mild steel and plastics). Cement encapsulation. Mainly actinide contamination.<br><br>ILW: Contaminated and activated tools and instruments (mostly composed of steel). Activation products, fission products and actinides. Lead present. |
| Defence Activities                 | ✓   | ✓   | Uranium, plutonium and tritium contamination. Activation products in other wastes. Cement encapsulation.                                                                                                                                                                             |

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*Table 16. Equivalent Debris (Used Process Equipment) wastes generated within the UK.*

| Activity                           | LLW | ILW | Comments                                                                                                                                                                                                                                                                                                                                                                                                                                                 |
|------------------------------------|-----|-----|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Nuclear Power Stations Operational | ✗   | ✓   | Irradiated reactor components. Principally steel. For encapsulation. Activation products.                                                                                                                                                                                                                                                                                                                                                                |
| Fuel Manufacturing and Enrichment  | ✗   | ✓   | Uranium contaminated.                                                                                                                                                                                                                                                                                                                                                                                                                                    |
| Nuclear Power Station Shutdown     | ✗   | ✓   | Activated components, including steel and graphite. For encapsulation in grout. Activation products.                                                                                                                                                                                                                                                                                                                                                     |
| Sellafield Site                    | ✓   | ✓   | A wide range of used process equipment, both surface contaminated and activated. For cement encapsulation. Contaminated with activation products, fission products and actinides.                                                                                                                                                                                                                                                                        |
| Nuclear Research Sites             | ✓   | ✓   | LLW: Large plant items. Mixture of fission products, activation products and actinides, includes tritiated steel. Lead and asbestos present in some wastes. NaK present in some wastes.<br>ILW: Plant components composed of stainless and mild steel, PVC, aluminum, glass and polythene. For cement encapsulation. Activation products, fission products and actinides. Mercury, beryllium, cadmium, bismuth and asbestos present in different wastes. |
| Defence Activities                 | ✓   | ✓   | Contaminated metal process equipment, also includes plastics and cellulosic materials. Uranium, plutonium and tritium contaminated. Activation product contamination in other wastes (e.g. reactor components).                                                                                                                                                                                                                                          |

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*Table 17. Equivalent Debris (HEPA filters) wastes generated within the UK.*

| Activity                           | LLW | ILW | Comments                                                                                                                                                                                                                                                                   |
|------------------------------------|-----|-----|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Nuclear Power Stations Operational | ✓   | ✓   | Either wooden or plastic framed. For encapsulation. Activation products, fission products and actinides.                                                                                                                                                                   |
| Fuel Manufacturing and Enrichment  | ✗   | ✓   | HEPA filters and pre-filters used in GEVS systems. Contaminated with U.                                                                                                                                                                                                    |
| Nuclear Power Station Shutdown     | ✓   | ✗   | For encapsulation. Contaminated with activation products, fission products and actinides.                                                                                                                                                                                  |
| Sellafield Site                    | ✓   | ✓   | HEPA filters from a wide range of processes. For cement encapsulation. Activation products, fission products and actinides.                                                                                                                                                |
| Defence Activities                 | ✓   | ✓   | Depleted, natural and enriched uranium and plutonium contamination. Cement encapsulation.                                                                                                                                                                                  |
| Nuclear Research Sites             | ✓   | ✓   | LLW: Ventilations system filters. For cement encapsulation. Contaminated mainly with actinides and fission products.<br>ILW: Filters (with other wastes). For compaction and cement encapsulation. Contamination with actinides, fission products and activation products. |

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Table 18. Equivalent Other Debris Waste generated within the UK.

| Activity               | LLW | ILW | Comments                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |
|------------------------|-----|-----|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Defence Activities     | ✓   | ✓   | Includes cotton and polypropylene liquid filters. Cement encapsulation. Activation and fission products.<br><br>LLW: Compacted LLW, including general and soft trash, including organics, glassware and metal waste. Cement encapsulation. Activation products, fission products and actinides. Lead and asbestos present in some wastes. Trace amounts of cadmium.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |
| Nuclear Research Sites | ✓   | ✓   | ILW: Legacy heterogeneous debris wastes (including PVC, polythene, aluminum, stainless and mild steel). Activated reactor components, activated and contaminated fuel element debris and cladding, and contaminated redundant equipment and small tools. Some solids to be shredded and cement encapsulated. Activation products, fission products and actinides. Toxic metals present in some wastes, including lead and beryllium.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |
| Sellafield Site        | ✓   | ✓   | LLW:<br>(1) Heat exchanger lagging material. Cement encapsulation. Activation product contaminated.<br>(2) Plant decommissioning wastes. Cement encapsulation. Mainly activation products and fission products.<br>(3) Plant operational wastes, includes used PPE, redundant tools and equipment. Cement encapsulation.<br>ILW:<br>(1) Plutonium contaminated material (PPE, filters, plant items and tools etc.). Cement encapsulation.<br>(2) Isotope cartridges, tools and instruments. Cement encapsulation. Activation products, fission products and actinides.<br>(3) Glass fibre filters (with steel surround). Fission product and actinide contaminated.<br>(4) Miscellaneous beta/gamma waste (including items contaminated with vitrification glass). Cement encapsulation for most (some ILW stored raw pending treatment in 2040). Activation products, fission products and actinides.<br>(5) Maintenance scrap. Cement encapsulation. Mainly fission products and actinides. |



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Nuclear Power  
Station Shutdown

✓ ✓

LLW: Compactable and non-compactable wastes. Either supercompaction, incineration or metal decontamination/recycling, followed by encapsulation (dependent on waste type).

Nuclear Power  
Stations  
Operational

✓ ✓

ILW: Magnox and steel metal components (e.g. splitter blades, fuel element debris). Cement encapsulation. Activation products, fission products and actinides.

LLW: Compactable and non-compactable wastes, e.g. PPE. Either supercompaction, incineration or metal decontamination, followed by encapsulation (dependent on waste type).

ILW :

(1) Graphite items, for encapsulation. Mainly contaminated with activation and fission products

(2) Glass fibre filter cartridges (stainless steel supports). For encapsulation. Mainly activation products, fission products and actinides.

Fuel  
Manufacturing  
and Enrichment

✓ ✓

LLW = Compactable Contaminated Waste

ILW = Magnesium fluoride filters

Both contaminated with U and trace Tc, Ru and Np.

### 6.1.3. Solid Waste Generation Sources in France

**Fuel Production** - There are a few historic uranium mines where mine tailings were disposed. George-Besse I is the original enrichment facility for France operated by European Gaseous Diffusion Uranium Enrichment Consortium (EURODIF), where operations stopped in June 2012. The latest enrichment facility is the Georges-Besse II plant which has been operating since 2011 by Société d'Enrichissement du Tricastin (SET) (part of the AREVA group). This facility uses centrifugation technology, similar to that used at the Urenco facilities in the UK, Germany and Netherlands.

**Power Generation** - EDF operate 58 nuclear power plants in France, which generated 408 TWh of nuclear power in 2010. One European Pressurized Reactor (EPR) is being constructed at Flamanville Site (Flamanville 3), an experimental reactor (Jules-Horowitz, Material Testing Reactor) is being constructed on the Cadarache Site, whilst the ITER fusion project and an EPR reactor at Penly site are under study.

Most of the waste resulting from the operation of pressurized-water reactors (PWR) by EDF consists of VLL, IL or LIL-SL waste. The waste contains beta and gamma emitters and only a few or no alpha emitters. The waste may be divided into two categories:

- Process waste resulting from the purification of circuits and the treatment of liquid or gaseous effluents, in order to reduce their activity level prior to discharge. The

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waste comprises ion-exchange resins, water filters, evaporator concentrates, liquid sludges, pre-filters, absolute filters and iodine traps; and

- Technological waste arising from maintenance activities. The waste may be solid (rags, paper, cardboard, vinyl sheets or bags, wood or metal pieces, rubble, gloves, protective clothing, etc.) or liquid (oils, solvents, decontamination effluents, including chemical cleaning solutions).

The volume of LIL-SL waste packages from nuclear reactor sites has dropped from about 80 m<sup>3</sup>/TWh(e) in 1985 to slightly more than 10 m<sup>3</sup>/TWh(e) in 2001. The decisive factors leading to the drop during the 1985-95 decade are chiefly organizational (reduction of potential waste at source, feedback sharing, good practices) and technical (implementation of changes to the re-draining of liquid effluents, denser packaging of certain waste by grouping and/or pre-compacting). Improvement actions are carried out particularly with regard to the following issues: (a) “waste zoning”; (b) waste reduction at source (ion-exchange resins, water filters and technological waste), and (c) waste sorting before routing to the best management system.

Spent Fuel Recycling - Areva operate the recycling facilities at La Hague, Normandy. Many of the waste streams arising will be similar to those arising at Sellafield, due to similarities in the overall PUREX process employed. However there are some notable differences, for example:

- The generation of iodine filter wastes (silver-based or otherwise) which are not generated at Sellafield.
- Insoluble ‘fines’ arising from reprocessing are vitrified with HLW, rather than being encapsulated and treated as ILW in the UK.

R&D - France have research establishments in the field of nuclear-power generation and other disciplines. No detailed waste breakdown could be found for these facilities during the timescale of writing this report.

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| Half Life<br>Activity      | Very Short Half-Life<br>(< 100 Days)                      | Short Half-Life<br>(< 31 years)                                                                                                                                                                     | Long Half-Life<br>(> 31 Years)                                                                                                                                                                                                                                                                                                         |
|----------------------------|-----------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Very-Low-Level<br>(VLL)    | Residues from medical<br>uses of radioactive<br>material. | <b>VLL Waste</b><br>Wastes due to the operations, maintenance and dismantling of<br>nuclear power plants, fuel-cycle facilities and research<br>establishments. Typical activity levels < 100 Bq/g. |                                                                                                                                                                                                                                                                                                                                        |
| Low-Level (LL)             |                                                           | <b>LIL-SL Waste</b><br>From the operation and<br>dismantling of nuclear<br>power plants, fuel-cycle<br>facilities and research<br>establishments.                                                   | <b>LL-LL Waste</b> <ul style="list-style-type: none"> <li>Graphite waste. Typical activity: 10 kBq/g - 300 kBq/g (beta-emitter radionuclides).</li> <li>Radium-bearing waste. Typical activity: 10 Bq/g - 3 kBq/g (alpha-emitter radionuclides)</li> </ul>                                                                             |
| Intermediate-Level<br>(IL) |                                                           |                                                                                                                                                                                                     | <b>IL-LL Waste</b> <ul style="list-style-type: none"> <li>Structural residues from the reprocessing of spent fuel (i.e. fuel hulls and end-pieces).</li> <li>Technological waste (e.g. used tools and equipment).</li> <li>Residues from effluent processing (e.g. bitumised sludges). Typical activity: 1 MBq/g - 1 GBq/g.</li> </ul> |
| High-Level (HL)            | N/A                                                       | <b>HL Waste</b><br>Spent fuel reprocessing fission products/minor actinides.                                                                                                                        |                                                                                                                                                                                                                                                                                                                                        |

Figure 8. Summary of Solid Waste Sources in France (compiled based on information in Ref 243).

#### 6.1.4. Summary

DBD's analysis of radioactive wastes show that the UK has many current and future wastes that are equivalent to Hanford SSW, including:

Debris waste:

- Used process equipment;
- Contaminated tools & instruments;
- HEPA filters; and
- Other debris waste.

Non-debris waste:

- Granular activated carbon;
- spent ion exchange resin; and
- Other non-debris waste.

Each of the above SSW equivalent wastes are present as both LLW and ILW. The equivalent SSWs are generated across the full range of UK nuclear sites, from a wide range of processes. Wastes are both surface contaminated (with fission products, activation products and actinides) and in some cases also activated via neutron irradiation. Many of

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the above wastes are, or will be conditioned, prior to final disposal by encapsulation in a cement grout (a description of this is given in Section 6.2).

Of particular note (based upon discussions with WRPS to date) is that the UK has a substantial inventory of spent ion exchange resin waste. This ion exchange resin waste has been generated from a range of effluent, pond and process water clean-up operations. The spent ion exchange materials cover a wide range of proprietary materials, include both cation and anion exchange resins and both organic and inorganic resins. Waste processing varies between different sites, with some ion exchange materials being directly encapsulated in a cement grout and others being treated first to remove certain radionuclides of concern. The driver for such treatment is the requirement to meet the waste acceptance criteria of disposal sites. Ion exchange resins at some sites have been, or are planned to be, encapsulated in an organic polymer (for example see Section 6.3.3.2). The conditioning of equivalent SSW in the UK is described in Section 6.2.

The only specific Hanford SSW for which the UK does not generally have a direct equivalent is silver mordenite beds. DBD's understanding is that silver mordenite will be used as an iodine getter to clean up off gases (i.e. act as iodine filters) at the WTP. By contrast, general practice in the UK (certainly at Sellafield) is for gaseous streams that routinely contain significant iodine content to be put through caustic scrubbing and for the effluents to be discharged as a liquid stream to sea. Silver mordenite filters are not commonly used in the UK. By contrast, DBD's understanding is that such systems are used extensively in France (and other countries influenced by French design practices, e.g. Japan) and are originally a French technology development.



## 6.2. Low Level Radioactive Waste Conditioning

The UK has a large amount of experience managing radioactive waste, including the conditioning of both LLW and ILW via cement encapsulation. The UK also has specific experience management of items of specific interest to WRPS, such as the polymer encapsulation of ion exchange resins. Section 6.2 describes the range of LLW and ILW conditioning facilities utilized in the UK. This section demonstrates the range of conditioning facilities and processes used in the UK for processing SSW equivalent wastes.

In the UK, hydraulic cements are used in cement encapsulation. These have the ability to react with water under ambient conditions and form a hardened and water-resistant product. Cements typically comprise of Ordinary Portland Cement (OPC) mixed with other materials to improve the characteristics of waste forms and overcome incompatibility problems associated with the chemical composition of certain waste types. Such mixtures may include the addition of Pulverized Fuel Ash (PFA) and Blast Furnace Slag (BFS). The formulations for such composite cements are underpinned by research and development carried out by the UK nuclear industry. Grout formulations are referred to throughout Section 6.2.

### 6.2.1. Low-Level Waste (LLW) Conditioning

The majority of UK LLW which is deemed unsuitable for re-use, recycling or incineration is sent to the LLWR in Cumbria (see Section 6.4.1). LLW management practices are mandated by a hierarchy of options to reduce environmental impact, with waste prevention as a priority and waste disposal as a last option. This is known as the waste hierarchy (Figure 9) and flows from the regulatory requirement to demonstrate BAT in all operations.

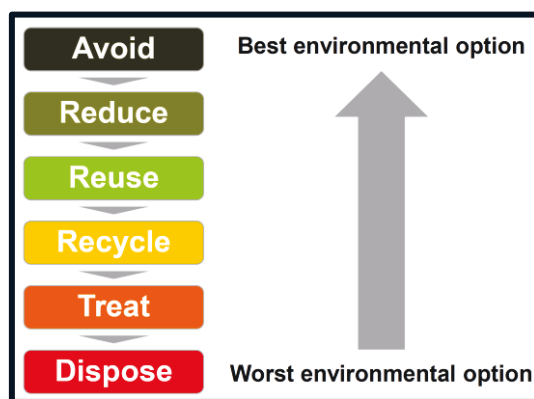


Figure 9. The Waste Hierarchy of Management Options.

Where practicable waste material is re-used or recycled following decontamination, or where suitable is incinerated. Other material, predominantly rubble and soil from nuclear plant decommissioning, with very Low-Levels of radioactivity, can be routed to permitted landfill sites for disposal rather than to the LLWR. Options for the management of LLW are shown in Table 19.

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*Table 19. Options for the Management of LLW in the UK.*

| Activity         | Description                                                                                                              |
|------------------|--------------------------------------------------------------------------------------------------------------------------|
| Super-compaction | High-force compaction to improve packing efficiency of waste in storage containers - reducing waste volume by up to 70 % |
| Incineration     | Thermal treatment; to burn combustible wastes and reduce waste volumes.                                                  |
| Metal Treatment  | Segregation, size-reduction, shot-blasting and melting to treat and re-cycle metal.                                      |
| Diversion        | Diversion and transfer of low active-LLW and very LLW to suitable facilities other than the LLWR site.                   |
| Disposal         | Disposal of LLW in ISO freights, filled and capped with grout.                                                           |

Since 1959 about 1 million cubic meters of LLW from the nuclear power industry, hospitals, research establishments and the defense programs have been consigned to the LLWR. Suitable waste is first super-compacted to minimize its volume, and wastes are placed in large metal containers, termed ISO containers (Figure 10). The ISO containers are then grouted using low viscosity cement (see Section 6.2.1.1) and placed in concrete-lined vaults (see Section 6.4.1)<sup>6</sup>.

<sup>6</sup> A very small amount of waste has been directly grouted (un-containerized) at the LLWR. The most notable example was the WAGR heat exchangers. This was a special arrangement.



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*Figure 10. Supercompaction of LLW Drums into 'pucks' and Placement in a Half-Height ISO Freight.*

In addition to the conditioned waste at the LLWR, at 1 April 2013 there were small volumes of LLW that had been immobilized in cement-based matrices stored at:

- Hinkley Point A (shutdown nuclear reactor site) - filters;
- Sellafield - decommissioning waste from WAGR (<sup>7</sup> treatment of this waste discussed in more detail in Section 6.3.1.4); and
- Devonport (Defense Site)- sludge, ion exchange material and filters

The proportion of cement that makes up these conditioned products typically varies between about 40% and 80% by mass depending on the particular waste.

Furthermore, any LLW generated at the Dounreay site is grouted (see Section 6.2.1.2) and sent to the new Dounreay LLW vaults adjacent to the site (see Section 6.4.2).

For LLW, the main grouting facilities are the LLWR Grouting Facility, the Dounreay Encapsulation Plant and the Winfrith Mobile Cementation Plant (see Sections 6.2.1.1, 6.2.1.2 and 6.2.1.3, respectively).

<sup>7</sup> Depending on the contamination levels, waste from decommissioning WAGR may not be classed as LLW. High concentrations of carbon-14 may mean that it is classed as ILW and therefore not suitable for disposal at LLWR. There are also potentially activated metallic components under decay that prevent it being classified as LLW.

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#### 6.2.1.1. LLWR Grouting Facility

Waste (including SSW equivalent waste) arrives at the Low-Level Waste Repository (LLWR) Grouting Facility in ISO containers, as shown in Figure 11.



*Figure 11. View of Demonstration ISO Prior To Grouting (Ref 246).*

The aim of the LLWR Grouting Facility is to fill the voidage in the containers with grout and in doing so encapsulate the disposed wastes. Figure 12 is a photograph of the LLWR Grouting Facility. The silos in Figure 12 contain the dry grout material which is mixed with water inside the facility before pouring.



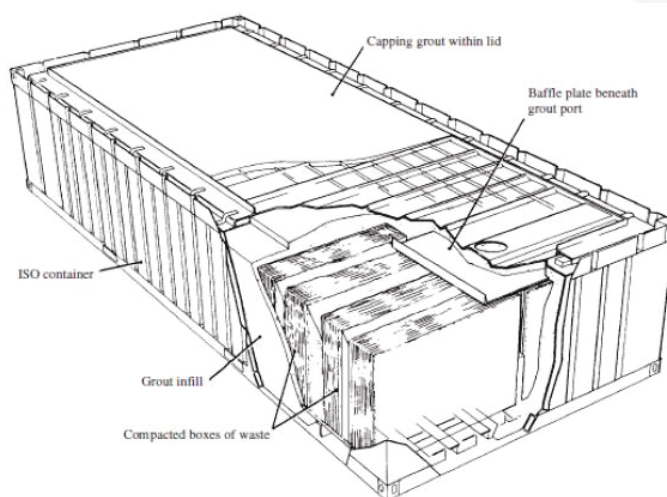
*Figure 12. The LLWR Grouting Facility.*



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The LLWR Grouting Facility can handle up to four containers at one time. To ensure that the wet grout, when poured into the ISO container, is sufficiently spread around the wastes (such as compacted pucks) there is a baffle plate underneath the grout port (as can be seen in Figure 13). This ensures that voidage is eliminated as much as possible. As the container is being grouted, it is tilted. This allows as much of the air as possible to escape before it is moved back to horizontal for the final part of the fill (Ref 246).



*Figure 13. Cut-Away Schematic Drawing View of a Typical Half-Height ISO Container (Ref 246).*

A cut through of a demonstration container after grouting is shown in Figure 14. This shows the minimal amount of voidage obtained from the technique used at the LLWR Grouting Facility. Waste tends to occupy about 60% of the internal volume of an ISO container, ~38.5% is typically filled by grout and void space from residual 'inaccessible void space' is 1.5% (Ref 247).



*Figure 14. Cut-Through of Grouted Demonstration ISO Container (containing encapsulated wood, rubble, concrete blocks and metal pipes) (Ref 246).*



The grout used typically has an initial water to solids ratio of about 0.4, which consists of 3 parts Pulverized Fuel Ash (PFA) to one part Ordinary Portland Cement (OPC) with a super-plasticizer. Such a mixture has been selected after extensive trials (Ref 248) to ensure that the grout exhibits the characteristics listed in Table 20.

*Table 20. Characteristics of the Grout Used With the LLWR Grouting Facility.*

| Characteristic       | LLWR Grout                                                                        |
|----------------------|-----------------------------------------------------------------------------------|
| Viscosity            | Low - to ensure good flow                                                         |
| Set time             | 16 hours - no free water after this                                               |
| Shrinkage            | Low - <2%                                                                         |
| Compressive Strength | After 48 hours = >150 kN/m <sup>2</sup><br>After 90 days = >400 kN/m <sup>2</sup> |

The grouted containers are then transported to one of the LLWR vaults for permanent storage (as per Section 6.4.1).

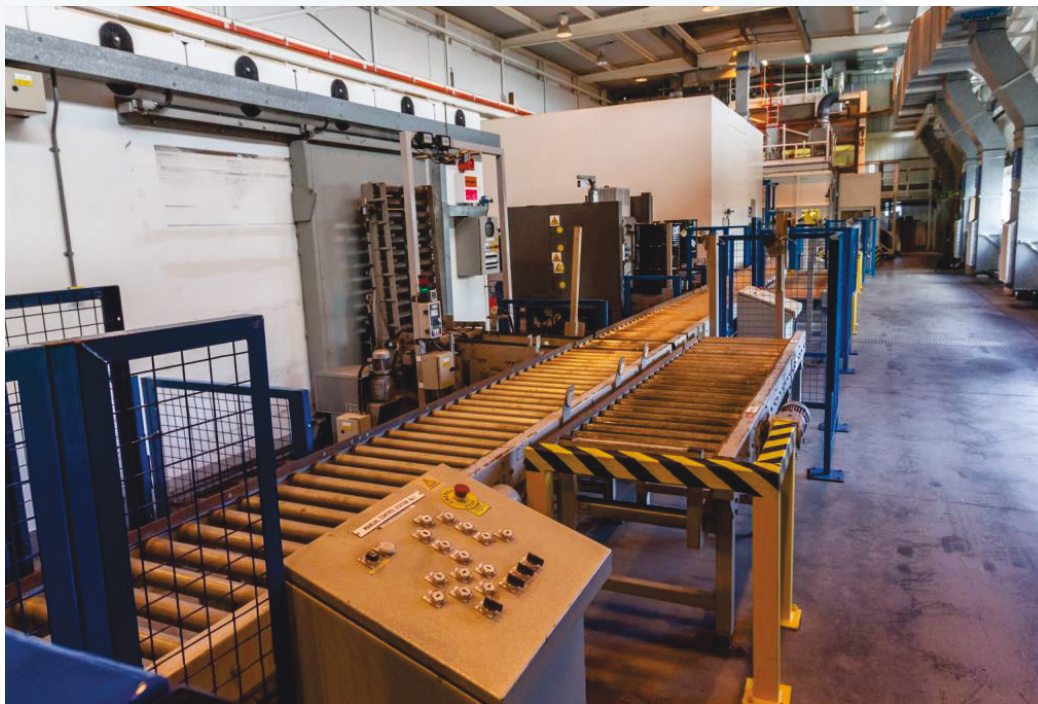
#### 6.2.1.2. Dounreay - LLW Encapsulation Plant

In Scotland, at the nuclear licensed site currently being decommissioned at Dounreay (see Appendix C) Low-Level Waste (LLW) is collected, managed and stored on / near site. It is predicted that the decommissioning of Dounreay site will produce up to 175,000 m<sup>3</sup> of solid LLW that will need to be managed (which is 80% of the solid radioactive waste by volume that is expected to be created during operation and decommissioning of the site). Here, solid LLW is comprised of materials which have been lightly contaminated with radioactivity, including metals and concrete, glass, soils and other materials, such as polythene sheets, plastic gloves and paper (Ref 249).

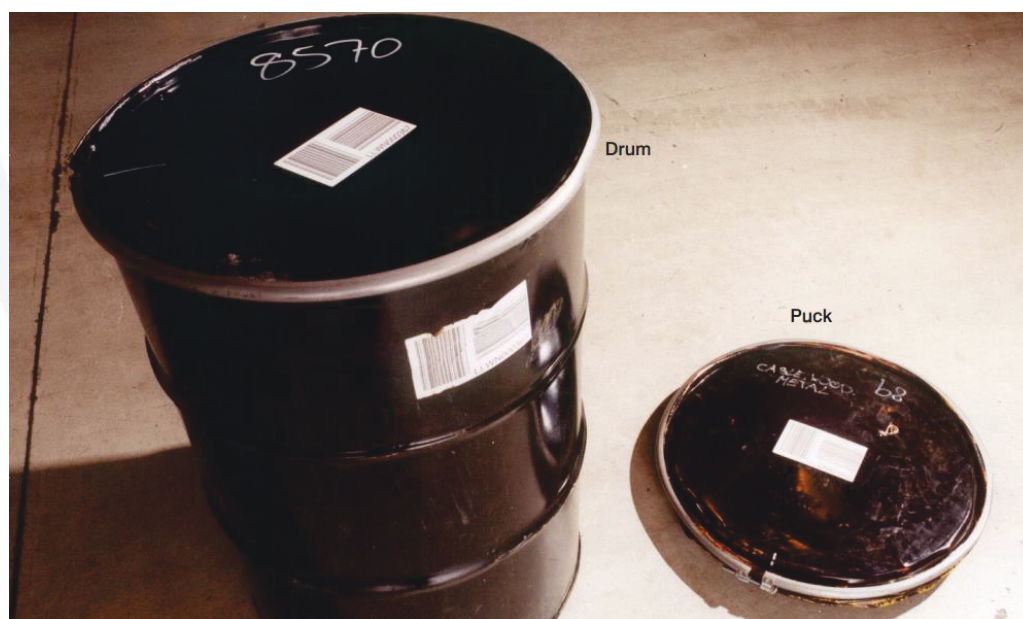
LLW is collected in 200 liter mild steel drums (Ref 250) and transported to the Waste Receipt Assay Characterization and Supercompaction facility (WRACS) (shown in Figure 15). At WRACS the drums are sent through assay characterization to determine if they comply with the LLW acceptance criteria before size reduction (Ref 251) LLW drums are then supercompacted, typically to a ratio of 5:1, as shown in Figure 16. A new supercompactor was installed in the facility and has been operational since July 2015 (shown in Figure 17). The compacted drums, referred to as "pucks", are stored in carbon steel ISO containers (same type as those used at LLWR, Drigg) (Ref 251). For a half-height ISO container it would hold approximately 200 - 250 compacted drums. Figure 18 and Figure 19 show the loading of pucks into ISO-freight containers at the WRACS facility at Dounreay.



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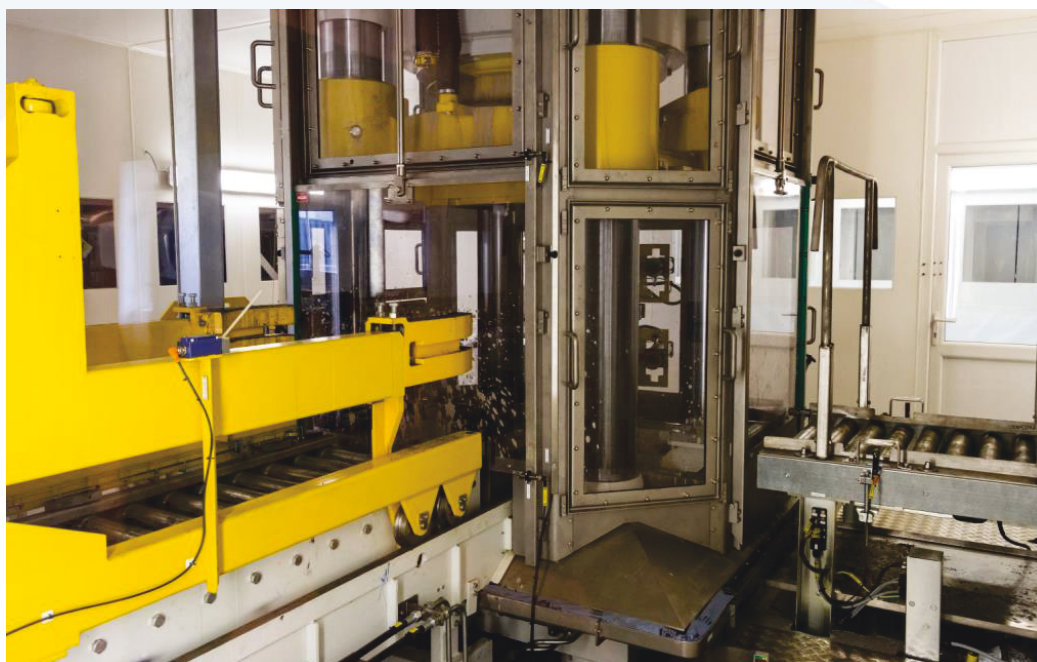


*Figure 15. Photograph Showing the Interior of the Waste Receipt Assay Characterization and Supercompaction Facility (WRACS) at Dounreay (Ref 252).*



*Figure 16. Photograph of a 200 liter Mild Steel Drum, before and after Compaction at the Dounreay Waste Receipt Assay Characterization and Supercompaction Facility (WRACS) (Ref 252).*

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*Figure 17. Photograph Of The New 45 Tonne Super Compactor Installed At The Dounreay Waste Receipt Assay Characterization And Supercompaction Facility (WRACS) Which Has Been Operational Since July 2015 (Ref 252).*



*Figure 18. Photograph of a Super Compacted Drum (puck) Being Loaded in to an ISO-Freight Container in the Dounreay Waste Receipt Assay Characterization and Super Compaction Facility (WRACS) (Ref 252).*



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*Figure 19. Photograph of an ISO-Freight Container in Dounreay's WRACS Facility with Super Compacted LLW Waste Drums Being Loaded (Ref 251).*

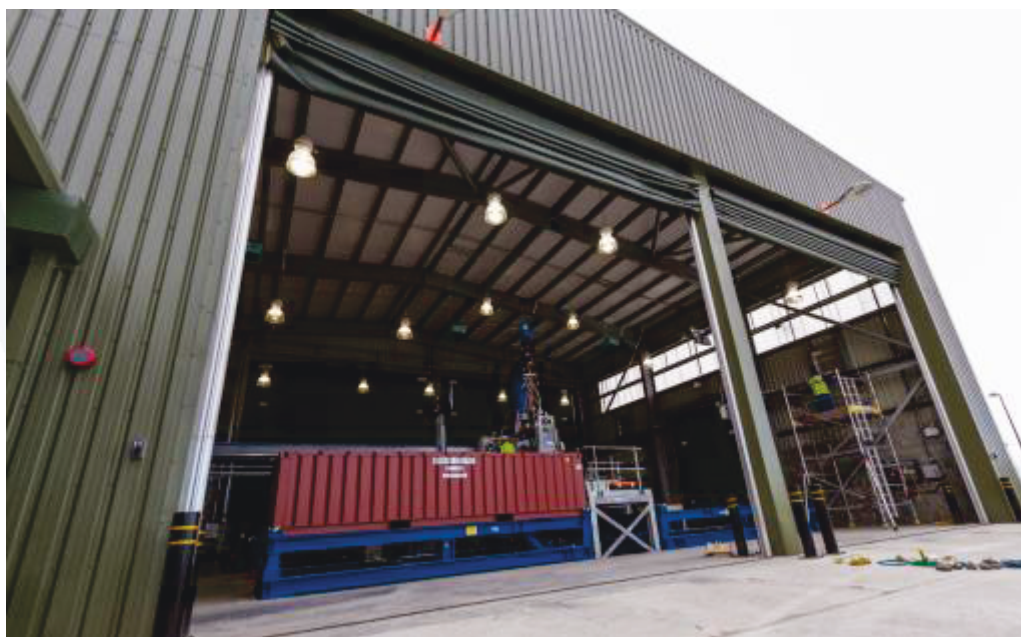
Other LLW items that are too large to fit into drums (e.g. steelwork, pipework and equipment decommissioning LLW, and operational LLW (Ref 250) can be packed directly into ISO containers (Ref 251).

Once an ISO container is full, it is taken to the encapsulation plant, which uses a similar process to that used at the grouting facility at the national Low-Level Waste Repository (LLWR) in Cumbria to full LLW ISO-containers with cement-based grout (Ref 249). The encapsulation plant at Dounreay (shown in Figure 20) has the capacity to grout up to four containers per day (Ref 249) The ISO containers are placed in buffer storage on arrival and when ready for encapsulation, the containers are placed on a tilting table by a forklift truck (Ref 253) (shown in Figure 21). The tilting of the container allows the grout to fill as much of the void space as possible during the filling process. Grout is poured in to the void space at a rate of approximately 10 m<sup>3</sup>/hour via a port in the roof of the container (refer to Section 6.2.1 to see a diagrammatic representation of this since it is the same process as used at LLWR). Grouting fills any void space in the container and the formula of grout ensures that the resulting chemical conditions of the grouted container will limit the release of radionuclides in the far future, even if penetrated by groundwater (Ref 249).

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*Figure 20. Photograph of the Encapsulation Plant at Dounreay. Silos Contain Dry Grout Materials (Ref 249).*



*Figure 21. Photograph of an ISO-Freight Container on the Tilting Stand, Ready for Grouting, At the Dounreay Encapsulation Plant (Ref 253).*





*Figure 22. Photograph of the Inside of the Dounreay Encapsulation Plant, Showing the Top of the Grout Mixing Batch Equipment (Ref 253).*

The grouted ISO-freight container is then left in the plant overnight, allowing the grout to cure before being moved to a holding area until transportation and final disposal in the vaults at the new Low-Level Waste Disposal Facility, adjoining the licensed site (Ref 251). In the LLW vault, the containers will initially be stacked four-high and once it is full, gaps between the containers will be backfilled with cementitious material in order to fully immobilize the material (and any radionuclides within) (Ref 249).

#### 6.2.1.3. Winfrith - Mobile Cementation Plant

Tradebe Inutec operate a mobile cementation plant from the Winfrith site. This mobile unit is used to encapsulate waste generated throughout the UK, either on site at Winfrith or remotely at other UK nuclear licensed sites.

Other mobile cementation facilities have also been developed and used by other companies, including but not limited to, NSG, James Fisher and Doosan Babcock, for encapsulating non-debris waste from a wide range of UK nuclear licensed sites.



### 6.3. Intermediate-Level Waste (ILW) Conditioning in the UK

For most UK ILW, packaging consists of encapsulation in cement-based materials within 500 liter stainless steel drums, 3 m<sup>3</sup> stainless steel boxes or 3 m<sup>3</sup> drums. Large items are packaged in higher capacity stainless steel or concrete boxes<sup>8</sup>. The largest waste containers designed by Radioactive Waste Management Limited to be used at a number of sites in the future include 2 m and 4 m long boxes. Wastes may first be treated to reduce their water content to an optimum level for packaging. Certain materials and small items of equipment can be supercompacted, while other solid wastes are cut up to reduce their size. Encapsulated packages are placed in engineered shielded storage facilities. Some ILW from nuclear power stations is being packaged in thick walled ductile cast iron containers without encapsulation of the wastes. The aim of the containers is to make the shielding part of the package rather than part of the storage facility.

There are a number of ILW packaging plants operating at Sellafield. These plants are packaging a variety of solid wastes from spent fuel reprocessing. ILW packaging plants are also operating at Dounreay, Harwell, Trawsfynydd and Windscale. Further packaging plants are being built and planned as part of forward programs. To date about 28,000 cubic meters of ILW have been packaged, producing about 54,000 packages that are held in modern engineered storage facilities.

Increasing quantities of Intermediate-Level Waste (ILW) at Sellafield and at other sites are being conditioned for safe longer-term storage by immobilizing the wastes in cement-based or polymer matrices within steel or concrete containers. On 1 April 2013 there were accumulations of conditioned ILW at:

- Sellafield - Magnox fuel cladding, Enhanced Actinide Removal Plant (EARP) floc, Advanced Gas-cooled Reactor (AGR) and Light Water Reactor (LWR) fuel cladding, Plutonium Contaminated Material (PCM), centrifuge cake, barium carbonate slurry and Multi-Element Bottle (MEB) crud, pond sludge, fuel stringer debris and decommissioning wastes from Windscale Advanced Gas-cooled Reactor (WAGR), miscellaneous beta / gamma waste and maintenance scrap, all in cement-based matrices;
- Dounreay - Materials Testing Reactor (MTR) liquors in a cement-based matrix;
- Harwell - sludges and liquors in cement-based matrices;
- Winfrith - sludges in a cement-based matrix; and
- Trawsfynydd - ion exchange material in an organic polymer, and Magnox fuel element debris, miscellaneous activated components and pond debris in cement-based matrices.

The composition of conditioned ILW is governed by the nature of the waste, but typically varies between about 50% and 80% encapsulating material by mass.

<sup>8</sup> A limited number of concrete packages are currently in use, but more are planned to be used in the future when decommissioning programs progress so far as to remove large items.



Some ILW waste at Sellafield site (including miscellaneous beta gamma waste, AGR steel and graphite from fuel) is being stored in boxes and drums with no conditioning/grouting. These packages will be opened up and conditioned from 2040 onwards, along with waste from decommissioning and failed ILW drums, in the planned new decommissioning ILW encapsulation plant facility.

#### 6.3.1. Sellafield ILW Facilities

ILW produced from reactor and spent fuel storage and reprocessing operations on the Sellafield site which did not meet the requirements for near-surface disposal at the LLWR was historically stored on the site in a number of silos.

During the 1980s, concerns regarding the safety storing of some of the ILW in legacy facilities combined with the construction of further oxide reprocessing facilities on the site led to the development of a suite of encapsulation facilities being designed and constructed. These facilities including the

- Waste Encapsulation Plant (WEP);
- Magnox Encapsulation Plant (MEP);
- Waste Packing Encapsulation Plant (WPEP) for ILW; and the
- Waste Treatment Complex (WTC) for Plutonium Contaminated Material (PCM) wastes.

These facilities compact (where suitable) and encapsulate ILW within grout inside a 500 liter drum, which was broadly accepted as suitable for interim storage and eventual geological disposal in the UK (see Section 6.4.4). It is estimated that since 1990, in excess of 20,000, 500 liter drums of ILW have been encapsulated on the Sellafield site.

Following the completion of the first series of encapsulation facilities the focus on ILW on the Sellafield site in the 1990s and 2000s subsequently changed to managing the ILW produced from legacy facilities which were either not suitable for consignment to the existing processes (due to size or waste form) or where there was insufficient capacity to accept these.

##### 6.3.1.1. Sellafield - Waste Encapsulation Plant (WEP)

Since 1994 the Waste Encapsulation Plant (WEP) at Sellafield processes a variety of ILW waste streams arising from oxide reprocessing activities on the Sellafield site. The WEP facility uses encapsulation to produce a 500 liter encapsulated product drum which is suitable for interim storage and eventual geological disposal in the UK. This facility treats a number of waste streams, including:

- Hulls and Ends - The hulls are the zirconium or stainless steel fuel cladding sections which remain following the dissolution of spent fuel within the THORP dissolvers. These are typically cylindrical sections of zircaloy or stainless steel of 50-75 mm (2-3") length. Hulls from LWR may also contain sizable end sections of the fuel assemblies and those from arising from AGR fuel may also contain amounts of slotted can debris. If dissolution is not fully complete it is possible that the hulls



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may contain a small residual quantity of undissolved spent fuel. Coarse fines of spent fuel cladding which are decanted or filtered from the settled THORP dissolver solution are also present. This feed is transferred to WEP in a Solid Waste Export Facility (SWEF) container covered by water.

- **Centrifuge Cake** - This waste stream arises from the centrifuging of the THORP dissolver liquor prior to chemical separation to remove fine particulate of insoluble fission products and spent fuel cladding prior to chemical separation operations. This feed is transferred to WEP in as aqueous slurry in a SWEF container and typically contains approximately 5 wt% solids.
- **Barium Carbonate Slurry** - This waste stream is a barium carbonate slurry produced from the treatment of the liquid effluents from the THORP dissolver off gas system. This system produces a viscous slurry which is typically 15-30 wt% solids.
- **MEB CRUD and Funda Filter Pre-Coat** - These waste streams arise from the storage of spent fuel prior to reprocessing in THORP. LWR fuel is transported and stored within cylindrical containers known as Multi Element Bottles (MEBs). MEBs are used to prevent to the contamination of spent fuel flasks and spent fuel pond water with radioactive metallic particulate material (known as CRUD) which may be adhered to the cladding from reactor operations. Prior to reprocessing the MEBs are flushed before they are opened to access the spent fuel assemblies. The THORP storage and feed pond water is also filtered using pressure leaf filtration (known as a Funda Filter) to remove any particulate CRUD which may be present. The filter pre-coat is periodically replaced due to an accumulation of solids. This system produces an aqueous slurry which is typically 15-30 wt% solids.

Within the WEP facility there are two different encapsulation processes used depending on whether the feeds are solid Hulls and Ends or aqueous slurries.

For the solid waste streams the hulls are dewatered whilst in the SWEF and then tipped in a controlled manner in to the 500 liter drum and are monitored for residual uranium content to ensure that conditions for acceptance are not breached. The drum is then dewatered prior to grouting to remove any residual water present with the hulls.

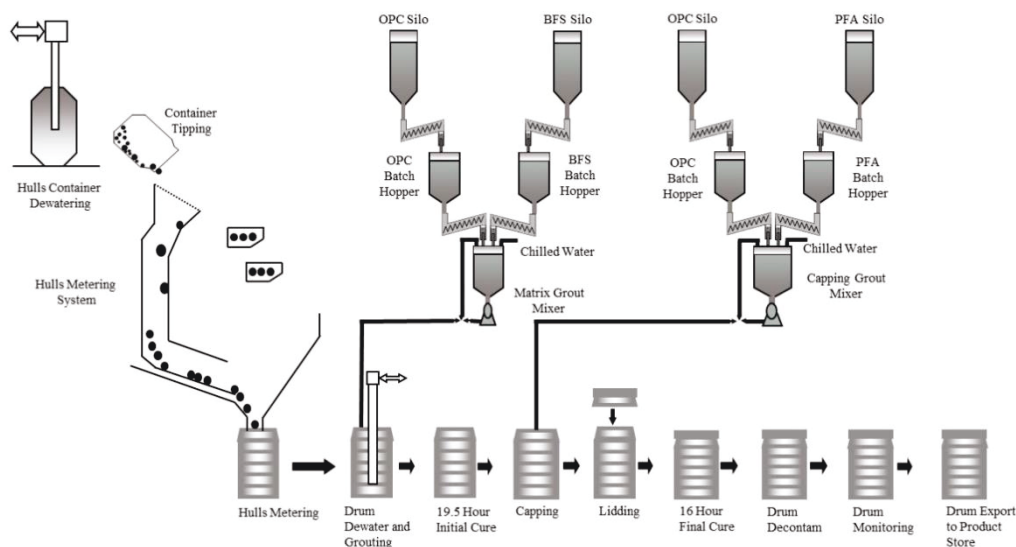
A mixture of Ordinary Portland Cement (OPC), Blast Furnace Slag (BFS) and chilled water are then added and a vibro-encapsulation process is used to minimize any voidage within the drum. The grout is then left to cure for approximately 20 hours. The mixture of OPC and BFS is used to optimize the strength and porosity of the product whilst preventing unacceptable heats of reaction and thermal stressing of the grouted product.

Following curing of the grout, a grout cap of OPC, Pulverized Fly Ash (PFA) and chilled water is then used to encapsulate the grouted waste within the container. The cap grout is then left to cure for approximately 20 hours and then the container is moved to a shielded interim storage facility on the Sellafield site.

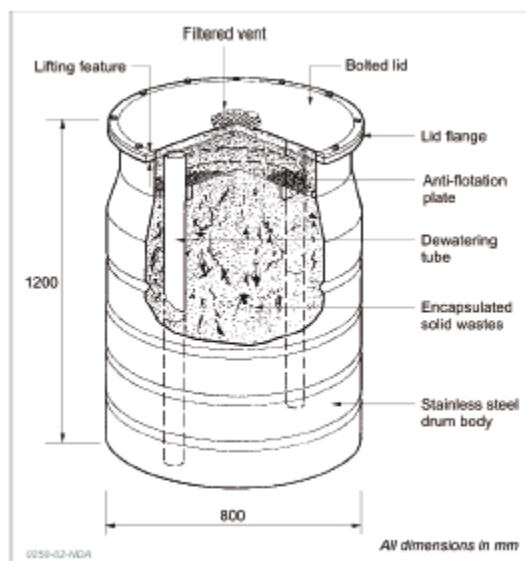
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A schematic of the WEP process for encapsulating solids and a diagram of a 500 liter drum containing hulls is shown in Figure 23 and Figure 24 below.



*Figure 23. Overview Of The Solid Waste Encapsulation Process (Hulls and Ends Grouting Process) Used At The Waste Encapsulation Plant (WEP), Sellafield, UK.*



*Figure 24. Encapsulated Solid Waste Drum From Hulls Encapsulation At The Waste Encapsulation Plant (WEP), Sellafield, UK.*

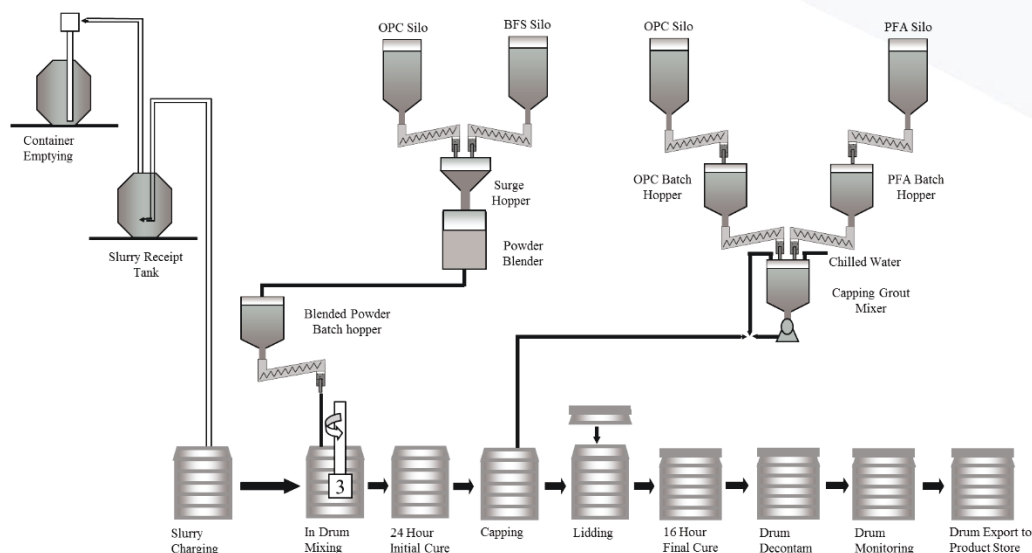
For slurries, a slightly different process is adopted, where the waste within the SWEF container is emptied via a slurry receipt tank prior to being transferred to the 500 liter product drum. Another difference in the process, is that in-drum mixing is used to

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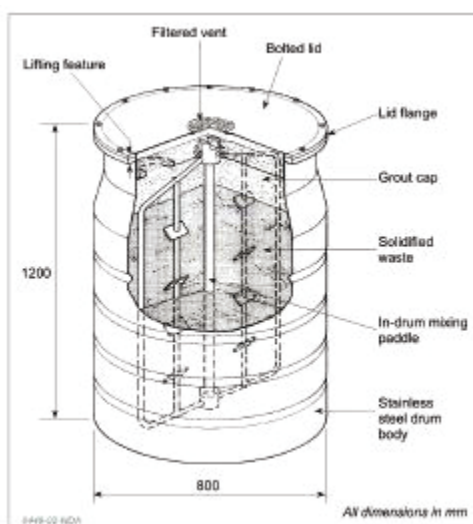


homogenize the grout and the waste stream using a sacrificial paddle which remains in the drum.

A schematic of the WEP process for encapsulating slurry waste streams and a diagram of a 500 liter drum containing slurry wastes is shown in Figure 25 and Figure 26 below.



*Figure 25. Overview of the Slurry Encapsulation Process (Slurry In-Drum Mix Process) Used At the Waste Encapsulation Plant (WEP), Sellafield, UK.*



*Figure 26. Encapsulated Solid Waste Drum From Slurry Encapsulation Used At The Waste Encapsulation Plant (WEP), Sellafield, UK (Ref 258).*

### 6.3.1.2. Sellafield - Magnox Encapsulation Plant (MEP)

The Sellafield Magnox Encapsulation Plant (MEP) was constructed to treat ILW arising from the reprocessing of Magnox spent fuel. The majority of the waste routed to MEP is the cladding of the Magnox fuel, known as swarf, this is a magnesium alloy containing small quantities of aluminum, iron and beryllium. Small quantities of uranium metal may also be present in the swarf. In a process similar to the WEP hulls encapsulation process, the Magnox swarf is encapsulated in a grout consisting of OPC and BFS in a 500 liter drum and the waste and grout are mixed using vibro encapsulation. Following curing a capping grout of OPC and PFA are added to the drum and the drum is subsequently lidded and stored.

Due to the reactive nature of Magnox swarf with water, the grouting process is carried out in the presence of an inert gas to minimize operational issues.

The MEP facility has been operational since 1990.

A schematic of the MEP process is shown in Figure 27 below.

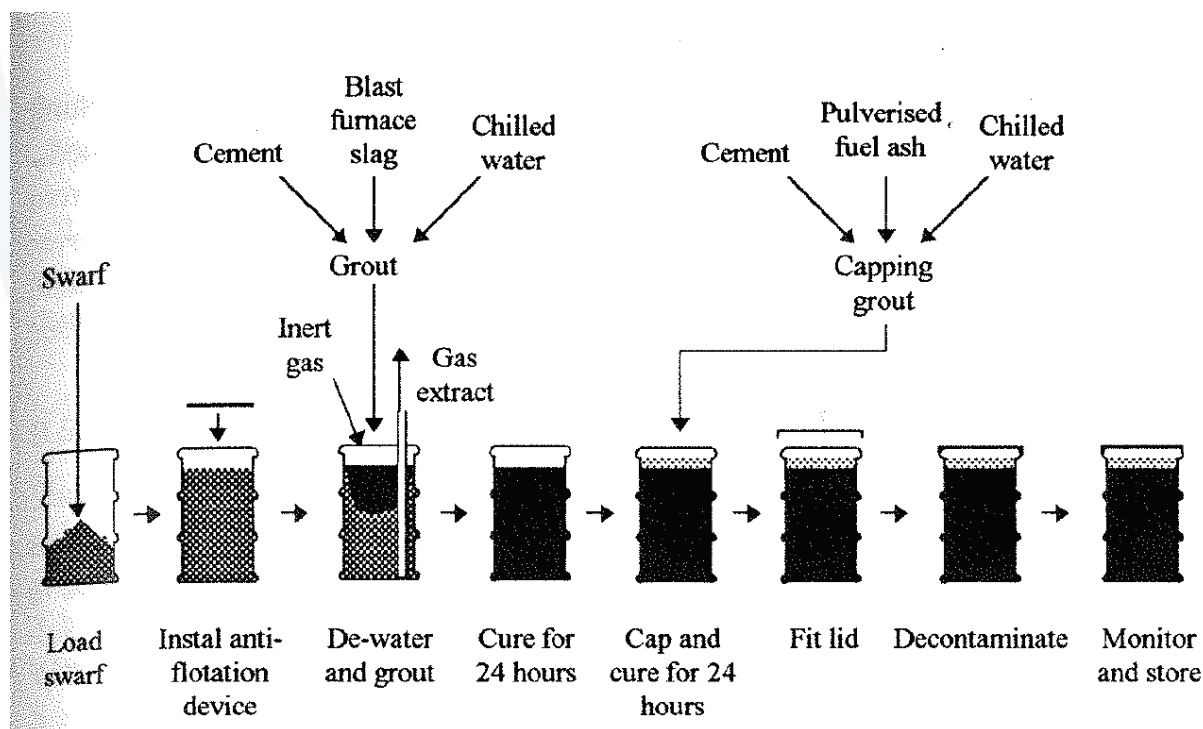


Figure 27. Overview of the Encapsulation Process Used At MEP, Sellafield, UK (Ref 255).

### 6.3.1.3. Sellafield - Waste Packaging and Encapsulation Plant (WPEP)

The Waste Packaging and Encapsulation Plant (WPEP) treats ILW waste streams arising from the Enhanced Actinide Removal Plant (EARP) at Sellafield. This is predominantly ferric floc containing various alpha nuclides in an aqueous solution. Prior to grouting the ferric floc is reacted with a conditioning agent to ensure that a satisfactory encapsulated



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product can be achieved. Following this step the process used in WPEP is essentially the same as that used in WEP slurry line.

WPEP has been in active operations in 1993.

#### 6.3.1.4. Sellafield - Waste Packaging Building

Intermediate and Low-Level waste arising from the decommissioning and dismantling of the Windscale Advanced Gas Reactor (WAGR) at Sellafield was handled through a grouting plant which was constructed in a cell adjacent to the reactor decommissioning cell.

The ILW was placed in to a 2.2m x 2.2m x 2.4m reinforced concrete shielded container, known as WAGR boxes. The dimensions of the container were chosen to avoid the need to size reduce reactor thermal shields and graphite blocks in situ (Ref 259). The type of shielding concrete used depends upon the activity of the wastes to be contained with higher density concrete being used for higher activity wastes.

Once the WAGR box is loaded with ILW this is pumped full of grout, although no agitation is applied to minimize voidage. A reinforced concrete lid is then cast on the top of the box to complete the package (Ref 259).

A diagram of the Waste Packaging Building is shown in Figure 28 and a diagram of the WAGR boxes used is shown in Figure 29.

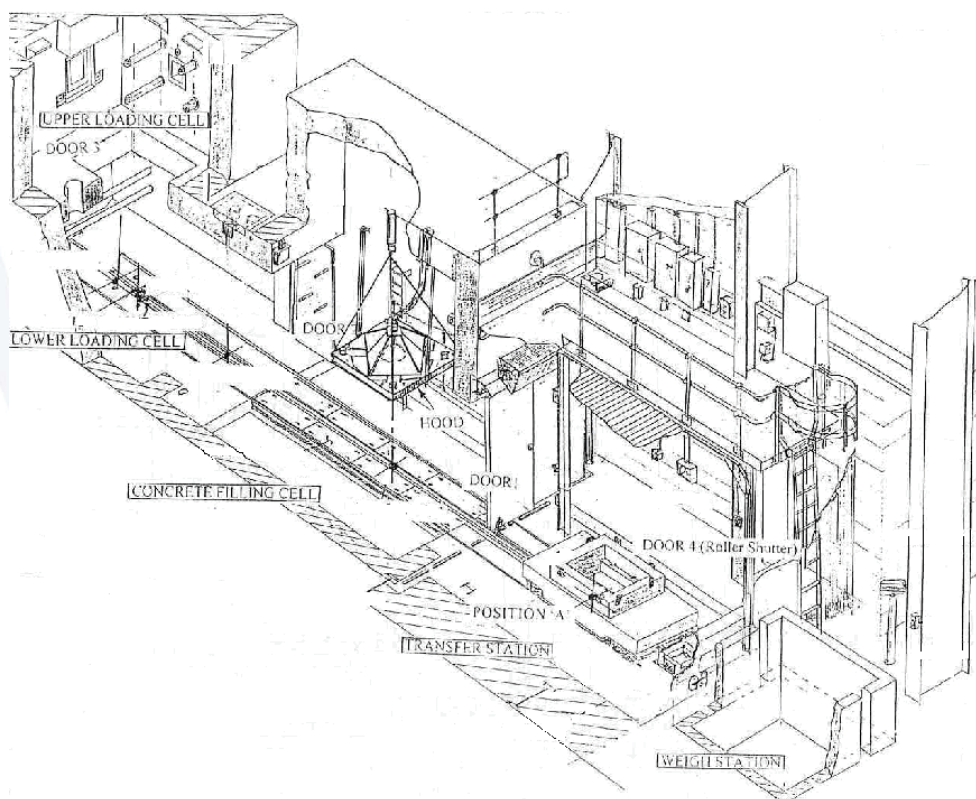


Figure 28. Overview of the WAGR Waste Packaging Building, Sellafield, UK (Ref 259).



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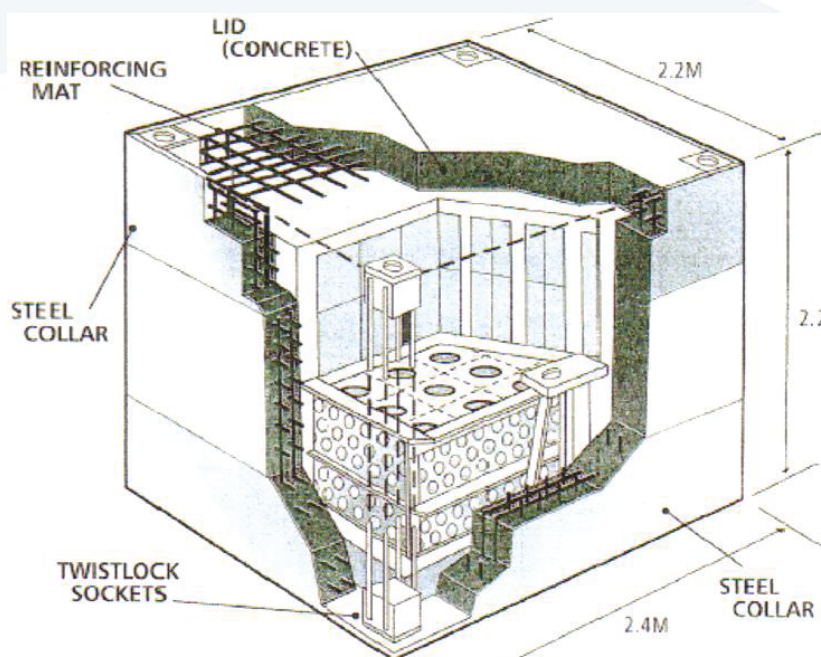


Figure 29. Diagram of the WAGR box (ILW container) (Ref 259).

#### 6.3.1.5. Sellafield - Box Encapsulation Plant (BEP)

Sellafield has proposed a large scale encapsulation plant for the encapsulation of large items of ILW in grout. This plant is in the design and build phase.

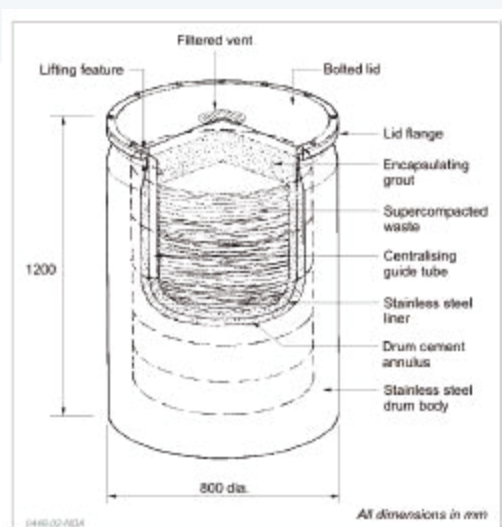
#### 6.3.1.6. Sellafield - Waste Treatment Complex (WTC)

The Waste Treatment Complex (WTC) handles plutonium contaminated material (PCM) from operations on the Sellafield site. This waste stream comprises of miscellaneous items such as PVC gloves and protective clothing, filters, small items of plant, tools, lab equipment and packaging cans. In the UK, PCM waste is material which is significantly contaminated with plutonium and has alpha activity in excess of the 4 GBq/te limit for LLW disposal. Typically PCM waste is segregated from other types of ILW in the UK.

Compactable PCM arrives at WTC bagged in PVC and contained within 200 liter mild steel sacrificial drums. These drums are then monitored to confirm their fissile content and then super-compacted into pucks. The liquid arising as a result of super-compaction is removed from the package and treated elsewhere. Typically between 3 and 5 of these super-compacted pucks are then placed in to 500 liter drums and an encapsulating grout is used around the pucks. The 500 liter drums are then transferred to an engineered drum storage facility for interim storage on the Sellafield site.

Figure 30 below shows a cross section of the WTC package.

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*Figure 30. The Encapsulated Product Drum Used At the Waste Treatment Complex (WTC), Sellafield, UK (Ref 258).*

WTC has been operating since 1998, with an operating capacity of up to 2000 product drums per year.

### 6.3.2. Dounreay ILW Facilities

#### 6.3.2.1. Dounreay Cementation Plant

Dounreay has constructed and operated a cementation plant for the aqueous fission product raffinate arising from the reprocessing of Materials Test Reactor (MTR) and Dounreay Fast Reactor (DFR) fuel at the Dounreay site. It is also intended that the raffinate from Prototype Fast Reactor (PFR) fuel will be cemented in the same way. A case has been made that the raffinate can be re-categorized as ILW rather than HLW as the heat output from the raffinate is well below  $2 \text{ kW/m}^3$  and it is no longer considered self-heating.

At the Dounreay Cementation Plant (DCP) the acidic fission product raffinate is neutralized with sodium hydroxide, placed in a 500 liter stainless steel drum. A mix of cement powders are then added and the encapsulated raffinate is then allowed to cure before a capping grout is added and the package is sealed (Ref 261).

The 500 liter drums used are similar to those used at Sellafield for the encapsulation of ILW slurries in the WEP and WPEP facilities.

A schematic of the DCP is shown below in Figure 31.

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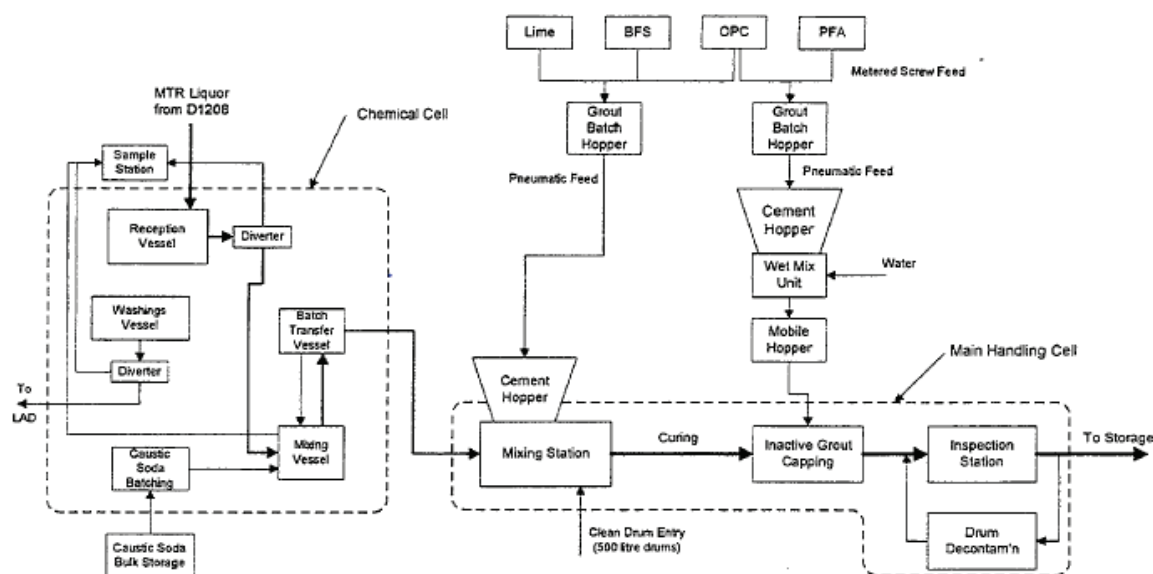


Figure 31. Overview Diagram of the Dounreay Cementation Plant (DCP), Dounreay, UK (Ref 261).

The specific cement powder formulation was evolved from an extensive programme of development work. Initially the preferred matrix materials for incorporating nitrate based wastes were a mixture of BFS and Ordinary Portland Cement (OPC) with a weight ratio of 9:1. However later work indicated that improved wasteform dimensional stability characteristics could be obtained by adding 5% lime  $\text{Ca}(\text{OH})_2$  to the cement powder formulation. Note: the particular reference that forms the specific technical basis for this work is covered by NDA IP and will form part of the next phase of work being undertaken by DBD.

### 6.3.2.2. Dounreay - Shaft & Silos Headworks Facility

This is a future planned facility for Shaft & Silo waste retrievals at Dounreay. Work is still at an early stage on this project, but the plan is to sort / segregate the wastes, size reduce individual items where necessary, encapsulate loaded drums and compact them before disposal.

### 6.3.3. ILW Treatment Facilities on Other UK Sites

#### 6.3.3.1. Harwell - Waste Encapsulation Plant

Construction of the Harwell Waste Encapsulation Plant (WEP) started in 2006 to treat the stored legacy 500 liter drums of ILW being stored in vaults on the Harwell site.

Drums entering the facility are monitored visually and for contamination and weighed in the Drum Inspection Facility (DIF). The drum is then de-lidded and the grout is added. This is allowed to cure for a minimum of 16 hours before any residual liquor is removed and a capping grout is added. The drum lid is replaced and the capping grout is allowed to cure

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for a further 16 hours before the drum is moved to the DIF. In the DIF the lid bolts are tightened and the drum is visually examined, monitored and swabbed for contamination. The drum is then moved to an interim store (Ref 257).

### 6.3.3.2. Trawsfynydd - Resin Solidification Plant

The Resin Solidification Plant operates at the former Magnox power station site of Trawsfynydd to encapsulate ion exchange resins arising from legacy reactor operations. Polymer encapsulation of ion exchange resins is in vinyl ester styrene.

Vinyl ester is fed into a shielded drum fitted with a sacrificial mixing paddle. Ion exchange resin is then added to the drum from a hopper and the contents of the drum are mixed. After addition of the promoter, the waste form is allowed to cure.

A schematic diagram of the process used at Trawsfynydd is shown in Figure 32.

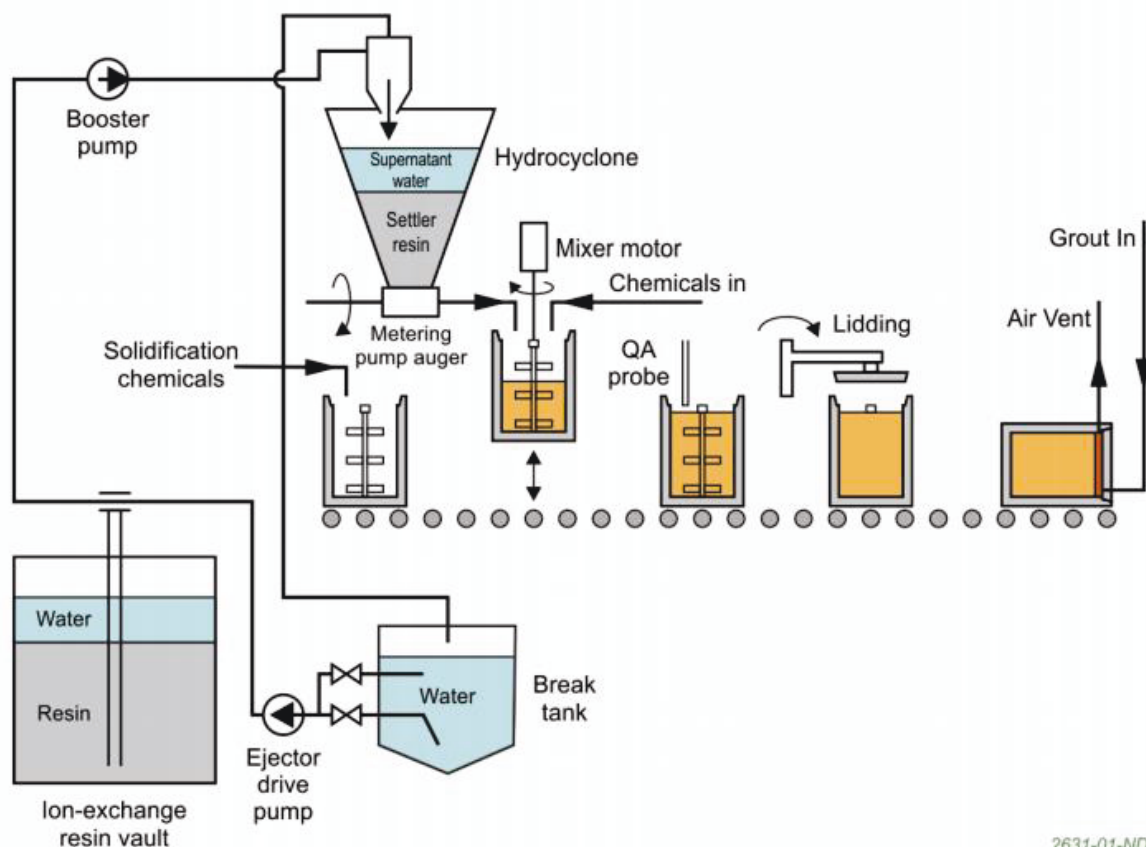


Figure 32. Overview Of The Polymer Encapsulation Process Used For Ion Exchange Materials At Trawsfynydd, UK (Ref 260).





#### 6.3.3.3. Solid Waste Conditioning in France

Broadly, France operates a range of waste conditioning and processing facilities similar to those in the UK. These are summarized below for solid VLL, LIL-SL, IL-LL & LL-LL waste (Ref 243):

- Combustible: waste shipped in metal or plastic drums, processed in the CENTRACO incineration unit and encapsulated in 450 L metal drums (disposed of at the CSFMA).
- Contaminated scrap metal: waste shipped in metal drums or boxes (2 m<sup>3</sup>, 4 m<sup>3</sup> or 8 m<sup>3</sup>), processed in the CENTRACO melting unit and the resulting 200 L ingots are disposed of at the CSFMA or CSTFA.
- Some metal scrap recycled in the form of biological shielding.
- Compactible: Compacted / collected on-site at facilities where the waste is generated (e.g. EDF NPPs, CEA facilities), transferred in 200 L metal drums to the CSFMA press for compaction and encapsulated in concrete in 450 L metal drums (depending on the radioactive level, either sent to CSFMA or kept in a store on-site at facility where generated).
- Non-compactible: conditioned in 5 m<sup>3</sup> metal boxes.
- Ion-exchange resins: encapsulation in an epoxy matrix (MERCURE process) and placed in a concrete container reinforced with a lead-tight steel liner.
- Ventilation filters: disposed of at the CSFMA or at the CSTFA.
- Other radioactive technological waste from NPPs: conditioned in concrete containers and disposed of at CSFMA.

High-Level waste is evaporated in order to concentrate it and then vitrification immobilizes the radionuclides. The technology used for vitrification in France at La Hague is very similar to that technology used at Sellafield Site in the UK, since there was a significant amount of collaboration work on establishing this as a processing method for highly radioactive waste.

#### 6.3.4. Summary

As can be seen from Section 6.2, the UK has a rich history in the development and practical application of grouting / encapsulation facilities. There is substantial relevant UK learning and experience from conditioning SSW equivalent wastes through UK facilities that could be applied to Hanford site SSW. Such relevant learning and experience covers the full range of conditioning, including the:

- Choice of conditioning methodology (e.g. cement and / or polymer encapsulation);
- Formulation of the encapsulating media (e.g. cement formulation and proportions of Ordinary Portland Cement to Pulverized Fuel Ash / Blast Furnace Slag etc.); and
- Design and operation of conditioning plants.

Broadly, France operates a range of waste conditioning and processing facilities similar to those in the UK, the learning from which may also be relevant to Hanford site SSW.



## 6.4. Radioactive Waste Storage and Disposal

This section describes the various radioactive waste storage and disposal facilities operated in the UK. The UK learning and experience from disposing of SSW equivalent wastes at such sites may be applicable and beneficial to developing the case for the disposal of SSW at the Hanford site IDF. For example, one key area, which may be of interest, is the development of performance assessment methodologies for assuring the environmental safety of near-surface disposal facilities. A brief description of the modelling approach taken during long-term radiological assessments is given for the LLWR and Dounreay LLW vaults.

### 6.4.1. Near-surface Disposal - Low-Level Waste Repository (LLWR)

As discussed previously, most UK LLW that cannot be diverted is disposed of at the Low-Level Waste Repository (LLWR) site near the village of Drigg in Cumbria (Figure 33).



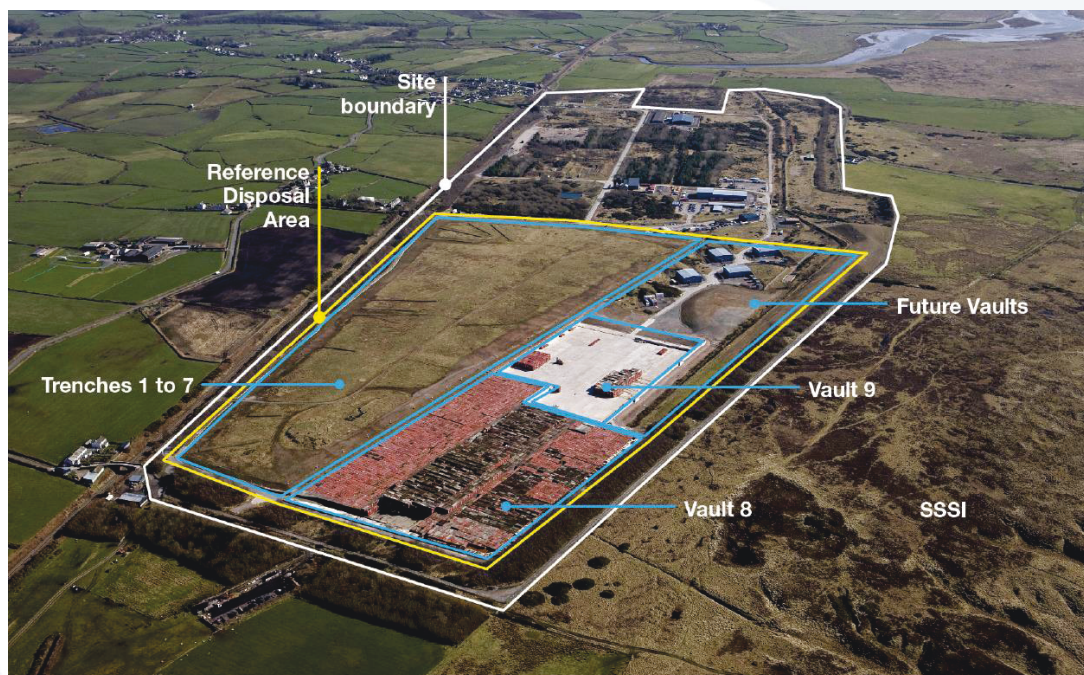
Figure 33. Location of the LLWR Site in Cumbria, UK.

The LLWR site was set up in 1957 by the UK Atomic Energy Authority (UKAEA) and disposed of LLW following the accepted practice of the time: tumble tipping waste into clay-lined trenches (without containerization) and covering with layers of soil and stone (Ref 262).

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From the late 1950s to the early 1990s waste was disposed of in a series of seven trenches. Changing industrial best practice led to these trenches being closed and they are now covered with a water resistant cap and a soil layer planted with a mixture of grasses and shrubs, providing protection from the elements and limiting the ingress of water (see Figure 34).



*Figure 34. The LLWR Site, Annotated With The Location Of The Historical Disposal Trenches And The Modern Vault System. The location of future vaults is also shown. SSSI = Site of Special Scientific Interest (Ref 262).*

In 1988 new industrial best practice led to a new approach to the treatment and disposal of LLW in the UK with the opening of 'Vault 8' (Figure 35).



*Figure 35 Vault 8 At The LLWR.*



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Vault 8 is an engineered facility for the long-term management of LLW. The vault system comprises of a concrete lined, open top vault for containerized LLW, with the vault walls and floor providing a barrier around the facility to minimize infiltration of groundwater into the waste. Vault 8 (Figure 36) was designed and constructed to contemporary 1980s standards and best practice. Performance guarantees for the vault structure were only required up until the point the vault is filled and capped. The conventional reinforced concrete structure was therefore designed for a nominal design life of 50 years.

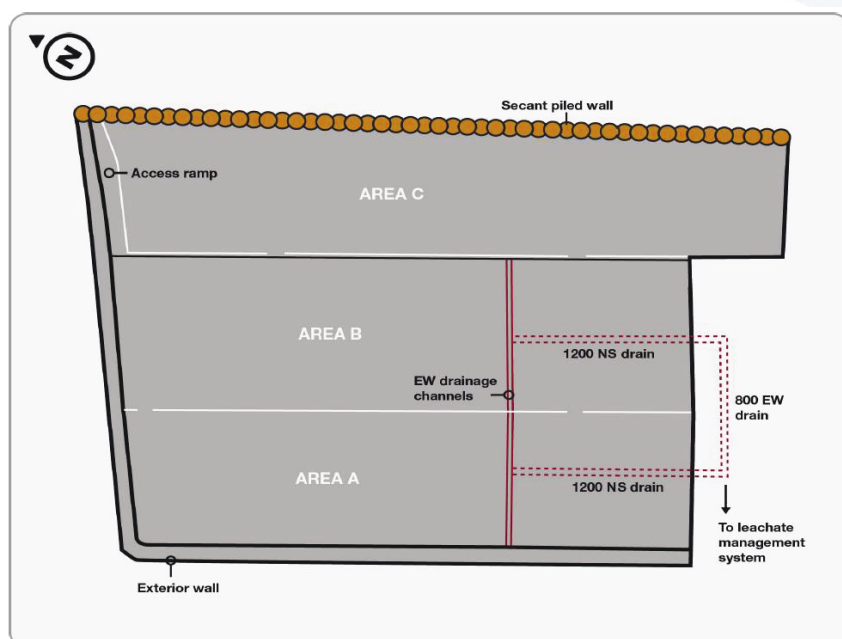


Figure 36. Vault 8 Schematic Drawing (Ref 263).

The only further engineering planned for Vault 8, prior to capping, involves filling the existing gaps between the containers with granular materials, to reduce void space and associated potential for settlement.

Commissioning of a newer vault, 'Vault 9', was finished in 2010 (Figure 37).



Figure 37. The Recently Opened Vault 9 at the LLWR (Ref 262).

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Vault 9 consists of a secant pile wall (providing structural support along one side of the vault), reinforced concrete retaining walls, a composite, layered bentonite and geomembrane liner system and a base concrete slab (Figure 38). The Vault 9 liner system also incorporates a leachate detection and collection layer.

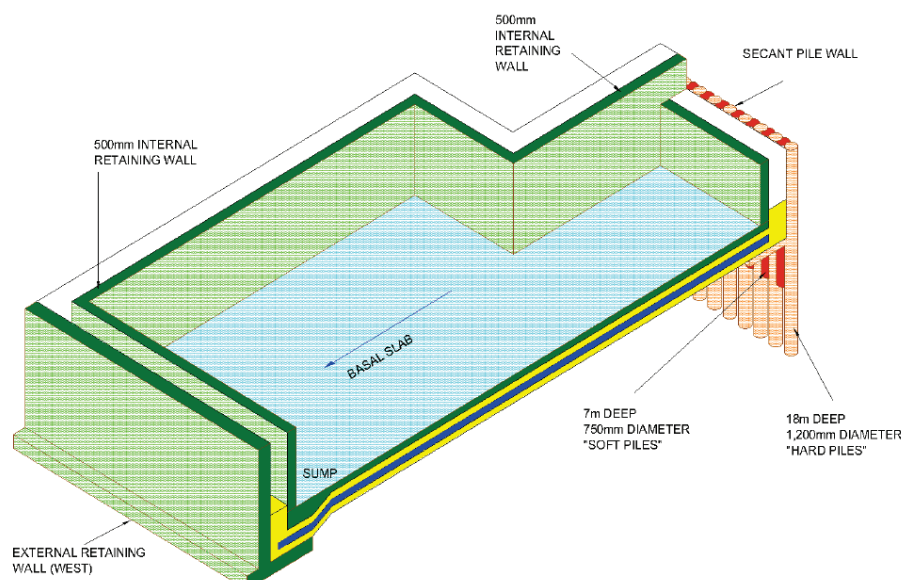


Figure 38. Vault 9 Schematic Drawing (Ref 263).

#### 6.4.1.1. Filling of the LLWR

Wastes generated throughout the UK (see Appendix F) are accepted for disposal at the LLWR only if they meet a set of stringent waste acceptance criteria (WAC) (as per Ref 264). An overview of the LLWR WAC is given in Section 4.2.1.

Waste has been accepted into the LLWR vaults since Vault 8 was commissioned in 1988. The current materials inventory for Vault 8 and the LLWR trenches (as of 31<sup>st</sup> March 2008) are shown in Table 37 in Appendix E, also included is a materials forecast inventory for future vaults (including the recently commissioned Vault 9). Although many SSW equivalents are not specifically included, an inventory of ion exchange resins and inorganic ion exchangers is included (highlighted in yellow in Table 37 shown in Appendix E. The forecast final inventory is for ~200 m<sup>3</sup> of inorganic ion exchangers and ~1,250 m<sup>3</sup>, of ion exchange resins in the LLWR vaults (Ref 265).

The key radionuclides of concern for the groundwater pathway at LLWR are H-3, C-14, Cl-36, Tc-99, I-129 and uranium isotopes. The final forecast inventory for these at the LLWR is shown Table 21. From DBD's understanding of the Hanford situation these radionuclides are also of prime importance for the disposal of SSW in the Hanford IDF (see Section 5.2). Also shown in Table 21 are radionuclides of concern for the gas generation and migration pathway (H-3, C-14 and Rn-222).

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*Table 21. Forecast Final Radionuclide Inventory For Radionuclides Of Key Importance To The Groundwater And Gas Migration Pathways At The LLWR (Ref 265).*

| Radionuclide | Inventory (TBq) |         |              | TOTAL        |
|--------------|-----------------|---------|--------------|--------------|
|              | Trenches        | Vault 8 | Vaults 9 -14 |              |
| C-14         | 0.10            | 0.08    | 4.69         | <b>4.87</b>  |
| Cl-36        | 0.02            | 0.59    | 0.25         | <b>0.86</b>  |
| Cs-137       | 16.0            | 41.6    | 80.2         | <b>137</b>   |
| H-3          | 502             | 32.6    | 37.6         | <b>572</b>   |
| I-129        | 0.003           | 0.004   | 0.01         | <b>0.02</b>  |
| Tc-99        | 0.20            | 2.81    | 11.9         | <b>14.9</b>  |
| U-232        | 0.0007          | 0.001   | 0.0006       | <b>0.002</b> |
| U-233        | 0.0003          | 0.06    | 0.02         | <b>0.08</b>  |
| U-234        | 5.88            | 0.46    | 2.70         | <b>9.04</b>  |
| U-235        | 0.28            | 0.04    | 0.13         | <b>0.45</b>  |
| U-236        | 0.02            | 0.03    | 0.01         | <b>0.06</b>  |
| U-238        | 6.70            | 0.50    | 2.59         | <b>9.79</b>  |

A wide range of other (stable) contaminants of concern are also currently disposed of to the LLWR and are forecast to be present in the final inventory. This includes potentially hazardous materials such as lead, mercury and cadmium.

#### 6.4.1.2. Hazardous / Special Wastes

There are restrictions on the consignment of hazardous/special wastes at LLWR - one of the driving factors of this is the Environmental Safety Case (Refs 262 - 269) restrictions and the coastal erosion predictions. The site modelling assumes that ISO containers will be exposed as the erosion progresses inland. Again this is a site specific factor. There have been additional restrictions placed upon certain metals - this is down to leachability and transport of metals which is taken into account in the safety case model alongside the radionuclide leachability and transport.

#### 6.4.1.3. Leaching / Groundwater pathways

The restriction upon different radionuclides (to levels below that in the LLW definition, Table 5) is based upon the site geology and hydrogeology of the LLWR site. This has modelled the transport of the radionuclides from source to exposed group. This has resulted in the limits provided in the CFA and it why there are radionuclide specific limits as some are modelled as more mobile than others. This is combined with the transport modelling of the special / hazardous materials. The performance assessment, evolution and release of key radionuclides from the LLWR post-closure are discussed below in Section 6.4.1.5.

#### 6.4.1.4. LLWR Closure

As the vaults within the LLWR are filled, any gaps between the ISO containers will be filled with a free draining granular material to reduce void space. A closed, single dome cap design has been chosen to cover the LLWR. The vault infill and the covering cap have been designed to:



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- Isolate and protect the disposed waste;
- Restrict rainfall infiltration;
- Control the release of landfill and radioactive gases from the wastes;
- Resist damage of the waste packages; and
- To perform passively without maintenance or any institutional intervention.

The domed profile will be achieved by stacking the half-height type ISO containers to a maximum of 8 high in Vault 9 and up to 9 high in Vaults 11 - 14 (Figure 39 and Figure 40).

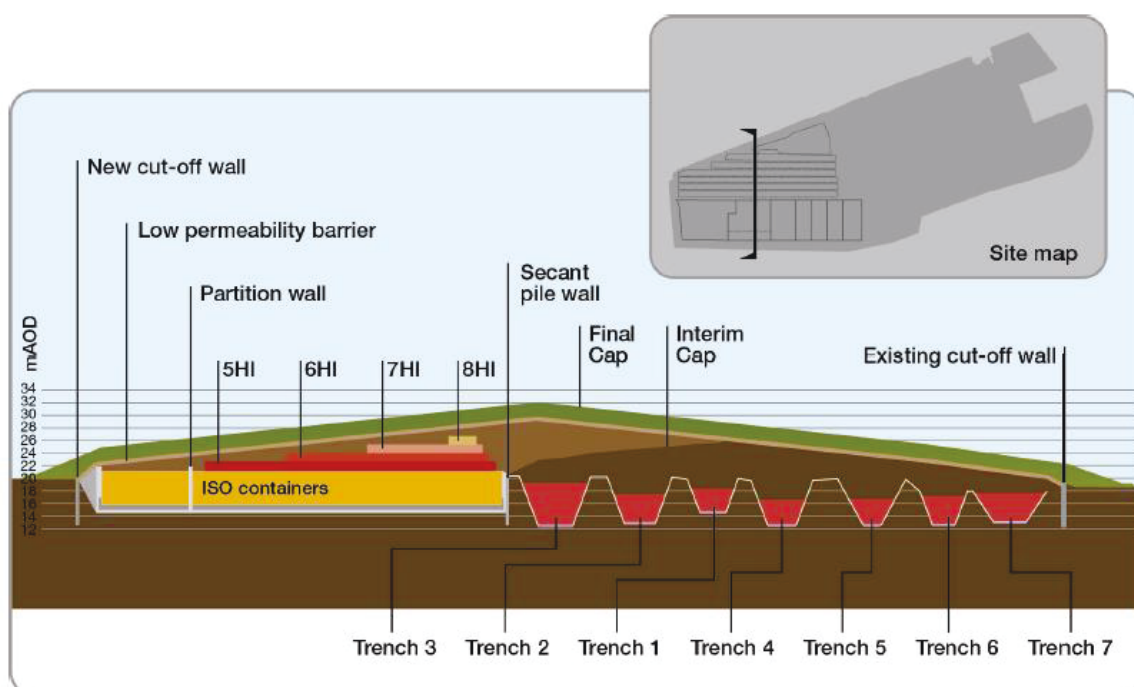


Figure 39. Profile Of The LLWR Post-Closure Through A Cross-section Of Vault 9 And The Trenches. HI = Half-Height ISO Containers, mAOD = Meters Above Ordnance Datum (Ref 263).

The cap is comprised of several specific layers including (from bottom to top) a gas collection layer, a low permeability barrier, a drainage layer, a bio-intrusion barrier, two filter layers, a moisture retention layer and a capping layer of surface soil planted with vegetation to maintain water and minimize erosion.

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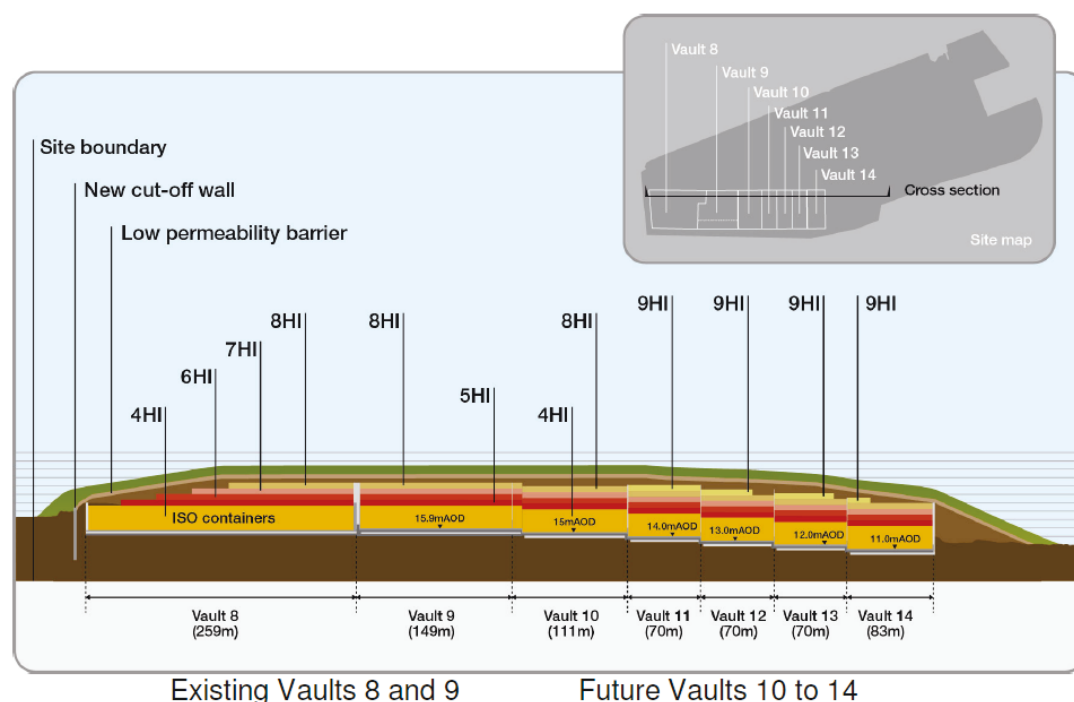


Figure 40. Profile of the LLWR Post-Closure through a Cross-section of Vaults 8 - 14. HI = half-height ISO containers, mAOD = meters above ordnance datum (Ref 263).

#### 6.4.1.5. LLWR Performance Assessment

To fulfill the performance assessment requirements of the LLWR post-closure long-term radiological assessments have been carried out. The UK learning and experience of developing such long-term radiological assessments may be of use to the development of a performance assessment methodology for the disposal of SSW equivalents in the Hanford site IDF.

The Environmental Safety Case (Refs 262 - 269) for LLWR is not straight-forward because of the emplacement of waste directly into the ground (i.e. pre-1988 disposal of LLW to the trenches) and coastal erosion of the site in the future. Hence it is important to understand the site evolution and performance and the learning from this can be applied elsewhere. To develop long-term radiological assessment the qualitative understanding of the LLWR site is continually developed. Such aspects include (Refs 266 and 267):

- Potential radiological and non-radiological hazards;
- Safety functions (e.g. isolation of the wastes, containment of contaminants and attenuation of releases); and
- The features, events and processes that provide, promote or reduce those functions.

Such qualitative understanding feeds into, and provides the basis for, quantitative modelling and assessments.

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A wide range of quantitative models and assessment methodologies have been developed for, and applied to, the performance assessment of the LLWR site post-closure. These focus on assessing the different exposure pathways by which contaminants are released, migrate and give rise to exposure. Four main exposure pathways have been identified:

1. Migration in groundwater;
2. Migration in gas;
3. Natural disruption and dispersion (e.g. coastal erosion); and
4. Human intrusion.

The exposure pathways have allowed potentially exposed groups to be identified, for example a well abstraction group for the migration in water pathway. Such potentially exposed groups receive external exposure, inhale and ingest dust, and consume contaminated products, e.g. drinking water, garden produce, marine foodstuffs, animal products etc. The following points provide a brief description of the process used to assess the groundwater migration pathway:

### 1. Conceptual Understanding

To understand the fate of radionuclides, in the post-closure period, as they are released and migrate away from the LLWR site a hydrogeological conceptual model has been developed (Figure 41).

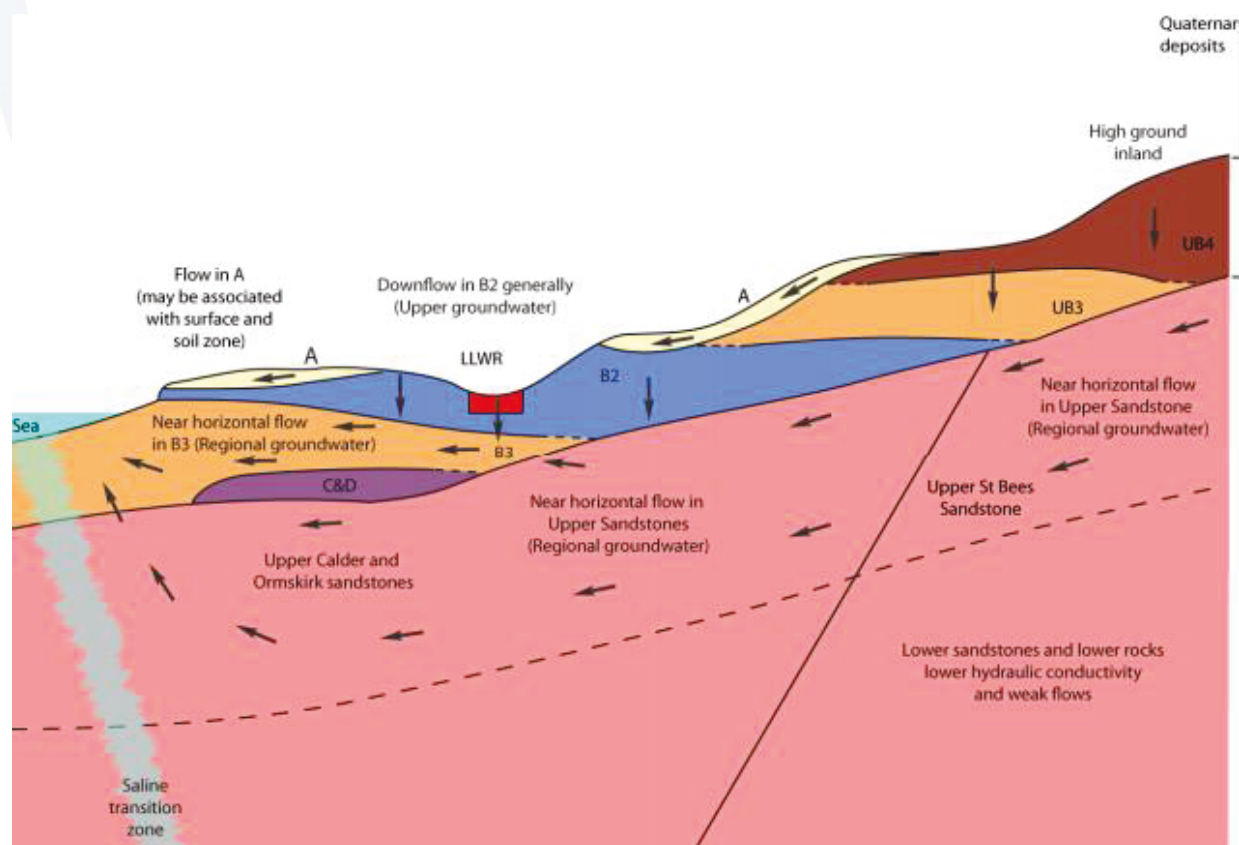


Figure 41. Hydrogeological Conceptual Model for the LLWR Site. Schematic E-W Section. Not to scale (Refs 267 and 268).



A range of lithofacies units underlies the LLWR site and an understanding of the hydrogeological behavior of these units has resulted in an understanding that groundwater paths away from the LLWR travel downwards through units B2 and B3 and then laterally in B3 to discharge in the inter-tidal region on the nearby coast.

## 2. Biogeochemical Processes

An understanding of the biogeochemical evolution of the LLWR has been undertaken using the Generalized Repository Model (GRM) (Figure 42). The GRM has also been applied to Eh, pH and gas generation modelling at Finnish and French waste sites.

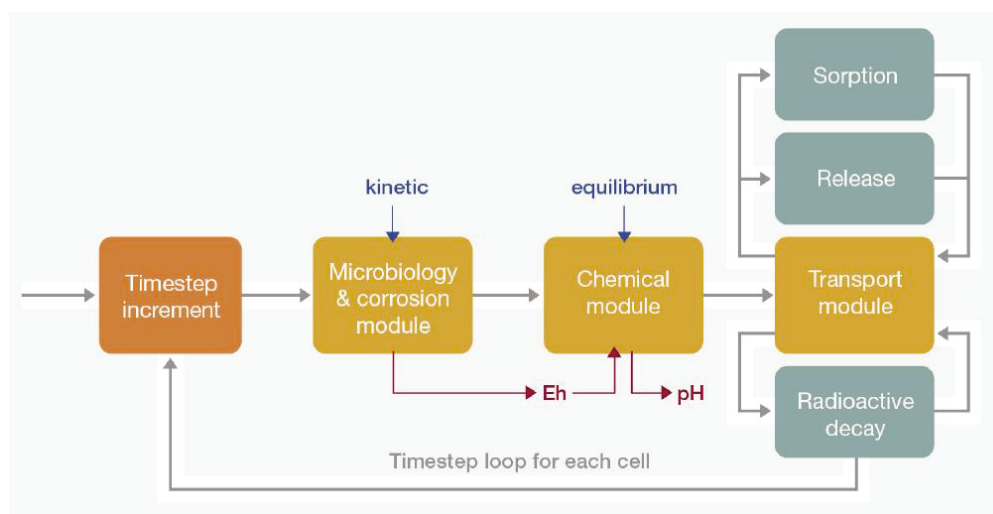


Figure 42. Flow Diagram Depiction Of The Generalized Repository Model (GRM), Used For Assessing Biogeochemical Evolution Of The LLWR (Ref 267).

The GRM has been used to investigate the chemical evolution of the ‘near field’ (the hydrogeological environment in the immediate vicinity of the LLWR). This has been used to understand the evolution of pH, C-14 partitioning and uranium and technetium speciation. These are key parameters in determining the mobility of different radionuclides. Key results for the LLWR groundwater migration pathway include confirmation that alkaline conditions will be maintained in the vaults over the period of interest (Figure 43) and a quantification of the proportion of C-14 that will be available for release into groundwater.

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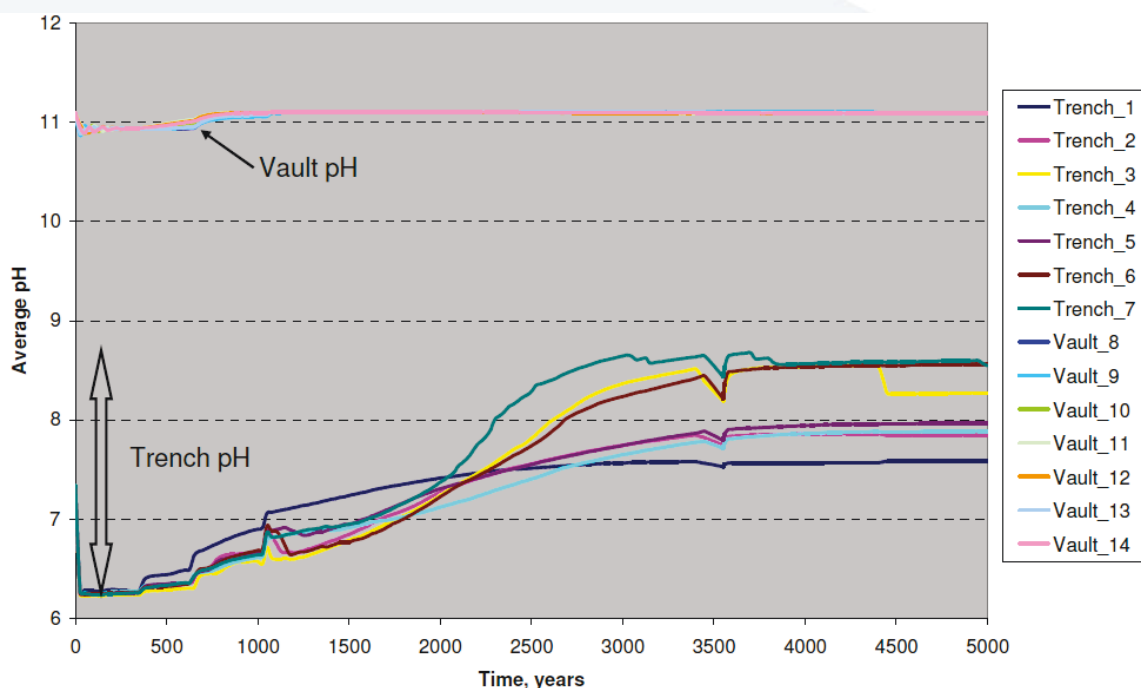


Figure 43. Evolution Of pH In the LLWR Trenches and Vaults (averaged values) (Ref 267).

### 3. Hydrogeological Modelling

A combination of finite element modelling and compartment flow modelling has been used to assess the groundwater transport of contaminants. Finite element modelling has created a 3-D groundwater flow model, which has been used to investigate detailed flows through the engineered system and the surrounding environment. An example of contaminant migration path lines is given in Figure 44.

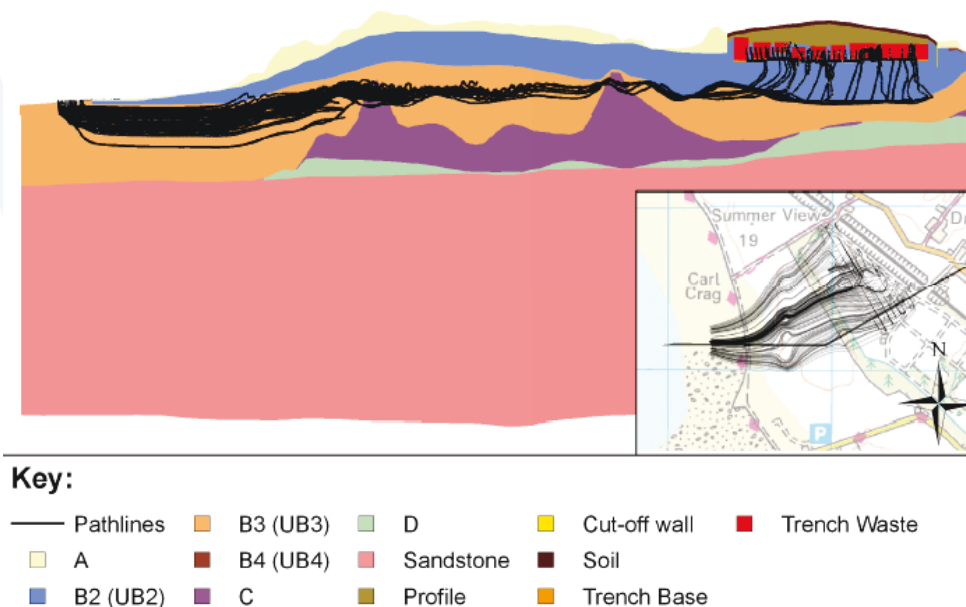


Figure 44. Section View of Path lines from Starting Positions in the LLWR Vaults & Trenches (Ref 266 and 267).





As finite element modelling is computationally intensive, compartment flow modelling has been used to compute the release and transport of radionuclides, both within and out of the repository. The model represents significant engineering features of the LLWR and the key features of the surrounding geology. The compartment flow model results indicate that solid materials in the trenches and vaults are not fully saturated, for much of the period of interest (a key finding which has implications for the release and transport of contaminants).

#### **4. Understanding Environmental Change and System Evolution**

Groundwater flows and, hence, releases of radionuclides will be influenced by climate change and coastal erosion. The aspects of climate change most important to the groundwater pathway are (Ref 269):

- Sea-level rise;
- Coastal recession; and
- Changes in precipitation and temperature.

An understanding of these has been developed and fed into both the hydrogeological modelling and development of different scenarios.

#### **5. Potentially Exposed Groups**

The key part of the modelling and assessment process is to ensure that doses to members of the public are kept as low as reasonably achievable (ALARA). This has been achieved through the use of a biosphere model, which has led to the establishment of different exposure modes and a series of potentially exposed groups (PEGs). For the groundwater migration pathway the four PEGs are the (Ref 267):

- (i) Well abstraction path - a source of drinking water and to water crops and animals;
- (ii) Marine biosphere path - consumption of marine products;
- (iii) Stream path - the farming of land adjacent to a nearby stream; and
- (iv) Estuary path - estuarine occupation and the flooding of adjacent pastureland.

The PEGs, combined with the modelled radionuclide releases along a range of pathways, have been used to generate probabilistic peak annual risks. For the groundwater pathway the peak risks are shown in Table 22.

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*Table 22. Peak Risk and Time Occurrence (by biosphere release path) For the Groundwater Release Pathway (Ref 267).*

| Biosphere Release Path | Probability of exposure to humans Peak Risk (year) | Time of Peak Risk (year) | Key Radionuclides     |
|------------------------|----------------------------------------------------|--------------------------|-----------------------|
| Well                   | 3.9 E-08                                           | 2250                     | Cl-36 / C-14 / I-129  |
| Marine                 | 1.6 E-09                                           | 2250                     | C-14                  |
| Estuary                | 1.6 E-09                                           | 2220                     | C-14                  |
| Stream                 | 5.0 E-10                                           | 3180                     | Cl-36 / Ca-41 / Mo-93 |

As can be seen in Table 22, the key radionuclides for the groundwater migration pathway are C-14, Cl-36 and I-129, with the well abstraction path presenting the highest risk.

#### 6.4.2. Near-surface Disposal - Dounreay LLW Vaults

New LLW vaults have recently been constructed at the Dounreay site (Ref 270), for the disposal of decommissioning and legacy wastes from the Dounreay site and the adjacent Vulcan defense site (see Figure 45 and Figure 46).



*Figure 45. The Recently Constructed LLW Vaults at the Dounreay site (Ref 270).*

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*Figure 46. An Interior View of One of the Recently Completed Dounreay LLW Vaults, Post-Construction (Ref 270).*

The new LLW Vaults are concrete vaults constructed so that the top of the waste is at least four meters below ground level, with the base of the vaults about 12 meters below that (Ref 271). The vaults have a roof over them while they are being filled with waste to keep rainwater out. After they are filled, the tops of the vaults will be closed off, the roofs removed, and the original ground profile reinstated through the emplacement of an engineered cap (Figure 47). Similarly to the LLWR, SSW equivalents at Dounreay will be conditioned and placed into ISO freight containers prior to emplacement in the LLW vaults (as per Section 6.2.1.2). Conditioned wastes will include both debris and non-debris SSW equivalent wastes (see Appendix F).

The waste acceptance criteria for the Dounreay LLW Vaults is the same as the LLWR for an ISO container of  $\leq 4$  GBq/tonne alpha contamination and  $\leq 12$  GBq/tonne beta-gamma contamination. Similarly to the LLWR, more specific criteria exist for long-lived radionuclides.



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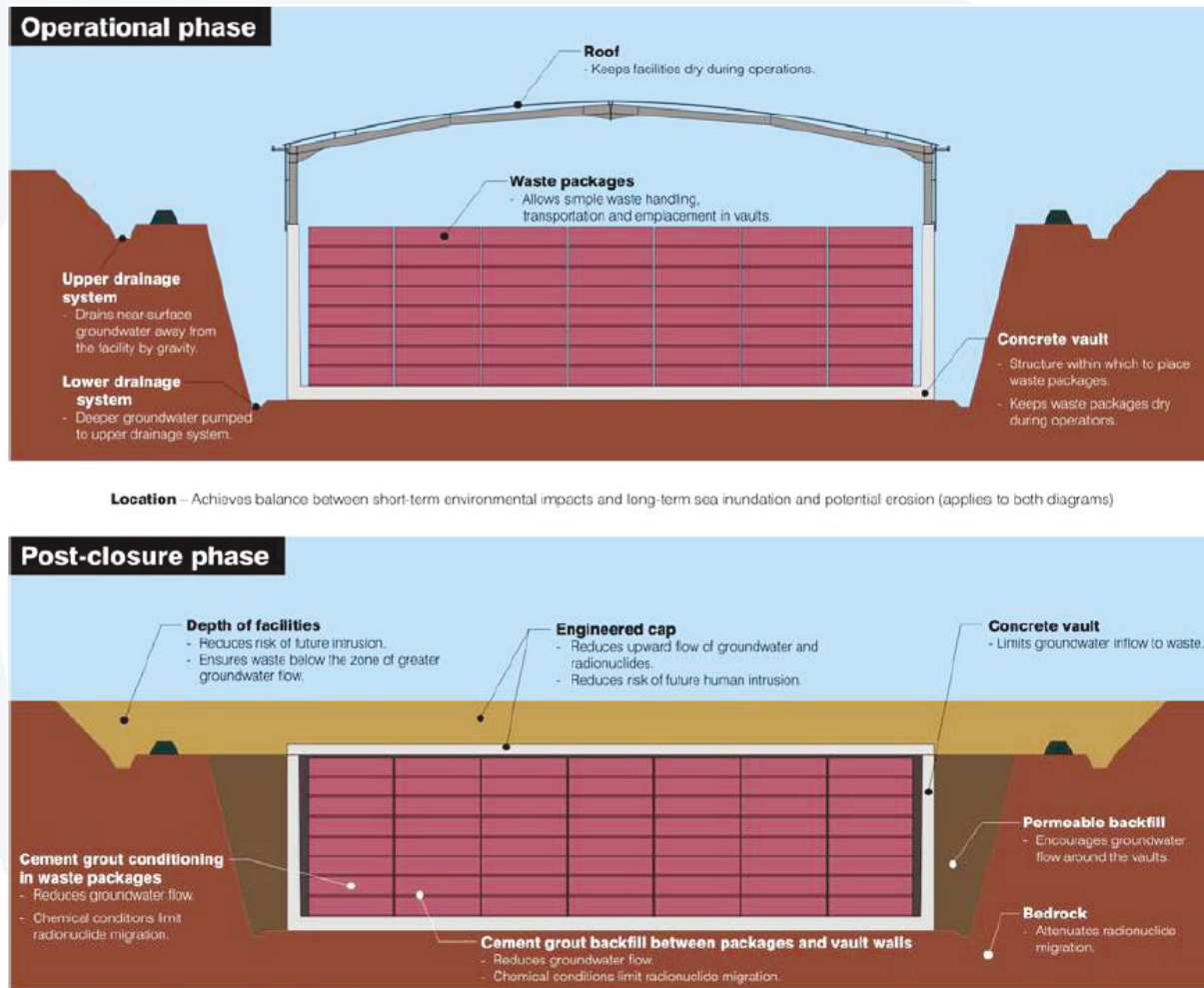


Figure 47. Schematics of the Dounreay LLW Vaults, Both during the Operational Phase and Also Post-Closure (Ref 272).

The future radionuclide inventory of the Dounreay LLW Vaults is shown in Table 38 and the materials inventory is shown in Table 39 (both tables shown in Appendix F). The Dounreay LLW inventory includes radionuclides that are present in Hanford site SSW and are of interest from a point of view of performance assessment, e.g. Tc-99, I-129.

Similarly to the LLWR, a range of modelling methodologies have been used to understand the evolution of the biogeochemical and hydrogeological environment. Such models represent both the near-field environment, i.e. immediately surrounding the closed vault, (as per Figure 48) and the far-field environment (as per Figure 49) (Ref 271).

It should be noted that the ground conditions, hydrogeology and biogeochemistry in the local area of Drigg / Dounreay are likely to be significantly wetter than those experienced at the Hanford Site. This is likely to affect comparable rates of activity migration from the site. Also for LLWR, the water table is close to the surface and the local population are very close to the site, so exposed groups are closer and the migration paths are shorter.

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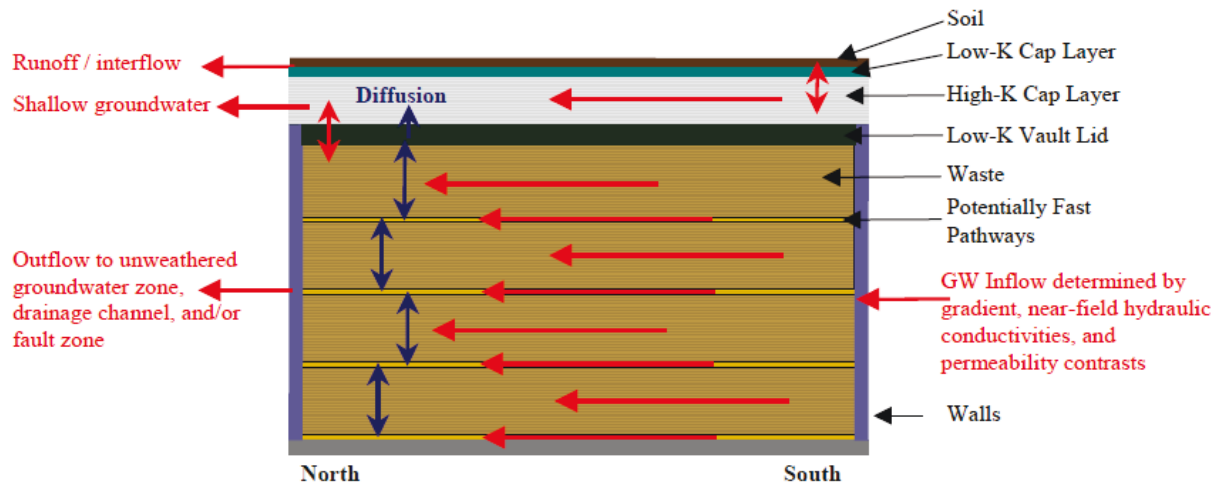


Figure 48. Schematic Representation of a Dounreay LLW Vault in a Near-field Performance Assessment Model. Red Arrows Show Advective Groundwater Flow Paths And Blue Arrows Show Diffusion Paths (Ref 271).

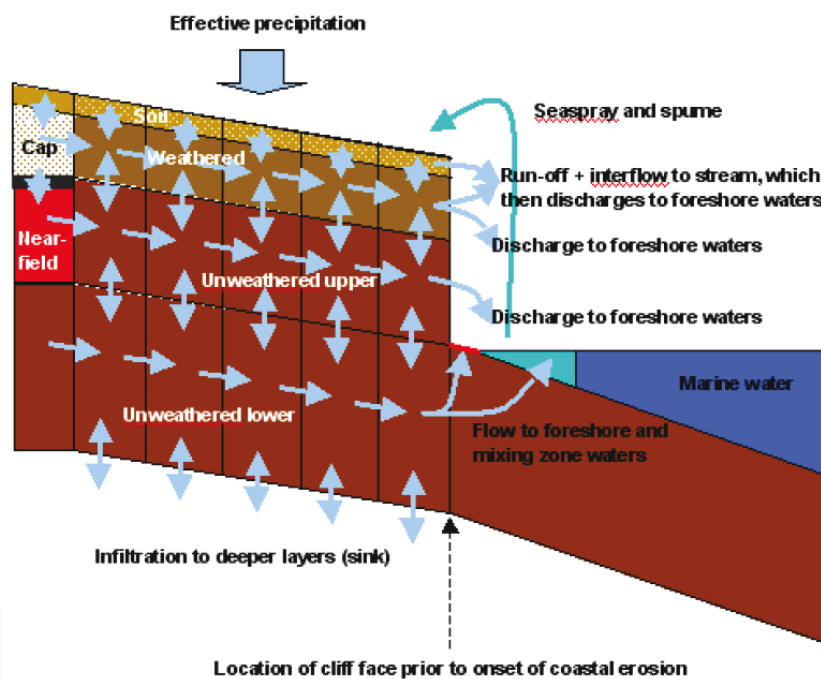


Figure 49. Geosphere Conceptual Model for the Far-Field Environment. Blue Arrows Show Water Flows between Compartments (Ref 271).

Combining the assessment of the release of radionuclides from such hydrogeological and biogeochemical models with potentially exposed groups (PEGs) enables the peak dose groups to be established over the long-term time-frame. For most scenarios, the maximum dose from the Dounreay LLW Vaults is to the 'Crofter' group (a group representing small-scale farmers). The predicted annual dose for the Crofter group peaks at ~0.01 mSv/year in the ~20,000 year time-frame (Figure 50).



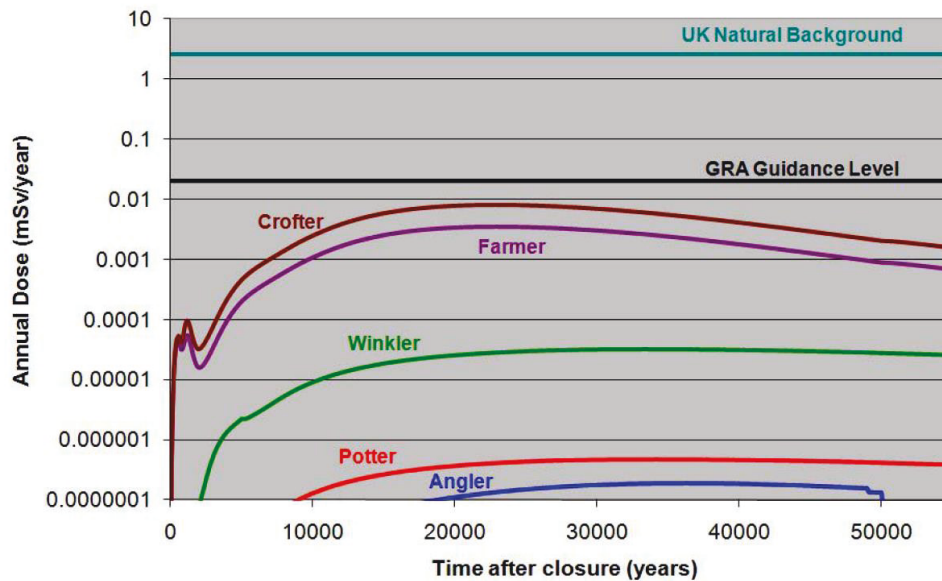


Figure 50. Calculated Annual Doses To Critical Groups During the Post-Closure of the Dounreay LLW Vaults (Ref 271).

The main radionuclides contributing to the Crofter dose are Pb-210, Po-210 and Ra-226, as a result of U-234 and its long-lived daughter Th-230, migrating through the geosphere and accumulating over very long timescales.

#### 6.4.3. Surface Storage - Interim Storage Facilities

A number of interim surface storage facilities are currently used for storing conditioned ILW and LLW unsuitable for consignment to the LLWR. Interim storage facilities are typically large shielded or unshielded facilities. Most wastes in interim storage will eventually be disposed of to a future GDF.

There are various difficulties in the design of storage facilities, for example in areas such as relating to heat loading, dose considerations, manual and automated handling and facility operability. For example, the UK has developed approaches for package performance and design, store performance and design, operation of storage systems and provision of assurance of the system over an intergenerational timescale (Ref 273).

Due to the UK's experience in the surface storage of conditioned ILW (and LLW unsuitable for near-surface disposal), there is much applicable learning and experience. Although not strictly within the remit of the SOW (Ref 2), the relevant UK learning and experience may be of relevance to the buffer storage of conditioned Hanford SSW wastes prior to IDF disposal.

The following UK nuclear sites operate surface storage facilities, storing a wide range of conditioned wastes, including SSW equivalent wastes described in Section 6.1 (Ref 274):

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#### 6.4.3.1. Sellafield

A wide range of storage facilities, including the Encapsulated Product Stores (EPS) 1-3 (for ILW), the Miscellaneous Beta Gamma Waste Stores (MBGWS), Engineered Drum Stores (EDS) 1-3 (for PCM) and the Windscale Advanced Gas-cooled Reactor (WAGR) Store (Ref 274).



*Figure 51. ILW above Ground Storage Facilities at Sellafield, Cumbria.*

#### 6.4.3.2. Magnox sites

Interim storage facilities exist at each site across the Magnox estate, including the Trawsfynydd ILW Store and the Encapsulated Resin Store (Ref 275).



*Figure 52. Polymer Encapsulated Resin Drums in Interim Storage at the Shutdown Trawsfynydd Magnox site.*



#### 6.4.3.3. Harwell & Winfrith

Intermediate-Level Waste (ILW) is already stored in an existing unit at Harwell (the Harwell Vault Store). An additional storage facility is needed to support further decommissioning activities. The new storage facility will store 400 concrete boxes of ILW and will be around 90 m in length, 30 m wide and 14 m high (Ref 276). Waste is currently stored in the 'Treated Rad-waste Store' at Winfrith (Ref 277).

#### 6.4.3.4. Dounreay

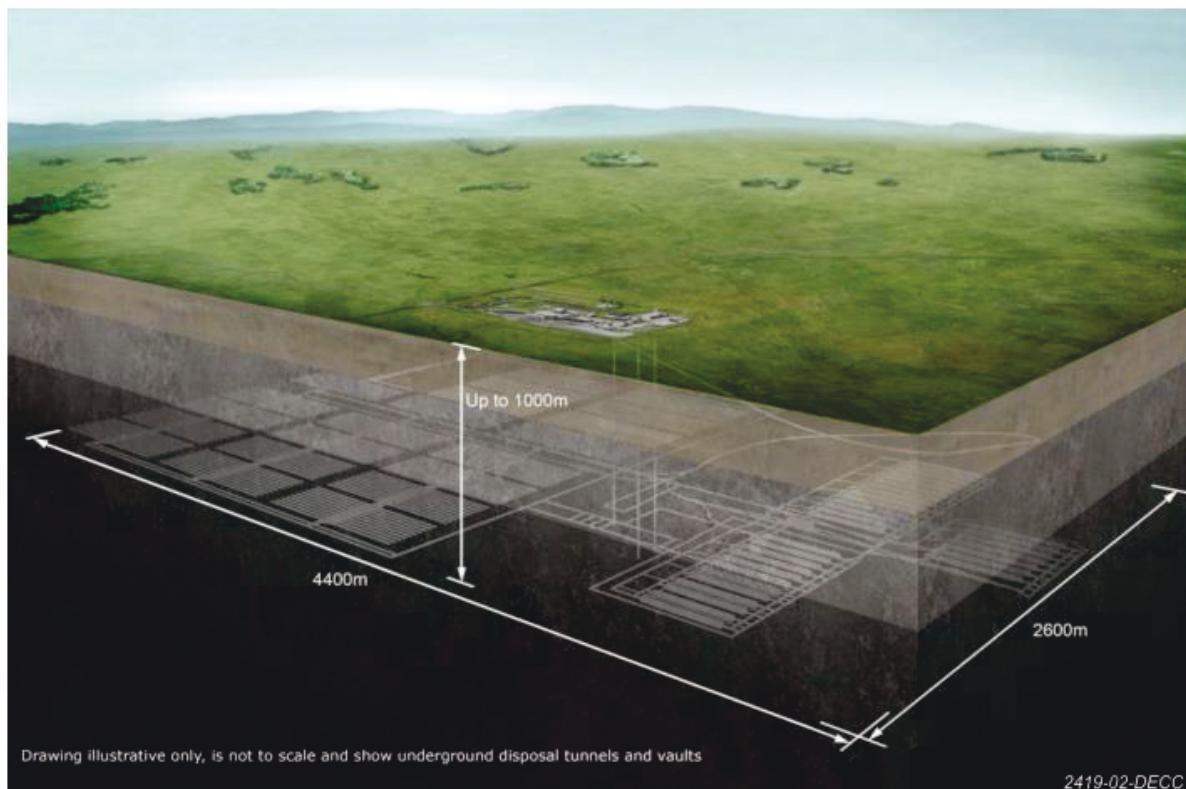
Conditioning / packaging facilities and ILW storage facilities include the Dounreay Cementation Plant (DCP) Store, Drum and Box Store, and the 4 m Box Store. The ILW arises / will arise from Dounreay decommissioning operations. DSRL will process and store a variety of solid and liquid effluents by encapsulation in cement.

ILW interim storage facilities will be required to be in use until a Geological Disposal Facility (GDF) is available.



#### 6.4.4. Deep Disposal - Geological Disposal Facility

The long-term solution for the management of conditioned ILW (and LLW unsuitable for disposal at the LLWR) is disposal of packages by final emplacement in an engineered repository (Geological Disposal Facility [GDF]) at between 200 meters and one kilometer deep in the ground (Figure 53). Although not relevant to this package of work, all HLW packages and spent fuel will also be disposed of in the GDF.



*Figure 53. Artists Impression of a Geological Disposal Facility (GDF) In the UK (Ref 278).*

A large amount of work has been undertaken in the UK with regards to developing a framework for implementing geological disposal. Of particular relevance to the disposal of Hanford site SSW, in the near-surface IDF, is the work that has been undertaken to understand package stability and durability, package leach rates and underpin the Disposability Assessment process.

One specific piece of work includes a project at Hunterston A (funded by the NDA) to look at the safety case of carrying out near-surface disposal (approximately 25 m) of ILW graphite on site. In this instance, the prime radionuclides of interest were carbon-14 and chlorine-36, with a few further activation products as well. The findings from this study can be researched further if of interest.





#### 6.4.4.1. Package Stability

The stability of waste packages and stacking is ensured by the strict controls on material types and voidage in the packages, this applies to both LLW and ILW. Any organic materials which can break down / degrade are managed and voidage is tightly controlled. This ensures that the waste form is a monolith and structurally stable without areas of internal collapse or pressurisation from decay of organic materials.

#### 6.4.4.2. Package Leach Rates

Package leach rates are related to variables such as the characteristics of the surrounding disposal environment (e.g. hydrogeology, biogeochemistry etc.) and the specific encapsulation method utilized. Common UK methods for approximating grouted product leach rates include using factors such as the encapsulated product exposure surface, solubilities and concentration differences to estimate the mass transfer of radionuclides/contaminants. If this is of interest to WRPS DBD may be able to review and convey the UK practices (i.e. sources and methods) for evaluating leach rates.

As there is no site selected for the ILW repository RWMD have made assumptions on release of radionuclides from waste packages over the full decay period. As a mitigating feature the repository backfill is part of the engineered barrier system and is designed to chemical condition the groundwater flow through the repository and retard the transport of radionuclides.

#### 6.4.4.3. Disposability Assessment Process

Conditioned wastes for disposal to a GDF are required to meet the requirements of the Generic Waste Package Specifications (GWPS) (Refs 279 and 280). The GWPS defines and describes the packaging standards and specifications and is used in the UK as the basis for the packaging of ILW and LLW not suitable for the LLWR.

An underlying principle behind the GWPS is for radioactive wastes to be packaged in a passively safe form. As can be seen from Section 6.2, this is usually achieved through the immobilization of the waste in a cementitious waste form, either through the encapsulation of larger, solid waste items or the incorporation of smaller items, sludge or liquid waste into the cement matrix. In all such cement conditioning cases, it is necessary to develop a tailored cement formulation to ensure that the particular physical and chemical properties of the waste can be accommodated and the resulting properties of the waste form are satisfactory.

To ensure that waste packages will be compliant with the GWPS, the Disposability Assessment process (Ref 281) is undertaken to show that packaged wastes will be compatible with plans for transportation and emplacement in the planned future geological repository. A Letter of Compliance (LoC) (Ref 282) is issued for each specific design of waste package which has been shown to be disposable by way of the Disposability Assessment process. The process has multiple stages where the applicant must demonstrate compliance at each stage in an increasing level of detail.



#### 6.4.5. Waste Storage and Disposal in Europe (France)

France has storage facilities for radioactive waste and three permanent surface disposal facilities for radioactive waste: two for low-level and intermediate-level short-lived waste (one in its post-operation monitoring stage and one in service) and one for very-low-level waste (Ref 20). Currently under construction is the conditioning and storage facility for activated waste (ICEDA) storage facility for the intermediate-level long-lived waste of EDF, as well a deep geological repository for intermediate-level long-lived and high-level waste and a sub-surface disposal facility for low-level long-lived waste (Ref 243).

| Activity \ Half Life    | Very Short Half-Life<br>(< 100 Days) | Short Half-Life<br>(< 31 years)                                                                                                              | Long Half-Life<br>(> 31 Years)                                                                                                                                                                                                       |
|-------------------------|--------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Very-Low-Level (VLL)    | Management by<br>radioactive decay   | <b>VLL Waste</b><br>Surface disposal (at CSTFA). Some materials are recycled.<br>Activity of less than 100 Bq/g.                             |                                                                                                                                                                                                                                      |
| Low-Level (LL)          |                                      | <b>LIL-SL Waste</b><br>Surface disposal (at CSFMA facility), excluding tritiated waste and some sealed sources similar to US LLRW and UK LLW | <b>LL-LL Waste</b> <ul style="list-style-type: none"> <li>Graphite waste: temporarily stored in shut-down reactors where generated.</li> <li>Radium-bearing waste: temporarily stored on CEA's Saclay and Cadarache sites</li> </ul> |
| Intermediate-Level (IL) |                                      |                                                                                                                                              | <b>IL-LL Waste</b>                                                                                                                                                                                                                   |
| High-Level (HL)         | N/A                                  | <b>HL Waste</b><br>Stainless-steel containers kept in cooled stores at La Hague.<br>Typical activity levels: ~ 7 GBq/g.                      |                                                                                                                                                                                                                                      |

Figure 54. Summary of Solid Waste Storage and Disposal in France (compiled based on information in Reference 243).

#### 6.4.6. Summary

Section 6.4 describes UK radioactive waste storage and disposal facilities where conditioned UK SSW equivalent wastes are stored and disposed. An overview of UK near-surface disposal facilities, the LLWR and the Dounreay LLW Vaults, is given with brief descriptions of:

- The engineering design during the operational phase;
- The forecast final materials and radionuclides inventories;
- The engineering design post-closure; and
- The steps carried out to develop performance assessment methodologies, covering:
  - conceptual modelling;
  - biogeochemical modelling;
  - hydrogeological modelling;
  - developing an understanding of environmental change; and

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- assessing risks to potentially exposed groups along a range of release pathways.

The forecast final materials and radionuclide inventories for the LLWR and the Dounreay LLW Vaults demonstrate that SSW equivalent wastes are being disposed of and considered in performance assessments of UK near-surface disposal facilities. The UK learning and experience from the approaches taken during the performance assessment of near-surface disposal facilities is potentially applicable to understanding the future risk posed by SSW wastes disposed of to the HIF.

The use of surface storage facilities (known as 'stores', for interim storage) is also outlined. Although not strictly within the remit of the SOW, the relevant UK learning and experience may be of relevance to the buffer storage of conditioned Hanford SSW wastes prior to IDF disposal.

The approach the UK is taking for the disposal of conditioned ILW (and LLW unsuitable for near-surface disposal) in a Geological Disposal Facility (GDF) is indicated. An emphasis is placed on describing the aspects of GDF development that are of relevance to Hanford SSW, such as understanding package stability/durability and package leach rates, as well as the disposability assessment process.



## 6.5. Radioactive Waste Management Programs

The radioactive waste management solutions and approaches described in Sections 6.1 - 6.4 have been arrived at from a combination of 'top-down' and 'bottom up' approaches. Top down direction includes governmental policy and legislation, industry guidance and waste strategy planning, whilst 'bottom-up' development includes underpinning research and development (R&D) and industry development of best practices and solutions.

Section 6.5 briefly lists a range of UK legislative requirements, industry guidance and R&D that are relevant to the management of SSW equivalent wastes in the UK. This not only provides a context under which UK radioactive waste management takes place, but also identifies potentially applicable guidance, R&D and waste planning for the management of Hanford site SSW.

### 6.5.1. Legislation

The Environmental Permitting Regulations (EPR) 2010 require radioactive waste producers to minimize the volume and activity of waste generated on nuclear sites and dispose of solid wastes by optimized disposal routes. This is achieved through the utilization of the waste hierarchy and the application of the Best Available Techniques (BAT). The operators are required to make BAT arguments / a BAT case that radioactive wastes are disposed of via optimized routes, minimizing environmental impacts. The EPR 2010 also drive the requirement of waste disposal sites to produce Environmental Safety Cases, demonstrating the long-term environmental safety (including performance assessments) of near-surface disposal facilities.

#### 6.5.1.1. Guidance for Near-surface Disposal

The UK environmental regulators have produced requirements for near-surface disposal facilities that operators have to meet. These are described in the Environment Agency's Guidance on the Requirements for Authorization document. This consists of five Principles, fourteen top-level Requirements, and several hundred more detailed requirements that near-surface operators must meet.

#### 6.5.1.2. Guidance for Deep Disposal

The UK body charged with implementing a deep geological disposal facility (GDF) is Radioactive Waste Management Ltd who, along with predecessor organizations, have produced a series of guidance and specification on waste packages (e.g. as per Refs 279 and 280).

#### 6.5.1.3. Research and Development (R&D)

A wide range of cement encapsulation R&D has been undertaken in the UK, as well as polymer encapsulation R&D and GDF R&D (e.g. as per Ref 248). From an initial review, it appears that some of this information is not publically available, but there is potential to:

- Investigate the range of publicly available data and aggregate this into one document;



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- Investigate access to information owned by the UK's Nuclear Decommissioning Authority (NDA). DBD are experienced in providing access to such documents to international clients.

#### 6.5.1.4. Strategy

UK waste management strategy has been developed by the UK's Department for Energy and Climate Change (DECC) and the Nuclear Decommissioning Authority (NDA) for the management of solid LLW (Ref 283) and for the management of HAW (including ILW) (Ref 284). This filters down into how SSW equivalent wastes are managed on UK nuclear sites.

#### 6.5.1.5. Waste Planning

Each nuclear site in the UK is tasked with producing an Integrated Waste Strategy (IWS), which is an overarching document for the site-specific management of waste (e.g. at Sellafield and other waste generators) (e.g. as per Ref 285). Such integrated waste planning may be beneficial for the management of SSW wastes produced during DFLAW operations at Hanford site.



## 7. Review and Comparison - Hanford and UK / Europe Wastes

An initial study of US and UK acceptance criteria for near-surface disposal (and by association, the requirements of LLW in a UK context), it has been found that:

- Significant similarities exist between the regulatory and engineering approaches in the US and UK for acceptance of LLW for disposal in near surface stores. This is to be expected as the principles behind each are similar.
- As a generalization (which is reviewed in theory in Section 4.5 and shown in practice by the indicative assessment of individual components in Section 5.2):
  - Most (if not all) US Class A tend to fall within UK LLW limits;
  - Some US Class B wastes fall within the boundaries of UK LLW, but some would be categorized as UK ILW;
  - Most US Class C wastes tend to fall within the UK ILW category;
  - It is likely that all US GTCC waste would be the equivalent of UK ILW.
- However, there are variations on an isotope by isotope basis and for discrete items, so the above is a broad generalization.

From an initial review of the DFLAW SSW streams (shown in Section 5 with more detail presented in Appendix A and Appendix B), it is difficult to make a direct comparison between US Class A, Class B, with Class C and the UK LLW and ILW categories. Looking at the waste streams as a whole, along with assumed densities and the activities averaged across each stream, it appears that:

- Debris waste (HEPA filters and other maintainable items larger than 60 mm particle size) would fit in US Class B on average (but could fit in either UK LLW or ILW categories)
- Non-Debris waste (particle sizes less than 60 mm - i.e. ion exchange resins, carbon beds, silver mordenite materials) would fit in US Class A on average (and fit in the UK LLW category)

However the indicative assessment of individual waste components (discussed in Section 5.2 with the results listed in Appendix B) found that:

- Although around 70 % of all of the SSW components seem to be predicted to fall within US Class A and UK LLW categories, there could be some US Class B (about 20 % of the wastes) and some Class C items (about 10 % of the wastes) which may fall within the UK ILW category.
- Potential Class B items include some HEPA filters and other debris;
- Potential Class C items include C5 zone vent spent HEPA filters for each facility (LAW, HLW and PTF).

These results are based on an initial study using the data presented in Ref 19 and some broad assumptions. More detailed accurate data on the waste generated will allow a more

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thorough assessment of the individual waste components and where they lie within the US and UK waste classifications regulations and waste acceptance criteria for disposal facilities and hence if they are suitable for a particular disposal method (i.e. near-surface or deep geological disposal).

With the specific exception of silver mordenite, all of the solid secondary wastes forms being generated during DFLAW operations appear to have similar / equivalent waste streams, processing options and disposal routings in the UK (as detailed in Section 4.4). From a review of wastes generated by UK sites, the UK wastes which are equivalent to DFLAW SSW arise at both LLW and ILW levels.

- In terms of Debris wastes (i.e. HEPA filters and maintainable items, all larger than 60 mm) there are multiple examples in the UK of these waste types arising at both LLW and ILW levels.
- For Non-debris wastes (particle sizes less than 60 mm) there again is a range of similar LLW and ILW waste types arising in the UK

Experience and research will therefore be available for further investigation on the methods and processes used in both grouting and near-surface disposal (LLW), versus grouting and interim surface storage pending long term GDF disposal (ILW).

A wide variety of waste processing plants in the UK (and to a lesser degree, France) has been reviewed and included in this document. A detailed comparison has not been made to the proposed waste processes for DFLAW wastes since (1) this is not the focus of this document and (2) detailed information is not yet available to DBD on this point. The purpose of including this information was to highlight to WRPS the range of processes employed, so items/processes of possible interest can be picked for future investigation.

To give a wider aspect to this review, French waste generation, processing and disposition has been considered. Wastes generated in France are generally similar to those arising in the UK (due to the full fuel cycle being undertaken in France). A notable point is that silver mordenite adsorbents are used extensively in France, and further information on their disposition may be available.



## 8. Possible Future Work Packages

### 8.1. SSW Processing at Hanford

It is DBD's understanding that DFLAW operations at Hanford will generate Solid Secondary Wastes (SSWs) that will be packaged and sent to IDF (an expandable, lined landfill). These SSWs will be in a number of forms and involve various disposal options:

- Drums compacted to pucks followed by macro-encapsulation in disposal boxes - For spent HEPA filters and other debris. Note: for large equipment items it is as yet unknown whether compaction into pucks is an applicable waste route.
- Grout stabilization within drums - For spent granular activated carbon material, spent ion exchange resins and spent silver mordenite material.

All SSW that is forecast to be LLRW will be packaged and grouted (or compacted) prior to disposal at IDF. It is currently assumed that debris is encapsulated using standard disposal grout formulation.

The waste consigned to IDF must meet stringent WAC to address a number of considerations, including the need to limit potential long term waste releases that are detrimental to human health or the environment. Key contaminants include  $^{99}\text{Tc}$ ,  $^{129}\text{I}$ ,  $^{137}\text{Cs}$ , and  $^{90}\text{Sr}$ , uranium isotopes, chromium, nitrates and mercury.

*Possible future work package: DBD are not yet aware if there are any predicted operational or technical issues associated with conditioning and disposal of the range of solid secondary wastes currently being considered at WRPS. DBD would be happy to offer assistance on this point. As an example DBD could review the specific processing techniques proposed for solid waste processing at WRPS (e.g. drum compaction to pucks and grouting for HEPAs).*

### 8.2. SSW Component Waste Classification

In DBD's initial study of US and UK acceptance criteria for near-surface disposal (and by association, the requirements of LLW in a UK context), it has been found that significant similarities exist between the regulatory and engineering approaches in the US and UK for acceptance of LLW for disposal in near-surface facilities.

DBD have evaluated the various types of UK SSW waste forms, equivalent to those at the Hanford site, to determine the applicability of UK waste management practices and methodologies in the disposition of Hanford SSW. With the specific exception of silver mordenite, all of the solid secondary wastes forms being generated during DFLAW operations appear to have equivalent waste forms, processing options and disposal routings in the UK.

*Possible future work package: DBD can provide a more thorough assessment of the individual SSW components and where they lie within the US and UK waste classifications*





*regulations and waste acceptance criteria for disposal facilities and hence if they are suitable for a particular disposal method (i.e. near-surface or deep geological disposal).*

### 8.3. UK / Europe Waste Disposition Techniques

DBD have evaluated the various types of UK waste forms equivalent to those at the Hanford site and the techniques utilized at UK nuclear sites for the disposition of these waste forms.

*Possible future work packages: DBD can investigate the following to support Hanford:*

- *Techniques established at the Sellafield site, or elsewhere as appropriate, for the disposition of HEPA filter waste forms as LLW instead of ILW;*
- *Waste recycling (e.g. metals recycling) and minimization techniques;*
- *The option of implementing UK VLLW segregation and disposal techniques;*
- *The option of implementing the UK waste management hierarchy (i.e. avoid, reduce, reuse, recycle, treat, dispose);*
- *Alternatives to silver mordenite adsorption, for example explore UK techniques for scrubbing of volatiles (e.g. I / C) from offgas streams;*
- *French approaches to the conditioning and disposal of silver mordenite wastes;*

### 8.4. UK Waste (LLW / ILW) Conditioning

In order to ensure a passively safe waste form for LLW over the lifetime of a near-surface disposal facility, and the protection of exposed groups from harmful contaminants, it is necessary to ensure that the grout formulation used, has been demonstrated to be stable for both the waste stream it encapsulates, and within the environment within which it is placed (e.g. ISO container, 55 gal drum etc.). The UK has developed a number of grout formulations to condition a wide range of waste types for disposal in different environments. Some specific developments on UK grout formulations include:

- Extensive trials conducted to ensure grout formulations have low viscosity (to ensure good flow), sets with no free water, has low shrinkage (e.g. < 2%) and meets minimum compressive strength requirements of > 400 kN/m<sup>2</sup> (58psi) after 90 days (Ref 248).
- Assurance that the specific chemical composition and physical properties of the final waste form limit the release of radionuclides, even if groundwater penetration occurs;
- Research in to encapsulating spent ion exchange resin from a range of operations, including cation and anion resins, organic and inorganic resins;

The UK also conditions a range of ILW waste forms (e.g. fuel cladding, PCM, centrifuge cake, barium carbonate slurry, pond sludge, spent IX resin etc.), some of which is analogous to Hanford SSW. Some ILW waste is pre-treated to reduce water content, some items are supercompacted and others are cut up (to size reduce). ILW waste at Sellafield (and other UK nuclear sites) is conditioned for safe long-term storage by immobilizing the



waste in cement-based or polymer matrices within steel or concrete containers. France has broadly the same waste conditioning and processing facilities to those in the UK, the waste forms, conditions and disposal methodologies, (and as a result the learning for Hanford) will be similar.

**Possible future work packages:** DBD can investigate the following to support Hanford:

- *Detailed investigation of UK waste conditioning / processing approaches for specific solid secondary waste types. E.g. ion exchange resin conditioning and disposal methods to support a viable ion exchange resin disposal route at Hanford;*
- *Detailed grout formulations (for ILW and / or LLW) and any latest thinking or learning from experience (LFE);*
- *Operating procedures and processes relating to UK conditioning of waste and any latest thinking / or learning from experience (LFE);*
- *Any of the tools or processes for the range of waste conditioning approaches (for UK LLW and ILW wastes) discussed in this document.*

## 8.5. UK Waste Disposal

The design of a final disposal vault must allow for passive storage of waste materials once operational activities at the site have ceased. In addition the design should account for the local environment to ensure the long term integrity of waste packages, and the minimal (as low as achievable) effect on the near and far field environment. For example, the LLWR site at Drigg in the UK:

- Consists of an engineered, concrete-lined vault for the long term management (and disposal) of LLW. Once full, the vault will be back-filled (to fill the void space between ISO containers) and capped;
- Includes a secant wall to provide structural support, a composite bentonite clay geomembrane liner, a concrete base, a leachate detection system and a collection layer. This is to prevent leaching of contaminants in to the environment;
- Will be closed by infilling and capping (domed design) to isolate and protect the disposed waste, restrict rainfall infiltration, control the release of landfill and radioactive gases, resist damage to waste packages and perform passively;
- Will have an engineered cap (dome) comprising several layers including gas collection, low permeability barrier, drainage layer, bio-intrusion barrier, two filter layers, moisture retention layer, capping layer of surface soil and vegetation (to minimize erosion).

**Possible future work packages:** DBD can investigate the following to support Hanford:

- *UK disposal routings for equivalent Hanford site SSW (e.g. for ion exchange resins, including the specific grout or polymer formulations used);*
- *Specific chemical or isotopic inventories for UK waste disposal / storage facilities (e.g. “why is such an isotope inventory so high, and how do you cope with this”);*



- *Description of the specific design or layout of UK waste storage / disposal facilities;*
- *Further detail on the restrictions and legal requirements for UK waste storage / disposal facilities.*

## 8.6. UK Environmental Assessment for Disposal Facilities

In addition, in order to meet the full requirements for packaging, receipt, grouting and disposal of LLW, the UK assesses waste acceptance criteria that account for chemical / radionuclide inventory, final waste form type and site specific criteria (e.g. coastal erosion). Such assessments utilize BAT to demonstrate that all practicable steps have been taken to minimize the final waste form volume, and that the doses to the public are kept As Low As Reasonably Achievable. Contaminants of concern for the UK are similar to those for Hanford, ( $^3\text{H}$ ,  $^{14}\text{C}$ ,  $^{36}\text{Cl}$ ,  $^{99}\text{Tc}$ ,  $^{129}\text{I}$ , uranium isotopes, lead, mercury and cadmium).

Restrictions on LLWR inventory are in place based upon environmental assessments. Developing the environmental safety case for LLWR has not been straight-forward, because of site-specific factors (e.g. coastal erosion) and previous placement of waste directly into the ground. Restrictions upon different radionuclides are also in place based on the site geology and hydrogeology. To understand LLWRs site evolution and performance, understanding has been (and continues to be) developed by the UK. Some of the activities completed include:

- Developing a range of quantitative models and assessment methods (to assess post-closure LLWR) including migration in groundwater, migration in gas, natural disruption and dispersion (e.g. coastal erosion) and human intrusion;
- Identification of exposed groups that might be subject to dose, inhale / ingest dust and / or consume contaminated products;
- Finite element and computational flow modelling to assess the transport of radionuclides through engineered systems and the surrounding environment;
- Assessment of package leach-rates using standard UK methodologies (for example using factors such as product exposure surface area, solubility and mass transfer estimation);
- Biosphere modelling to ensure members of the public dose is kept as low as reasonable achievable;
- Probabilistic assessments to determine peak dose to exposed groups.

In addition to the work completed on the environmental case for LLWR, similar work has been carried out for the Dounreay LLW disposal facility, an area with different environmental conditions to both Drigg and Hanford.

**Possible future work packages:** DBD can investigate the following to support Hanford:



- *Stability (durability) data of grouted waste packages (either ILW or LLW - including ion exchange resins) in UK waste storage facilities and disposal facilities long term;*
- *Leachability data of grouted waste packages, the disposition and migration of radionuclides (including key, mobile radionuclides such as Tc-99) from near-surface storage / disposal facilities, and subsequent dose impacts on nearby critical groups (both predicted and measured);*
- *Utilizing the environmental modelling approaches deployed at the UK LLWR and Dounreay LLW repository that help to underpin the environmental safety cases;*
- *Compiling a BAT case for waste disposal (utilizing DBD's previous experience with international clients on this basis).*

## 9. Conclusions

This report has been written to undertake a package of assessment of the expected solid secondary waste types and processes which will arise from the new plants operated during DFLAW operation at the Hanford site.

Work has been undertaken on areas as follows:

- Comparison and contrast of activity thresholds for UK and US wastes (including acceptance limits for near-surface storage/disposal facilities etc.) - to ensure terminologies and understanding is similar, giving a firm basis for future work.
- Compare and contrast DFLAW solid secondary wastes with those arising in the UK (and Europe where appropriate) - i.e. are there equivalents generated in the UK, and are there any important similarities / differences?
- Provide a wide, summary-level review of general waste practices in the UK (and Europe where appropriate) - i.e. review types of wastes generated on UK sites, waste processing options employed, and storage/disposal solutions used. This exercise is intended to give WRPS an appreciation of the overall waste 'landscape' in the UK, with a view to allowing further, more detailed work to be undertaken on areas of interest arising from this study.

In the main, it has been shown that there are equivalent waste types in the UK for all of the anticipated Hanford wastes, with isolated exceptions (i.e. silver mordenite). There are both similarities and differences in the processing and storage of these wastes, and some of these may be of interest for future work. All of these points are highlighted and discussed within this document.

DBD have presented this information for review by WRPS, and have suggested possible areas of work for future investigation, pending further discussion and agreement with WRPS. DBD would be pleased to discuss the information in this document and how we may be able to assist WRPS further in this matter.





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## Appendix A

The information listed here provides detail on the main radionuclide / chemical contaminants within certain waste streams, to support Section 5.

*Table 23. List of Which Radionuclides and Chemicals Are Primarily Present in the Spent HEPA Filter Waste Stream (out of all of the SSW) (Ref 17).*

| Radionuclide/Chemical | Total amount in spent HEPA filter waste stream | Fraction of the amount of each chemical in HEPA waste stream compared to the amount of each chemical in all of the SSW streams in total |
|-----------------------|------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------|
| <sup>137</sup> Cs     | 1429 Ci                                        | 51%                                                                                                                                     |
| <sup>238</sup> Pu     | 1.41 Ci                                        | 69%                                                                                                                                     |
| <sup>241</sup> Am     | 2.4 Ci                                         | 71%                                                                                                                                     |
| <sup>60</sup> Co      | 60.5 Ci                                        | 63%                                                                                                                                     |
| <sup>63</sup> Ni      | 3.2 Ci                                         | 58%                                                                                                                                     |
| <sup>90</sup> Sr      | 668 Ci                                         | 66%                                                                                                                                     |
| <sup>99</sup> Tc      | 10.7 Ci                                        | 88%                                                                                                                                     |
| B                     | 82 kg                                          | 62%                                                                                                                                     |
| Ca                    | 74 kg                                          | 58%                                                                                                                                     |
| Cr                    | 259 kg                                         | 94%                                                                                                                                     |
| Hf                    | 5 kg                                           | 62%                                                                                                                                     |
| K                     | 179 kg                                         | 56%                                                                                                                                     |
| Li                    | 215 kg                                         | 92%                                                                                                                                     |
| Mg                    | 25 kg                                          | 69%                                                                                                                                     |
| Na                    | 1806 kg                                        | 41%                                                                                                                                     |
| Pb                    | 1.2 kg                                         | 61%                                                                                                                                     |
| Ti                    | 27 kg                                          | 72%                                                                                                                                     |
| Zn                    | 244 kg                                         | 87%                                                                                                                                     |
| Zr                    | 40 kg                                          | 61%                                                                                                                                     |



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Table 24. Extract From IDF Inventory For Ion Exchange Resins. (Ref 17).

| Radionuclide / Chemical | Total amount in spent ion exchange waste stream | Fraction of the amount of each chemical in IX waste stream compared to the amount of each chemical in all of the SSW streams in total |
|-------------------------|-------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------|
| <sup>3</sup> H          | 0.49 Ci                                         | 49%                                                                                                                                   |
| Al                      | 185 kg                                          | 62%                                                                                                                                   |
| As                      | 40 g                                            | 54%                                                                                                                                   |
| C                       | 123 kg                                          | 69%                                                                                                                                   |
| Ce                      | 1.8 kg                                          | 90%                                                                                                                                   |
| Cl                      | 40 kg                                           | 96%                                                                                                                                   |
| Co                      | 10 g                                            | 49%                                                                                                                                   |
| Cr(VI)                  | 15 kg                                           | 97%                                                                                                                                   |
| Mo                      | 180 g                                           | 80%                                                                                                                                   |
| N                       | 465 kg                                          | 98%                                                                                                                                   |
| Na                      | 2453 kg                                         | 55%                                                                                                                                   |
| Np                      | 220 g                                           | 94%                                                                                                                                   |
| P                       | 38 kg                                           | 75%                                                                                                                                   |
| Pd                      | 10 g                                            | 84%                                                                                                                                   |
| S                       | 49 kg                                           | 94%                                                                                                                                   |
| Sb                      | 50 g                                            | 73%                                                                                                                                   |
| Se                      | 140 g                                           | 64%                                                                                                                                   |
| W                       | 70 g                                            | 94%                                                                                                                                   |



## Appendix B

This section contains the data calculated during the waste classification assessment process for each type of Solid Secondary Waste (SSW) from the Waste Treatment and Immobilization Plant (WTP). The overall classification requirements from US and UK regulatory perspectives, are shown in the main report in Sections 4.1 and 4.2 respectively. Note the data presented in here is a summary level assessment only for initial scoping purposes only.

Calculations have been completed based on the information provided within Ref 19, specifically using what is referred to as the '10-10 SSW fractions worksheet'.

In order to obtain the results shown in Table 11, the calculations involved the following:

- The total activities (in Curies) for each radionuclide within each SSW stream was added together (for streams that contained more than one component).
- The total volumes of SSW produced over the entire mission and the final state of the waste (i.e. compacted, grouted) was taken in to consideration (information obtained from Ref 19) to calculate the average concentration of each waste stream ( $\text{Ci}/\text{m}^3$ ). The resulting concentration values calculated are shown in Table 25.
- Specific radionuclides in each waste stream were assessed against the US waste classification limits (in line with the method outlined in Section 4.1), in order to classify the waste stream as Class A, Class B or Class C.
- The concentration values were then converted to UK units ( $\text{GBq}/\text{te}$ ). This was by using the Curies to Becquerel conversion factor ( $3.7 \times 10^{10}$ ) and by considering the final form of the waste (i.e. whether it is compacted, grouted) to calculate approximate densities of each waste stream. The resulting concentration values calculated are shown in Table 26.
- Each waste stream was then assessed against the overall UK waste classification limits (as described in Section 4.2) to classify the waste as LLW or ILW (please note that a discrete item assessment against specific radionuclides was not conducted at this stage, only an assessment against the total alpha and total beta/gamma activities within the streams). In order to assess if the waste is HLW, it would be necessary to assess the decay heat, which was not provided, however, because of the types of wastes considered here, the decay heat would not be large enough to constitute it as HLW anyway.

The final results of waste classification of the overall SSW streams are shown in Table 11 in the main body of the report. The final results of the indicative waste classification for individual component assessment (based on the assumption that the total waste volume for each stream is split evenly across each waste item) are shown in Table 27.

It is also necessary to consider the levels of chemical contaminants within each waste stream and the average concentrations of these in the final waste form as these would affect the disposability of the waste. This is summarized in Table 28 presented below.

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Table 25. Average Activity Concentration, Waste in Final Form (US units - Ci/m<sup>3</sup>).

| Nuclide | DEBRIS       |              | NON-DEBRIS         |                         |                                |
|---------|--------------|--------------|--------------------|-------------------------|--------------------------------|
|         | HEPA Filters | Other Debris | Ion Exchange Resin | LAW and HLW Carbon Beds | HLW Silver Mordenite Absorbent |
| 241-Pu  | 1.60E-03     | 2.60E-05     | 4.66E-09           | 1.49E-16                | 3.27E-15                       |
| 241-Am  | 8.75E-03     | 1.09E-04     | 1.26E-04           | 2.65E-15                | 1.72E-14                       |
| 240-Pu  | 5.09E-04     | 8.09E-06     | 1.45E-09           | 4.63E-17                | 1.02E-15                       |
| 239-Pu  | 2.41E-03     | 3.83E-05     | 6.86E-09           | 2.20E-16                | 4.83E-15                       |
| 238-Pu  | 5.13E-03     | 8.07E-05     | 1.44E-08           | 4.63E-16                | 1.02E-14                       |
| 237-Np  | 9.33E-04     | 1.62E-06     | 1.92E-04           | 2.76E-15                | 1.96E-17                       |
| 129-I   | 4.01E-05     | 1.21E-08     | 1.42E-06           | 2.29E-04                | 4.29E-03                       |
| 99-Tc   | 3.89E-02     | 8.25E-06     | 1.41E-03           | 9.44E-13                | 8.72E-15                       |
| 59-Ni   | 9.29E-05     | 1.28E-06     | 8.83E-06           | 1.10E-15                | 1.93E-14                       |
| 14-C    | 7.65E-04     | 6.25E-05     | 3.00E-05           | 4.04E-04                | 3.82E-03                       |
| 137-Cs  | 5.20         | 0.141        | 0.253              | 2.60E-10                | 5.66E-09                       |
| 90-Sr   | 2.43         | 4.36E-02     | 9.26E-04           | 6.91E-11                | 1.52E-09                       |
| 63-Ni   | 1.18E-02     | 1.57E-04     | 1.08E-03           | 1.36E-13                | 2.42E-12                       |
| 60-Co   | 0.220        | 2.20E-03     | 1.79E-02           | 3.66E-13                | 8.58E-13                       |
| 3-H     | 4.68E-07     | 1.85E-05     | 4.80E-04           | 2.14E-04                | 1.94E-06                       |
| 155-Eu  | 1.52E-04     | 2.18E-06     | 4.73E-06           | 7.99E-17                | 2.65E-16                       |
| 134-Cs  | 2.11E-06     | 5.36E-08     | 9.62E-08           | 1.21E-16                | 2.63E-15                       |
| 238-U   | 9.88E-06     | 1.58E-07     | 1.35E-12           | 9.77E-19                | 2.14E-17                       |
| 236-U   | 2.32E-07     | 3.62E-09     | 4.22E-14           | 2.89E-20                | 6.34E-19                       |
| 235-U   | 4.44E-07     | 6.92E-09     | 5.04E-14           | 4.43E-20                | 9.73E-19                       |
| 234-U   | 1.14E-05     | 1.77E-07     | 1.52E-12           | 1.10E-18                | 2.42E-17                       |
| 233-U   | 6.74E-05     | 1.05E-06     | 8.76E-12           | 5.90E-18                | 1.29E-16                       |
| 154-Eu  | 6.74E-04     | 9.79E-06     | 2.13E-05           | 3.60E-16                | 1.21E-15                       |
| 152-Eu  | 2.69E-05     | 3.86E-07     | 8.40E-07           | 1.37E-17                | 3.78E-17                       |
| 135-Cs  | 6.28E-08     | 1.55E-09     | 2.72E-09           | 2.72E-18                | 5.91E-17                       |
| 126-Sn  | 6.33E-05     | 1.85E-07     | 1.43E-05           | 2.05E-16                | 2.16E-18                       |
| 79-Se   | 2.29E-04     | 2.39E-07     | 2.22E-05           | 3.74E-15                | 5.05E-15                       |

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Table 26. Average Activity Concentration, Waste in Final Form (UK units - GBq/te).

| Nuclide | DEBRIS       |              | NON-DEBRIS         |                         |                                |
|---------|--------------|--------------|--------------------|-------------------------|--------------------------------|
|         | HEPA Filters | Other Debris | Ion Exchange Resin | LAW and HLW Carbon Beds | HLW Silver Mordenite Absorbent |
| 241-Pu  | 1.62E-02     | 5.24E-04     | 1.33E-07           | 6.48E-15                | 6.15E-14                       |
| 241-Am  | 8.81E-02     | 2.19E-03     | 3.60E-03           | 1.15E-13                | 3.23E-13                       |
| 240-Pu  | 5.13E-03     | 1.63E-04     | 4.13E-08           | 2.02E-15                | 1.91E-14                       |
| 239-Pu  | 2.43E-02     | 7.71E-04     | 1.95E-07           | 9.58E-15                | 9.09E-14                       |
| 238-Pu  | 5.17E-02     | 1.63E-03     | 4.11E-07           | 2.02E-14                | 1.91E-13                       |
| 237-Np  | 9.40E-03     | 3.27E-05     | 5.48E-03           | 1.20E-13                | 3.70E-16                       |
| 129-I   | 4.04E-04     | 2.44E-07     | 4.05E-05           | 9.95E-03                | 8.07E-02                       |
| 99-Tc   | 0.392        | 1.66E-04     | 4.01E-02           | 4.11E-11                | 1.64E-13                       |
| 59-Ni   | 9.36E-04     | 2.58E-05     | 2.51E-04           | 4.77E-14                | 3.63E-13                       |
| 14-C    | 7.71E-03     | 1.26E-03     | 8.54E-04           | 1.76E-02                | 7.19E-02                       |
| 137-Cs  | 52.4         | 2.84         | 7.21               | 1.13E-08                | 1.06E-07                       |
| 90-Sr   | 24.5         | 0.879        | 2.64E-02           | 3.01E-09                | 2.86E-08                       |
| 63-Ni   | 0.119        | 3.17E-03     | 3.09E-02           | 5.94E-12                | 4.54E-11                       |
| 60-Co   | 2.22         | 4.43E-02     | 0.509              | 1.59E-11                | 1.61E-11                       |
| 3-H     | 4.71E-06     | 3.72E-04     | 1.37E-02           | 9.30E-03                | 3.64E-05                       |
| 155-Eu  | 1.53E-03     | 4.39E-05     | 1.35E-04           | 3.48E-15                | 4.98E-15                       |
| 134-Cs  | 2.12E-05     | 1.08E-06     | 2.74E-06           | 5.26E-15                | 4.96E-14                       |
| 238-U   | 9.96E-05     | 3.18E-06     | 3.84E-11           | 4.25E-17                | 4.04E-16                       |
| 236-U   | 2.34E-06     | 7.29E-08     | 1.20E-12           | 1.26E-18                | 1.19E-17                       |
| 235-U   | 4.47E-06     | 1.39E-07     | 1.43E-12           | 1.93E-18                | 1.83E-17                       |
| 234-U   | 1.15E-04     | 3.57E-06     | 4.33E-11           | 4.80E-17                | 4.55E-16                       |
| 233-U   | 6.79E-04     | 2.11E-05     | 2.49E-10           | 2.57E-16                | 2.43E-15                       |
| 154-Eu  | 6.79E-03     | 1.97E-04     | 6.05E-04           | 1.57E-14                | 2.29E-14                       |
| 152-Eu  | 2.71E-04     | 7.77E-06     | 2.39E-05           | 5.97E-16                | 7.12E-16                       |
| 135-Cs  | 6.33E-07     | 3.12E-08     | 7.74E-08           | 1.18E-16                | 1.11E-15                       |
| 126-Sn  | 6.38E-04     | 3.73E-06     | 4.07E-04           | 8.90E-15                | 4.07E-17                       |
| 79-Se   | 2.31E-03     | 4.82E-06     | 6.31E-04           | 1.63E-13                | 9.49E-14                       |



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*Table 27. Indicative Waste Classifications (US & UK equivalent) for expected Individual Waste Arisings*

| Waste Component                                                                  | Waste Type         | Debris or Non | US Class | UK Class |
|----------------------------------------------------------------------------------|--------------------|---------------|----------|----------|
| Analytical Laboratory C2 zone vent HEPA                                          | SPENT HEPA FILTERS | DEBRIS        | Class A  | LLW      |
| Low-Activity Waste Vitrification Facility C2 zone vent HEPA                      |                    |               | Class A  | LLW      |
| Analytical Laboratory C3 zone vent HEPA                                          |                    |               | Class A  | LLW      |
| Pre-Treatment Facility C2 zone vent HEPA                                         |                    |               | Class A  | LLW      |
| High-Level Waste Vitrification Facility C2 zone vent HEPA                        |                    |               | Class A  | LLW      |
| Low-Activity Waste Vitrification Facility C3 zone vent HEPA                      |                    |               | Class A  | LLW      |
| High-Level Waste Vitrification Facility C3 zone vent HEPA                        |                    |               | Class A  | LLW      |
| Pre-Treatment Facility C3 zone vent HEPA                                         |                    |               | Class A  | LLW      |
| Pre-Treatment Facility Vessel Vents HEPAs                                        |                    |               | Class A  | LLW      |
| Pre-Treatment Facility Other Vessel Vents HEPAs                                  |                    |               | Class A  | LLW      |
| Low-Activity Waste Vitrification Facility C5 zone vent HEPA                      |                    |               | Class C  | LLW      |
| Low-Activity Waste Vitrification Facility Melter Offgas HEPA                     |                    |               | Class A  | LLW      |
| High-Level Waste Vitrification Facility exhaust from power fluidic devices HEPAs |                    |               | Class B  | LLW      |
| Analytical laboratory Hotcell Prefilters                                         |                    |               | Class B  | ILW      |
| Analytical Laboratory C5 zone vent HEPA                                          |                    |               | Class B  | ILW      |
| Pre-Treatment Facility exhaust from power fluidic devices HEPAs                  |                    |               | Class B  | ILW      |
| High-Level Waste Vitrification Facility Melter Offgas HEPA                       |                    |               | Class B  | ILW      |
| Pre-Treatment Facility C5 zone vent HEPA                                         |                    |               | Class C  | ILW      |
| Pre-Treatment Facility Vessel Vents In-Bleed HEPA                                |                    |               | Class C  | ILW      |
| High-Level Waste Vitrification Facility C5 zone vent HEPA                        |                    |               | Class C  | ILW      |
| Pre-Treatment Vessel Vent Oxidizer                                               | OTHER DEBRIS       | Class A       | LLW      |          |
| Low-Active Waste facility melter offgas submerged bed scrubber (1)               |                    | Class A       | LLW      |          |
| Low-Active Waste facility melter offgas submerged bed scrubber (2)               |                    | Class A       | LLW      |          |
| Low-Active Waste facility melter offgas catalytic oxidizer                       |                    | Class A       | LLW      |          |
| Pre-Treatment Spent Resin Collection and Dewatering Slurry Pumps                 |                    | Class A       | LLW      |          |
| Low-Active Waste facility melter offgas submerged bed scrubber (3)               |                    | Class A       | LLW      |          |
| High-Level Waste Vitrification Facility Melter Offgas Catalytic Oxidizer         |                    | Class A       | LLW      |          |
| High-Level Waste Vitrification Facility Melter Offgas Catalytic Reducer          |                    | Class A       | LLW      |          |
| Low-Active Waste facility Miscellaneous Metal                                    |                    | Class A       | LLW      |          |
| Low-Active Waste facility Agitation Drives                                       |                    | Class A       | LLW      |          |
| Treated LAW Evaporation (Post IX Pre-Treatment) Recirculation Pump               |                    | Class A       | LLW      |          |
| Vessel Pump Drives                                                               |                    | Class A       | LLW      |          |

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| Waste Component                                                                   | Waste Type   | Debris or Non | US Class | UK Class |
|-----------------------------------------------------------------------------------|--------------|---------------|----------|----------|
| Low-Active Waste facility Discharge Thermal-wells                                 | OTHER DEBRIS | DEBRIS        | Class A  | LLW      |
| Low-Active Waste facility Melter Concentrate Receipt & Preparation ADS Pumps      |              |               | Class A  | LLW      |
| Low-Active Waste facility Agitator S&B                                            |              |               | Class A  | LLW      |
| Low-Active Waste facility Vessel Pumps                                            |              |               | Class A  | LLW      |
| Low-Active Waste facility Bubblers                                                |              |               | Class A  | LLW      |
| Low-Active Waste facility Level Detectors                                         |              |               | Class A  | LLW      |
| Low-Active Waste facility Glass Debris                                            |              |               | Class A  | LLW      |
| Pre-Treatment Vessel Vent High Efficiency Mist Eliminator                         |              |               | Class A  | LLW      |
| Pre-Treatment LAW Ultra-Filtration Heat Exchanger                                 |              |               | Class A  | LLW      |
| Pre-Treatment LAW Ultra-Filtration Recirculation Pumps                            |              |               | Class A  | LLW      |
| Melter Feed Recirculation Pump                                                    |              |               | Class A  | LLW      |
| Pre-Treatment facility Jumpers                                                    |              |               | Class A  | LLW      |
| Pre-Treatment facility Miscellaneous Metal                                        |              |               | Class A  | LLW      |
| Pre-Treatment Waste Feed Evaporation Feed Pump                                    |              |               | Class A  | LLW      |
| Pre-Treatment LAW Ultra-Filtration Feed Pumps                                     |              |               | Class A  | LLW      |
| Pre-Treatment Cesium Ion Exchange Feed Pumps                                      |              |               | Class A  | LLW      |
| High-Level Waste Facility Melter Concentrate Receipt & Preparation Agitator Drive |              |               | Class A  | LLW      |
| Pre-Treatment Waste Feed Evaporation Concentrate Pump                             |              |               | Class A  | LLW      |
| HLW Feed Receipt Solution Transfer Pump (Pre-Treatment facility)                  |              |               | Class A  | LLW      |
| High-Level Waste Facility Compactable Debris                                      |              |               | Class B  | LLW      |
| High-Level Waste Melter Concentrate Receipt & Preparation Pump Drive              |              |               | Class A  | LLW      |
| LAW Feed Receipt Transfer Pump (Pre-Treatment facility)                           |              |               | Class A  | LLW      |
| High-Level Waste Facility Miscellaneous Metal                                     |              |               | Class A  | LLW      |
| High-Level Waste Facility Discharge Thermal-wells                                 |              |               | Class A  | LLW      |
| High-Level Waste Facility Level Detectors                                         |              |               | Class A  | LLW      |
| High-Level Waste facility Melter Offgas High Efficiency Mist Eliminator           |              |               | Class A  | LLW      |
| LAW Ultrafiltrator (Pre-Treatment facility)                                       |              |               | Class B  | LLW      |
| High-Level Waste facility Pool Thermal-wells                                      |              |               | Class B  | LLW      |
| High-Level Waste Melter Concentrate Receipt & Preparation ADS pumps               |              |               | Class B  | LLW      |
| HLW Melter Feed Pumps                                                             |              |               | Class B  | LLW      |
| HSH L.T. Debris                                                                   |              |               | Class B  | LLW      |
| HLW Melter Concentrate Receipt & Preparation Agitator (Pre-Treatment facility)    |              |               | Class B  | LLW      |
| HLW Melter Concentrate Receipt & Preparation Feed Pumps (Pre-Treatment Facility)  |              |               | Class B  | LLW      |
| HSH Melter Debris                                                                 |              |               | Class B  | ILW      |
| High-Level Waste Facility Bubblers                                                |              |               | Class B  | ILW      |
| Cesium Ion Exchange Vessel (Pre-Treatment)                                        |              |               | Class B  | ILW      |

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| Waste Component                                                    | Waste Type       | Debris or Non | US Class | UK Class |
|--------------------------------------------------------------------|------------------|---------------|----------|----------|
| Cesium Ion Exchange (IX) Resin                                     | IX RESIN         | NON-DEBRIS    | Class A  | LLW      |
| Low-Activity Waste facility Melter Offgas Hg Adsorber carbon bed   | CARBON BED       |               | Class A  | LLW      |
| High-Level Waste Melter Offgas Carbon bed                          | CARBON BED       |               | Class A  | LLW      |
| High-Level Waste Facility Melter Offgas Silver Mordenite Adsorbent | OTHER NON-DEBRIS |               | Class A  | LLW      |

Table 28. Expected concentrations of key contaminants (uranium and chemicals) that could impact disposal

|                                                          |       | DEBRIS             |              | NON-DEBRIS               |                         |                                |
|----------------------------------------------------------|-------|--------------------|--------------|--------------------------|-------------------------|--------------------------------|
|                                                          |       | Spent HEPA Filters | Other Debris | Spent Ion Exchange Resin | LAW and HLW Carbon Beds | HLW Silver Mordenite Absorbent |
| <b>Uranium Isotopes</b><br>Units: Ci/m <sup>3</sup>      | 233-U | 4.15E-09           | 6.44E-11     | 5.39E-16                 | 3.63E-22                | 7.96E-21                       |
|                                                          | 234-U | 1.29E-09           | 2.01E-11     | 1.73E-16                 | 1.25E-22                | 2.75E-21                       |
|                                                          | 235-U | 5.25E-11           | 8.19E-13     | 5.97E-18                 | 5.25E-24                | 1.15E-22                       |
|                                                          | 236-U | 3.95E-11           | 6.16E-13     | 7.19E-18                 | 4.92E-24                | 1.08E-22                       |
|                                                          | 238-U | 1.16E-09           | 1.85E-11     | 1.58E-16                 | 1.14E-22                | 2.51E-21                       |
| <b>Contaminant Chemicals</b><br>Units: kg/m <sup>3</sup> | Cr    | 0.382              | 1.31E-04     | 5.80E-02                 | 6.38E-13                | 5.89E-12                       |
|                                                          | Hg    | 0                  | 7.57E-08     | 3.26E-05                 | 0.881                   | 7.65E-05                       |
|                                                          | Cl    | 0                  | 0.442        | 74.9                     | 2.48E-05                | 1.40E-09                       |
|                                                          | F     | 6.14E-04           | 7.00E-04     | 8.74E-02                 | 61.4                    | 10.9                           |



## Appendix C

The information presented in this section is to support Section 6.1 in the main report. It summarizes various facilities within the UK and the waste types generated at each, equivalent to Hanford SSW types.

To identify equivalent waste types to Hanford site SSW types, an analysis of the UK Radioactive Waste Inventory (UK RWI), and relevant data sheets within this, has been undertaken (Refs 22 - 2842). The SSW equivalents are documented in a series of tables in the following sections (Table 29, Table 30, Table 31, Table 32, Table 33 and Table 34). Each table briefly details the WRPS SSW equivalent wastes and the associated UK waste classifications for these waste types. Brief descriptions are given for each waste comprising of information on waste composition, key radiological and chemical contaminants and waste conditioning methodologies.

### C-1 Nuclear Fuel Manufacturing & Enrichment

The manufacture of nuclear fuels produces low and very Low-Level uranium contaminated radioactive waste. Within the UK uranium is enriched at the Capenhurst site and fuel is fabricated at the Springfields site (see Figure 7). Uranium is not mined within the UK, so there are no uranium mining facilities containing mine tailings.

#### Capenhurst Site

Urenco Ltd is engaged in uranium enrichment and uranics management at the Capenhurst site in Cheshire. The site receives natural uranium hexafluoride for  $^{235}\text{U}$  enrichment in gas centrifuge plants. Enriched uranium hexafluoride is sent to the Springfields site for conversion into uranium dioxide, which is used in the fabrication of nuclear fuel.

#### Springfields Site

The Springfields site near Preston, Lancashire, is owned by the NDA and operated by Westinghouse Electric UK Ltd. Site activities include manufacture of oxide fuels for advanced gas cooled reactors (AGR) and light water reactors (LWR), manufacture of uranium hexafluoride and its conversion, processing of residues, decommissioning and demolition of redundant plants and buildings.

Current and future radioactive wastes (equivalent to Hanford site SSW) generated during UK nuclear fuel manufacturing & enrichment are shown in Table 29.



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Table 29. Composition of SSW Equivalents from UK Nuclear Fuel Manufacturing and Enrichment Activities\*.

|                                       | Waste Composition                | LLW | ILW | Comments                                                                                                        |
|---------------------------------------|----------------------------------|-----|-----|-----------------------------------------------------------------------------------------------------------------|
| <b>Debris Waste</b><br>(>60 mm Ø)     | Used Process Equipment           | ✗   | ✓   | Uranium contaminated.                                                                                           |
|                                       | Contaminated Tools & Instruments | ✓   | ✗   |                                                                                                                 |
|                                       | HEPA Filters                     | ✗   | ✓   | HEPA filters and pre-filters used in GEVS systems. Contaminated with U.<br>LLW = Compactable Contaminated Waste |
|                                       | Other Debris Waste               | ✓   | ✓   | ILW = Magnesium fluoride filters<br>Both contaminated with U and trace Tc, Ru and Np.                           |
| <b>Non-debris Waste</b><br>(<60 mm Ø) | Granular Activated Carbon        | ✓   | ✗   | Contaminated with U and hydrogen fluoride                                                                       |
|                                       | Spent Ion Exchange Resin         | ✗   | ✗   |                                                                                                                 |
|                                       | Silver Mordenite Beds            | ✗   | ✗   |                                                                                                                 |
|                                       | Other Non-debris Waste           | ✗   | ✗   |                                                                                                                 |

\*Data in Table 29 generated from Refs 29 - 35.

## C-2 Nuclear Power Stations (Operating)

The UK has eight operating nuclear power stations (see Figure 7). One of the operating nuclear power stations is a pressurized water reactor (Sizewell B) and the others are advanced gas-cooled reactors (AGRs). Nuclear power currently generates about a fifth of the UK's electricity supply. Waste from future nuclear reactors (nuclear new build) has not been considered.

### AGR Reactor Sites

EDF Energy through its license holder company EDF Energy Nuclear Generation Ltd operates Advanced Gas-cooled Reactor (AGR) power stations at seven sites: Dungeness B in Kent, Hartlepool in County Durham, Heysham 1 and 2 in Lancashire, Hinkley Point B in Somerset, Hunterston B in Ayrshire and Torness in East Lothian.

### Sizewell B (PWR) Site

EDF Energy also operates the Sizewell B Pressurized Water Reactor (PWR) power station at Sizewell in Suffolk.

Current and future radioactive wastes (equivalent to Hanford site SSW) generated by UK operating nuclear power stations are shown in Table 30.

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Table 30. Composition Of SSW Equivalents From Operating UK Nuclear Power Stations\*.

|                                | Waste Composition                | LLW | ILW | Comments                                                                                                                                                                                                                                                                                                                                                                                                                               |
|--------------------------------|----------------------------------|-----|-----|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Debris Waste<br>(>60 mm Ø)     | Used Process Equipment           | ✗   | ✓   | Irradiated reactor components. Principally steel. For encapsulation. Activation products.                                                                                                                                                                                                                                                                                                                                              |
|                                | Contaminated Tools & Instruments | ✓   | ✓   | Contaminated metal plant items. Mixture of stainless and mild steel. For encapsulation. Mainly activation products.                                                                                                                                                                                                                                                                                                                    |
|                                | HEPA Filters                     | ✓   | ✓   | Either wooden or plastic framed. For encapsulation. Activation products, fission products and actinides.                                                                                                                                                                                                                                                                                                                               |
|                                | Other Debris Waste               | ✓   | ✓   | LLW: Compactable and non-compactable wastes, e.g. PPE. Either supercompaction, incineration or metal decontamination, followed by encapsulation (dependent on waste type).<br>ILW :<br>(1) Graphite items, for encapsulation. Mainly contaminated with activation and fission products<br>(2) Glass fiber filter cartridges (stainless steel supports). For encapsulation. Mainly activation products, fission products and actinides. |
| Non-debris Waste<br>(<60 mm Ø) | Granular Activated Carbon        | ✓   | ✓   | For gaseous iodine abatement. Potential fission product contamination.                                                                                                                                                                                                                                                                                                                                                                 |
|                                | Spent Ion Exchange Resin         | ✓   | ✓   | Proprietary ion exchange materials (some of which organic in nature), mixed with sludge, sand and water. Includes both anion and cation exchange resins. Some resins for cement encapsulation, others for dry draining and storage in ductile cast iron casks (dependent on waste stream). Contaminated with activation products, fission products and actinides.                                                                      |
|                                | Silver Mordenite                 | ✗   | ✗   |                                                                                                                                                                                                                                                                                                                                                                                                                                        |
|                                | Other Non-debris Waste           | ✓   | ✗   | (1) Silica gel exhaust gas desiccant. For encapsulation. Tritium is major contaminant.<br>(2) Alumina-platinum catalyst granules. For encapsulation. Tritium and activation products are major contaminants.                                                                                                                                                                                                                           |

\*Data in Table 30 generated from Refs 36 - 58.

### C-3 Nuclear Power Stations (Shutdown)

Eleven former nuclear power stations, based on the British Magnox design, have stopped producing electricity. The last of these was shut down in December 2015. The Magnox nuclear power stations are now being dismantled and their spent nuclear fuel removed for reprocessing. So far reasonable quantities of VLLW, in addition to LLW have been removed from the Magnox stations and treated or disposed of in facilities including the LLWR.

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## Magnox Sites

All Magnox nuclear power stations are owned by the NDA and all, apart from Calder Hall, are managed by Magnox Ltd. The ten Magnox Ltd power station sites are: Wylfa in Anglesey, Berkeley in Gloucestershire; Bradwell in Essex; Dungeness A in Kent; Hinkley Point A in Somerset, Oldbury in South Gloucestershire, Sizewell A in Suffolk, Chapelcross in Dumfries and Galloway, Hunterston A in Ayrshire and Trawsfynydd in Gwynedd. Calder Hall is managed by Sellafield Ltd. All of these stations are no longer operational and are being decommissioned. Current and future radioactive wastes (equivalent to Hanford site SSW) generated by shutdown UK nuclear power stations are shown in Table 31.

*Table 31. Composition of SSW Equivalents from Shutdown UK Nuclear Power Stations\*.*

|                                       | Waste Composition                | LLW | ILW | Comments                                                                                                                                                                                                                                                                                                                                         |
|---------------------------------------|----------------------------------|-----|-----|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <i>Debris Waste</i><br>(>60 mm Ø)     | Used Process Equipment           | ✗   | ✓   | Activated components, including steel and graphite. For encapsulation in grout. Activation products.                                                                                                                                                                                                                                             |
|                                       | Contaminated Tools & Instruments | ✓   | ✗   | Irradiated steel from fuel handling and pond operations up to 1 meter in diameter. For encapsulation. Activation products, fission products and actinides.                                                                                                                                                                                       |
|                                       | HEPA Filters                     | ✓   | ✗   | For encapsulation. Contaminated with activation products, fission products and actinides.                                                                                                                                                                                                                                                        |
|                                       | Other Debris Waste               | ✓   | ✓   | LLW: Compactable and non-compactable wastes. Either supercompaction, incineration or metal decontamination/recycling, followed by encapsulation (dependent on waste type).<br><br>ILW: Magnox and steel metal components (e.g. splitter blades, fuel element debris). Cement encapsulation. Activation products, fission products and actinides. |
| <i>Non-debris Waste</i><br>(<60 mm Ø) | Granular Activated Carbon        | ✗   | ✗   | Proprietary ion exchange materials (both organic and inorganic) mixed with iron shot, sand and cement paste/grout. Some polymer encapsulated. Mainly contaminated with fission products. Some actinide and activation product contamination.                                                                                                     |
|                                       | Spent Ion Exchange Resin         | ✗   | ✓   |                                                                                                                                                                                                                                                                                                                                                  |
|                                       | Silver Mordenite                 | ✗   | ✗   | (1) Granular exhaust desiccant (activated alumina and molecular sieve sodium aluminum silicates). For cement encapsulation <sup>9</sup> . Tritium is main contaminant.<br>(2) Sand pressure filters (sand, gravel and sludge). For encapsulation.                                                                                                |
|                                       | Other Non-debris Waste           | ✗   | ✓   |                                                                                                                                                                                                                                                                                                                                                  |

\*Data in Table 31 generated from Refs 59 - 85.

<sup>9</sup> R&D trials have been carried out on desiccant “washing” to reduce activity and carry out incineration as an alternative to disposal.

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## C-4 Nuclear Reprocessing

A large amount of the UK's radioactive waste is from reprocessing spent nuclear fuels. Reprocessing formerly took place at both Dounreay and Sellafield, but now only takes place at the Sellafield site (see Figure 7) where spent fuel from most of the UK's power stations undergoes chemical processes to recover uranium and plutonium. The majority of wastes (by volume) from the Sellafield site are related to legacy waste treatment and facility decommissioning activities.

### Sellafield Site

The Sellafield site is owned by the NDA and is operated by Sellafield Ltd. Sellafield is a complex and diverse site which includes decommissioning the UK's nuclear legacy, spent fuel storage ponds, reprocessing, waste treatment and waste storage plants. The site, which currently employs approximately 10,000 full time equivalent staff, is located on the West Cumbrian coast adjacent to the Irish Sea on the western outskirts of the Lake District National Park. Sellafield is home to the world's first commercial nuclear power station - Calder Hall (a 'Magnox' station), which generated electricity from 1956 to 2003. Three other nuclear reactors were also present on site (all now shutdown), including the two Windscale Pile reactors (defense activities) and the prototype Windscale Advanced Gas-cooled Reactor (WAGR). Today the site is home to a wide range of operations with an emphasis on the decommissioning of redundant buildings associated with early defense work, spent fuel management including Magnox and Oxide fuel reprocessing and the safe management and storage of nuclear waste.

Current and future radioactive wastes (equivalent to Hanford site SSW) generated on the Sellafield site is shown are Table 32.

*Table 32. Composition of SSW Equivalents from Sellafield Site\*.*

|                            | Waste Composition                | LLW | ILW | Comments                                                                                                                                                                                                                                                                                |
|----------------------------|----------------------------------|-----|-----|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Debris Waste<br>(>60 mm Ø) | Used Process Equipment           | ✓   | ✓   | A wide range of used process equipment, both surface contaminated and activated. For cement encapsulation. Contaminated with activation products, fission products and actinides.                                                                                                       |
|                            | Contaminated Tools & Instruments | ✓   | ✓   | A wide range of contaminated tools and instruments, both surface contaminated and activated. For cement encapsulation. Contaminated with activation products, fission products and actinides.                                                                                           |
|                            | HEPA Filters                     | ✓   | ✓   | HEPA filters from a wide range of processes. For cement encapsulation. Activation products, fission products and actinides.                                                                                                                                                             |
|                            | Other Debris Waste               | ✓   | ✓   | LLW:<br>(1) Heat exchanger lagging material. Cement encapsulation. Activation product contaminated.<br>(2) Plant decommissioning wastes. Cement encapsulation. Mainly activation products and fission products.<br>(3) Plant operational wastes, includes used PPE, redundant tools and |



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|                             | Waste Composition         | LLW | ILW | Comments                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |
|-----------------------------|---------------------------|-----|-----|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                             |                           |     |     | equipment. Cement encapsulation.<br>ILW:<br>(1) Plutonium contaminated material (PPE, filters, plant items and tools etc.). Cement encapsulation.<br>(2) Isotope cartridges, tools and instruments. Cement encapsulation. Activation products, fission products and actinides.<br>(3) Glass fiber filters (with steel surround). Fission product and actinide contaminated.<br>(4) Miscellaneous beta/gamma waste (including items contaminated with vitrification glass). Cement encapsulation for most (some ILW stored raw pending treatment in 2040). Activation products, fission products and actinides.<br>(5) Maintenance scrap. Cement encapsulation. Mainly fission products and actinides. |
|                             | Granular Activated Carbon | x   | x   | TBC - Likely to be generated from offgas sampling for volatiles (small volumes)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |
|                             | Spent Ion Exchange Resin  | x   | ✓   | Ion exchange material generated from the site ion exchange effluent treatment plant and from cleaning pond water. Clinoptilolite and sand, also zeolite (as proprietary ion exchange materials). Also a range of further proprietary ion exchange materials. For encapsulation in grout, assessment for polymer encapsulation for some ion exchange material to take place. Mainly contaminated with fission products and actinides.                                                                                                                                                                                                                                                                  |
| Non-debris Waste (<60 mm Ø) | Silver Mordenite Beds     | x   | x   |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |
|                             | Other Non-debris Waste    | x   | ✓   | (1) Fuel cladding and swarf (magnesium alloys, aluminum, stainless steel and zircaloy). Cement encapsulation. Activation products, fission products and actinides.<br>(2) Hydrocyclone solids (sands, grits and fine particles) from effluent treatment. For encapsulation. Activation products, fission products and actinides.<br>(3) Centrifuge cake. Encapsulated in cement. Activation products, fission products and actinides.                                                                                                                                                                                                                                                                 |

\*Data in Table 32 generated from Refs 86 - 126.



## C-5 Nuclear Research and Development

Nearly all of the waste from research and development (R&D) into nuclear energy is a legacy of UK Government funded programs stretching back to the 1940s. Legacy nuclear sites include the Dounreay site (fast breeder reactor research), the Harwell site and the Winfrith site. A small research reactor was operated at the Silwood Park site until 2012. Fusion research is still carried out at the Culham site. See Figure 7 for locations.

### Dounreay Site

The Dounreay site in Caithness, Scotland, is owned by the NDA and operated by Dounreay Site Restoration Ltd (DSRL). The site was the UK center for fast reactor research and development comprising three reactors, fuel reprocessing and various other fuel cycle facilities. The reactors and other facilities are no longer operational and are being decommissioned.

### Harwell and Winfrith Sites

The Harwell site in Oxfordshire and the Winfrith in Dorset are owned by the NDA and managed by Magnox Ltd. These sites carried out nuclear research and development work. All facilities, including a number of research, experimental and prototype reactors, have closed down and have either already been decommissioned or are currently being decommissioned.

Decommissioning at Harwell is currently underway, two reactors have been completely removed and the fuel has been removed from the remaining three reactors, which are now in decommissioning. More than 100 other facilities have been removed from the site and others are being decommissioned. Historic wastes are being retrieved from their existing storage locations and repackaged for longer-term storage and eventual disposal. It is expected that decommissioning will be completed by 2025.

Winfrith has had at various times, nine research and development reactors. The last operational reactor at Winfrith closed in 1995, since then the focus for the site has been on decommissioning. Decommissioning of Winfrith facilities is currently taking place and waste is being transferred off-site, with the aim of achieving an interim site end state by 2021.

### Silwood Park Site

Imperial College previously operated a small, low power research reactor (CONSORT II) at Silwood Park, Ascot in Berkshire. The reactor provided teaching and research facilities, but is now shut down and being decommissioned.

### Culham Site

The United Kingdom Atomic Energy Authority (UKAEA) manages the UK fusion research program and operates the Joint European Torus (JET) on behalf of the European Fusion Development Agreement at Culham in Oxfordshire.

Current and future radioactive wastes (equivalent to Hanford site SSW) generated on UK nuclear research and development sites are shown in Table 33.

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Table 33. Composition of SSW Equivalents from UK Nuclear Research Sites\*.

|                                | Waste Composition                | LLW | ILW | Comments                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
|--------------------------------|----------------------------------|-----|-----|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Debris Waste<br>(>60 mm Ø)     | Used Process Equipment           | ✓   | ✓   | LLW: Large plant items. Mixture of fission products, activation products and actinides, includes tritiated steel. Lead and asbestos present in some wastes. NaK present in some wastes.<br>ILW: Plant components composed of stainless and mild steel, PVC, aluminum, glass and polythene. For cement encapsulation. Activation products, fission products and actinides. Mercury, beryllium, cadmium, bismuth and asbestos present in different wastes.                                                                                                                                                                                                                                    |
|                                | Contaminated Tools & Instruments | ✓   | ✓   | LLW: Contaminated tools (stainless steel, mild steel and plastics). Cement encapsulation. Mainly actinide contamination.<br>ILW: Contaminated and activated tools and instruments (mostly composed of steel). Activation products, fission products and actinides. Lead present.                                                                                                                                                                                                                                                                                                                                                                                                            |
|                                | HEPA Filters                     | ✓   | ✓   | LLW: Ventilations system filters. For cement encapsulation. Contaminated mainly with actinides and fission products.<br>ILW: Filters (with other wastes). For compaction and cement encapsulation. Contamination with actinides, fission products and activation products.                                                                                                                                                                                                                                                                                                                                                                                                                  |
|                                | Other Debris Waste               | ✓   | ✓   | LLW: Compacted LLW, including general and soft trash, including organics, glassware and metal waste. Cement encapsulation. Activation products, fission products and actinides. Lead and asbestos present in some wastes. Trace amounts of cadmium.<br>ILW: Legacy heterogeneous debris wastes (including PVC, polythene, aluminum, stainless and mild steel). Activated reactor components, activated and contaminated fuel element debris and cladding, and contaminated redundant equipment and small tools. Some solids to be shredded and cement encapsulated. Activation products, fission products and actinides. Toxic metals present in some wastes, including lead and beryllium. |
| Non-debris Waste<br>(<60 mm Ø) | Granular Activated Carbon        | ✗   | ✗   |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |
|                                | Spent Ion Exchange Resin         | ✓   | ✓   | LLW: Inorganic ion exchange resins. Cement encapsulation. Activation products, fission products and actinides.<br>ILW: Inorganic ion exchange columns. Polymer immobilization of ion exchange material in columns, then cement encapsulation. Contaminated with Cs-137 and Sr-90.                                                                                                                                                                                                                                                                                                                                                                                                           |

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| Waste Composition      | LLW | ILW | Comments                                                                                                       |
|------------------------|-----|-----|----------------------------------------------------------------------------------------------------------------|
| Silver Mordenite Beds  | x   | x   |                                                                                                                |
| Other Non-debris Waste | x   | ✓   | ILW: Crushed graphite spheres. For immobilization using either polymer or cement. Contaminated with actinides. |

\*Data in Table 33 generated from Refs 127 - 200.

## C-6 Defense Activities

The main sources of defense waste are nuclear weapons production and operation of the nuclear-powered UK fleet of submarines. Smaller quantities arise from general use of radioactive materials within the armed forces and at defense establishments (see Figure 7 for an indication of site locations).

The Ministry of Defence (MoD) is a major user of radioactive materials in its naval nuclear propulsion and atomic weapons programs, and in other activities. The management of radioactive waste generating sites are operated under the following arrangements:

- The Atomic Weapons Establishment (AWE) at Aldermaston and Burghfield in Berkshire undertakes research and development, design, manufacturing, servicing and decommissioning of nuclear warheads;
- Naval dockyards at Devonport in Devon, the Clyde submarine base at Faslane near Helensburgh in Dunbartonshire (Scotland) and Rosyth near Dunfermline in Fife (Scotland) support the operation, refueling, refitting and decommissioning of the nuclear submarine fleet;
- Development of nuclear propulsion systems is carried out at the Naval Reactor Test Establishment Vulcan at Dounreay (Scotland). The two reactors on site are now shutdown;
- At Derby, Rolls-Royce Marine Power Operations Ltd develops and manufactures reactor cores and associated equipment for the nuclear submarine fleet;
- At Barrow in Cumbria, BAE Systems Marine Ltd builds, tests and commissions nuclear powered submarines;
- Eskmeals Range in Cumbria was used for test firing of depleted uranium projectiles; and
- The Joint Supply Chain Services regional center located at Donnington in Shropshire and HM Naval Base at Portsmouth in Hampshire store radioactive wastes.

Current and future radioactive wastes (equivalent to Hanford site SSW) generated by UK nuclear defense activities is shown in Table 34.



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*Table 34. Composition of SSW Equivalents from UK Defense Activities\*.*

|                                                   | Waste Composition                | LLW | ILW | Comments                                                                                                                                                                                                                                                                                                                                   |
|---------------------------------------------------|----------------------------------|-----|-----|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <i>Debris Waste</i><br>( <i>&gt;60 mm Ø</i> )     | Used Process Equipment           | ✓   | ✓   | Contaminated metal process equipment, also includes plastics and cellulosic materials. Uranium, plutonium and tritium contaminated. Activation product contamination in other wastes (e.g. reactor components).                                                                                                                            |
|                                                   | Contaminated Tools & Instruments | ✓   | ✓   | Uranium, plutonium and tritium contamination. Activation products in other wastes. Cement encapsulation.                                                                                                                                                                                                                                   |
|                                                   | HEPA Filters                     | ✓   | ✓   | Depleted, natural and enriched uranium and plutonium contamination. Cement encapsulation.                                                                                                                                                                                                                                                  |
|                                                   | Other Debris Waste               | ✓   | ✓   | Includes cotton and polypropylene liquid filters. Cement encapsulation. Activation and fission products.                                                                                                                                                                                                                                   |
| <i>Non-debris Waste</i><br>( <i>&lt;60 mm Ø</i> ) | Granular Activated Carbon        | ✗   | ✗   |                                                                                                                                                                                                                                                                                                                                            |
|                                                   | Spent Ion Exchange Resin         | ✓   | ✓   | LLW: Proprietary organic ion exchange materials. Cement encapsulation (some processed first). Contamination with activation products, fission products and tritium.<br>ILW: Proprietary organic ion exchange materials. Cement encapsulation (some processed first). Contamination with activation products, fission products and tritium. |
|                                                   | Silver Mordenite Beds            | ✗   | ✗   |                                                                                                                                                                                                                                                                                                                                            |
|                                                   | Other Non-debris Waste           | ✓   | ✗   | Tritium molecular sieve desiccant. Cement encapsulation.                                                                                                                                                                                                                                                                                   |

\*Data in Table 34 generated from Refs 201 - 242.

## C-7 Medical and Industrial Sources and Minor Generators

The remaining UK radioactive wastes are generated from the use of radioactivity in medical diagnosis and treatment, and in industrial applications including sterilization of medical equipment and food, and non-destructive testing of materials (for integrity, thickness, density). A range of further minor generators also produce radioactive waste, these include hospitals, universities, the oil and gas industry etc.

As this the focus of this work is on SSW generated by the nuclear industry, radioactive wastes generated from medical and industrial sources and from other minor generators are not further considered.



## Appendix D

It should be noted that there are a number of radioactive waste incineration suppliers within the UK, whose services are used to minimize the volumes of radiological waste routed to near-surface storage.

Some typical examples of solid materials that are acceptable for incineration in the UK are detailed in Table 35.

*Table 35. Acceptable and Restricted Solid Combustible Wastes. (Info. from Ref 293).*

| Acceptable Solid Combustible Wastes | Provisionally Acceptable Solid Combustible Wastes |
|-------------------------------------|---------------------------------------------------|
| Wood                                | Rubber                                            |
| Paper                               | Ion exchange resins                               |
| Cardboard                           | Filters                                           |
| Cloth including cotton and PPE      | Graphite                                          |
| Plastics (non-halogenated)          | Grease                                            |

In addition some liquid materials can be accepted for incineration, these include:

- oils;
- synthetic fluids;
- organic scintillant (in vials);
- chemical wastes including solvents; and
- decontamination solutions.

Incinerating waste can reduce the volumes by up to 98% by burning combustible solid and create a stable homogenous waste form that is suitable for disposal

Specific restrictions will be determined through the permitting process, however, the criteria in Table 36 provide a general guide to the allowable limits for incineration of wastes in the UK.

*Table 36. General Guide to the Allowable Limits for Incineration of Wastes in the UK. (Info. from Ref 293).*

| Radionuclide         | Package Activity Limit (MBq) |                       |                |
|----------------------|------------------------------|-----------------------|----------------|
|                      | Acceptable                   | Likely to be Accepted | Maybe Accepted |
| All alpha            | <0.5                         | <8                    | <15            |
| C-14                 | <3,000                       |                       | <100,000       |
| H-3                  | <40,000                      |                       | <100,000       |
| All other beta/gamma | <10                          | <40                   | <8000          |

## Appendix E

This information presented in this section is to support Section 6.4.1 in the main report.

Table 37. Current and Future Materials Inventory In the LLWR Trenches and Vault 8 (as of 31<sup>st</sup> March 2008)  
(Ref 265).

| Values in m <sup>3</sup> of waste | Forward inventory<br>(Reference Case) |                                      |          |            |
|-----------------------------------|---------------------------------------|--------------------------------------|----------|------------|
|                                   | Trenches                              | V8 at 31 <sup>st</sup><br>March 2008 | V8-V14   | Beyond V14 |
| Aluminium metal                   | 1.61E+04                              | 3.34E+03                             | 2.44E+03 | 1.21E+02   |
| Aqueous Liquid                    | 1.15E+03                              | 2.50E+02                             | 3.94E+02 | 0.00E+00   |
| Asbestos                          | 7.00E+03                              | 6.96E+02                             | 1.31E+04 | 2.90E+02   |
| Biological Material               | 6.31E+01                              | 1.33E+00                             | 3.51E+01 | 9.33E+00   |
| Block Cement                      | 1.31E+04                              | 4.37E+03                             | 1.33E+05 | 1.86E+05   |
| Boral                             | 6.66E+01                              | 2.72E+00                             | 9.80E+02 | 0.00E+00   |
| Brass                             | 2.05E+03                              | 1.69E+02                             | 1.04E+01 | 3.57E-01   |
| Bronze                            | 8.83E+01                              | 8.66E+00                             | 4.82E+00 | 3.67E-01   |
| Ceramic                           | 3.10E+03                              | 2.20E+02                             | 1.65E+02 | 8.79E-01   |
| Complexants                       | 1.60E+03                              | 1.32E+02                             | 1.61E+03 | 1.88E+02   |
| Condensation Polymers             | 2.07E+03                              | 8.42E+02                             | 9.43E+02 | 5.58E+01   |
| Copper metal                      | 5.25E+03                              | 4.17E+02                             | 5.53E+02 | 5.83E+01   |
| Dural                             | 6.39E+01                              | 1.53E+00                             | 1.56E+01 | 1.25E+00   |
| Glass                             | 6.99E+03                              | 8.30E+02                             | 3.78E+03 | 9.04E+01   |
| Graphite                          | 2.16E+03                              | 4.62E+02                             | 2.84E+02 | 1.10E+04   |
| Halogenated Plastics              | 4.70E+04                              | 7.04E+03                             | 1.81E+04 | 7.61E+02   |
| Halogenated Rubber                | 9.55E+03                              | 1.35E+03                             | 1.23E+03 | 2.14E+01   |
| Inconel                           | 4.31E+02                              | 9.45E+00                             | 5.19E-01 | 0.00E+00   |
| Inorganic Ion Exchangers          | 1.60E+02                              | 2.26E+01                             | 1.81E+02 | 5.00E+00   |
| Inorganic Sludge Floc             | 0.00E+00                              | 0.00E+00                             | 1.71E+03 | 4.77E+02   |
| Ion Exchange Resins               | 1.27E+03                              | 9.75E+02                             | 2.63E+02 | 3.99E+00   |
| Lead metal                        | 2.79E+03                              | 3.79E+02                             | 9.04E+02 | 6.18E+00   |
| Magnox                            | 2.04E+02                              | 5.39E+01                             | 1.76E+02 | 7.53E-01   |
| Miscellaneous Liquid              | 7.14E+02                              | 3.15E+01                             | 2.83E+02 | 0.00E+00   |
| Molybdenum metal                  | 7.75E+01                              | 3.85E+00                             | 0.00E+00 | 0.00E+00   |
| Monel                             | 8.14E+01                              | 7.20E+00                             | 1.05E+00 | 2.02E-01   |
| Nickel metal                      | 1.51E+03                              | 7.18E+01                             | 0.00E+00 | 0.00E+00   |
| Nimonic                           | 6.39E+01                              | 1.30E+00                             | 3.21E+00 | 0.00E+00   |
| NonHalogenated Rubber             | 4.41E+03                              | 8.50E+02                             | 4.36E+03 | 9.28E+01   |
| Oil                               | 1.09E+03                              | 6.16E+01                             | 0.00E+00 | 0.00E+00   |
| Other Cellulosics                 | 1.05E+05                              | 1.82E+04                             | 3.62E+02 | 0.00E+00   |
| Other Ferrous Metal               | 1.68E+05                              | 1.62E+04                             | 1.13E+05 | 4.72E+04   |
| Other Inorganics                  | 4.43E+04                              | 6.05E+02                             | 6.20E+03 | 7.25E+03   |
| Other Metals                      | 1.18E+03                              | 2.61E+02                             | 1.50E+02 | 4.10E+01   |
| Other Organics                    | 3.44E+03                              | 4.13E+02                             | 7.45E+02 | 5.47E+00   |
| Paper and Cotton                  | 1.27E+04                              | 4.12E+03                             | 2.43E+04 | 1.54E+03   |
| Putrescible                       | 0.00E+00                              | 0.00E+00                             | 3.56E+02 | 2.44E+01   |
| Rubble                            | 1.22E+05                              | 1.09E+04                             | 2.05E+04 | 1.25E+03   |
| Soil                              | 7.20E+04                              | 2.73E+03                             | 3.62E+04 | 1.07E+04   |
| Stainless Steel                   | 4.84E+04                              | 3.46E+03                             | 3.47E+04 | 8.58E+03   |
| Splite                            | 6.39E+01                              | 1.29E+00                             | 5.28E-01 | 5.88E-03   |
| Thermoplastics                    | 2.31E+04                              | 2.56E+03                             | 4.39E+03 | 9.33E+01   |
| Unknown Cellulosics               | 1.51E+03                              | 1.82E+02                             | 4.71E+03 | 1.39E+03   |

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|                                    |          |                                         | Forward inventory<br>(Reference Case) |               |
|------------------------------------|----------|-----------------------------------------|---------------------------------------|---------------|
| Values in m <sup>3</sup> of waste  | Trenches | V8 at<br>31 <sup>st</sup> March<br>2008 | V8-V14                                | Beyond<br>V14 |
| Unknown Ferrous Metal              | 3.41E+03 | 8.83E+02                                | 4.67E+03                              | 3.42E+03      |
| Unknown Inorganics                 | 3.20E+02 | 1.08E+02                                | 4.50E+02                              | 5.49E+02      |
| Unknown Material                   | 6.48E+03 | 2.94E+03                                | 6.17E+04                              | 3.43E+03      |
| Unknown Metals                     | 1.26E+04 | 2.14E+03                                | 1.80E+03                              | 2.46E+02      |
| Unknown NonHalogenated<br>Plastics | 3.23E+03 | 1.17E+03                                | 8.19E+03                              | 2.86E+02      |
| Unknown Organics                   | 1.09E+03 | 6.32E+01                                | 1.14E+03                              | 7.89E-02      |
| Unknown Plastics                   | 4.65E+02 | 1.35E+02                                | 2.68E+03                              | 1.64E+03      |
| Unknown Rubber                     | 1.31E+04 | 1.94E+03                                | 8.06E+03                              | 9.04E+02      |
| Uranium metal                      | 1.59E+02 | 9.87E+00                                | 4.10E-02                              | 0.00E+00      |
| Wood                               | 4.03E+04 | 4.28E+03                                | 2.12E+04                              | 5.39E+02      |
| Zinc metal                         | 6.78E+02 | 4.87E+01                                | 4.67E+01                              | 1.93E-01      |
| Zircaloy                           | 9.22E+01 | 6.60E+00                                | 7.10E+00                              | 1.99E+00      |
| Compacted puck                     | 0.00E+00 | 0.00E+00                                | 2.00E+04                              | 1.69E+03      |
| Incinerator ash                    | 0.00E+00 | 0.00E+00                                | 9.95E+02                              | 1.02E+02      |
| Incinerator filter                 | 0.00E+00 | 0.00E+00                                | 9.95E+02                              | 1.02E+02      |
| Smelting slag                      | 0.00E+00 | 0.00E+00                                | 3.74E+03                              | 1.65E+03      |
| Smelting filter                    | 0.00E+00 | 0.00E+00                                | 3.74E+03                              | 1.65E+03      |



## Appendix F

The information presented in this section is to support Section 6.4.2 in the main report.

Table 38. Forecast Radionuclide Inventory Of The Two Currently Built LLW Vaults At Dounreay (LLW1+2), Existing LLW Storage Facilities And Demolition LLW (Demo. LLW). Activities in Bq (Ref 271).

| Radio-nuclide | LLW1+2             | Existing Facility | Demo. LLW | Total   | LLW1+2          | Existing Facility | Demo. LLW | Total   |
|---------------|--------------------|-------------------|-----------|---------|-----------------|-------------------|-----------|---------|
|               | Based on DRWI 2009 |                   |           |         | Decayed to 2025 |                   |           |         |
| H3            | 2.7E+12            |                   | 3.6E+08   | 2.7E+12 | 1.1E+12         |                   | 1.5E+08   | 1.1E+12 |
| Be10          | 1.2E+05            |                   | 5.9E+04   | 1.8E+05 | 1.2E+05         |                   | 5.9E+04   | 1.8E+05 |
| C14           | 5.5E+09            |                   | 2.2E+05   | 5.5E+09 | 5.5E+09         |                   | 2.2E+05   | 5.5E+09 |
| Cl36          | 1.7E+07            |                   | 8.6E+06   | 2.5E+07 | 1.7E+07         |                   | 8.6E+06   | 2.5E+07 |
| K40           | 8.7E+01            |                   |           | 8.7E+01 | 8.7E+01         |                   |           | 8.7E+01 |
| Ca41          | 2.3E+06            |                   | 3.0E+06   | 5.3E+06 | 2.3E+06         |                   | 3.0E+06   | 5.3E+06 |
| Mn53          | 1.3E+03            |                   |           | 1.3E+03 | 1.3E+03         |                   |           | 1.3E+03 |
| Mn54          | 2.0E+09            |                   | 2.8E+08   | 2.3E+09 | 4.7E+03         |                   | 6.6E+02   | 5.4E+03 |
| Fe55          | 1.7E+10            |                   | 5.2E+05   | 1.7E+10 | 2.9E+08         |                   | 8.5E+03   | 2.9E+08 |
| Co60          | 2.8E+11            | 5.4E+09           | 7.6E+09   | 2.9E+11 | 3.4E+10         | 6.6E+08           | 9.3E+08   | 3.6E+10 |
| Ni59          | 6.6E+07            | 7.4E+08           | 2.2E+07   | 8.3E+08 | 6.6E+07         | 7.4E+08           | 2.2E+07   | 8.3E+08 |
| Ni63          | 5.0E+09            | 5.6E+10           | 8.8E+08   | 6.2E+10 | 4.5E+09         | 5.0E+10           | 7.8E+08   | 5.5E+10 |
| Zn65          | 3.7E+03            |                   | 2.3E-05   | 3.7E+03 | 2.3E-04         |                   | 1.4E-12   | 2.3E-04 |
| Se79          | 4.0E+07            | 1.4E+07           | 2.1E+07   | 7.5E+07 | 4.0E+07         | 1.4E+07           | 2.1E+07   | 7.5E+07 |
| Kr81          | 1.4E+03            |                   |           | 1.4E+03 | 1.4E+03         |                   |           | 1.4E+03 |
| Kr85          | 5.2E+05            |                   |           | 5.2E+05 | 1.8E+05         |                   |           | 1.8E+05 |
| Rb87          | 4.0E+02            |                   | 1.2E+01   | 4.1E+02 | 4.0E+02         |                   | 1.2E+01   | 4.1E+02 |
| Sr90          | 1.4E+12            | 1.3E+12           | 3.0E+11   | 3.0E+12 | 9.4E+11         | 9.2E+11           | 2.0E+11   | 2.1E+12 |
| Zr93          | 5.9E+07            | 9.4E+07           | 3.1E+07   | 1.8E+08 | 5.9E+07         | 9.4E+07           | 3.1E+07   | 1.8E+08 |
| Nb91          | 1.3E+05            |                   |           | 1.3E+05 | 1.3E+05         |                   |           | 1.3E+05 |
| Nb92          | 4.1E+00            |                   |           | 4.1E+00 | 4.1E+00         |                   |           | 4.1E+00 |
| Nb93m         | 3.6E+08            | 5.4E+07           | 1.4E+08   | 5.5E+08 | 3.9E+08         | 7.6E+07           | 1.7E+08   | 6.4E+08 |
| Nb94          | 6.9E+07            | 2.3E+08           | 4.7E+07   | 3.4E+08 | 6.9E+07         | 2.3E+08           | 4.7E+07   | 3.4E+08 |

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| Radio-nuclide | LLW1+2             | Existing Facility | Demo. LLW | Total   | LLW1+2          | Existing Facility | Demo. LLW | Total   |
|---------------|--------------------|-------------------|-----------|---------|-----------------|-------------------|-----------|---------|
|               | Based on DRWI 2009 |                   |           |         | Decayed to 2025 |                   |           |         |
| Mo93          | 3.6E+08            |                   | 1.7E+08   | 5.3E+08 | 3.6E+08         |                   | 1.7E+08   | 5.2E+08 |
| Tc97          | 1.5E+00            |                   |           | 1.5E+00 | 1.5E+00         |                   |           | 1.5E+00 |
| Tc99          | 3.7E+08            | 6.2E+08           | 2.1E+08   | 1.2E+09 | 3.7E+08         | 6.2E+08           | 2.1E+08   | 1.2E+09 |
| Ru106         | 1.5E+10            |                   | 1.6E+09   | 1.6E+10 | 2.5E+05         |                   | 2.7E+04   | 2.7E+05 |
| Pd107         | 3.3E+05            | 8.6E+06           | 5.2E+05   | 9.5E+06 | 3.3E+05         | 8.6E+06           | 5.2E+05   | 9.5E+06 |
| Ag108m        | 6.0E+05            |                   | 6.4E-01   | 6.0E+05 | 5.5E+05         |                   | 5.8E-01   | 5.5E+05 |
| Ag110m        | 5.3E+03            |                   | 5.8E+02   | 5.9E+03 | 4.9E-04         |                   | 5.3E-05   | 5.4E-04 |
| Cd109         | 3.4E+05            |                   | 5.9E+00   | 3.4E+05 | 5.6E+01         |                   | 9.6E-04   | 5.6E+01 |
| Cd113m        | 1.0E+07            |                   | 5.9E+06   | 1.6E+07 | 4.4E+06         |                   | 2.6E+06   | 7.0E+06 |
| Sn119m        | 6.2E+02            |                   | 2.4E+01   | 6.5E+02 | 6.2E-04         |                   | 2.4E-05   | 6.5E-04 |
| Sn121m        | 8.8E+07            |                   | 8.7E+07   | 1.8E+08 | 7.2E+07         |                   | 7.1E+07   | 1.4E+08 |
| Sn123         | 1.3E+03            |                   | 1.5E+02   | 1.5E+03 | 3.3E-11         |                   | 3.7E-12   | 3.7E-11 |
| Sn126         | 4.2E+05            | 1.1E+08           | 2.1E+06   | 1.1E+08 | 4.2E+05         | 1.1E+08           | 2.1E+06   | 1.1E+08 |
| Sb125         | 1.9E+09            | 3.6E+07           | 1.2E+08   | 2.0E+09 | 3.4E+07         | 6.6E+05           | 2.3E+06   | 3.7E+07 |
| Sb126         | 5.8E+04            | 1.5E+07           | 2.9E+05   | 1.5E+07 | 5.8E+04         | 1.5E+07           | 2.9E+05   | 1.5E+07 |
| Te125m        | 4.5E+08            | 8.8E+06           | 3.0E+07   | 4.9E+08 | 8.2E+06         | 1.6E+05           | 5.5E+05   | 8.9E+06 |
| Te127m        | 3.6E-07            |                   | 1.9E-08   | 3.8E-07 |                 |                   |           |         |
| I129          | 5.9E+04            | 1.2E+06           | 1.8E+05   | 1.4E+06 | 5.9E+04         | 1.2E+06           | 1.8E+05   | 1.4E+06 |
| Cs134         | 4.5E+09            | 1.3E+07           | 6.4E+08   | 5.2E+09 | 2.1E+07         | 5.9E+04           | 2.9E+06   | 2.4E+07 |
| Cs135         | 2.7E+07            | 6.2E+07           | 2.7E+07   | 1.2E+08 | 2.7E+07         | 6.2E+07           | 2.7E+07   | 1.2E+08 |
| Cs137         | 2.3E+12            | 1.7E+12           | 5.9E+11   | 4.6E+12 | 1.6E+12         | 1.2E+12           | 4.1E+11   | 3.2E+12 |
| Ba133         | 1.7E+07            |                   |           | 1.7E+07 | 6.1E+06         |                   |           | 6.1E+06 |
| La137         | 1.2E+04            |                   |           | 1.2E+04 | 1.2E+04         |                   |           | 1.2E+04 |
| La138         | 2.5E-02            |                   |           | 2.5E-02 | 2.5E-02         |                   |           | 2.5E-02 |
| Ce144         | 2.2E+08            |                   | 3.3E+06   | 2.2E+08 | 1.4E+02         |                   | 2.1E+00   | 1.4E+02 |
| Pm145         | 8.7E+04            |                   |           | 8.7E+04 | 4.6E+04         |                   |           | 4.6E+04 |
| Pm147         | 1.4E+10            | 1.0E+09           | 9.7E+09   | 2.4E+10 | 2.0E+08         | 1.5E+07           | 1.4E+08   | 3.6E+08 |
| Sm147         | 1.6E+03            | 6.9E-02           | 1.1E+01   | 1.6E+03 | 1.6E+03         | 9.3E-02           | 1.1E+01   | 1.6E+03 |
| Sm151         | 4.7E+09            | 1.0E+11           | 6.0E+09   | 1.1E+11 | 4.1E+09         | 8.9E+10           | 5.3E+09   | 9.9E+10 |
| Eu152         | 2.2E+07            | 2.7E+11           | 3.8E+04   | 2.7E+11 | 9.4E+06         | 1.2E+11           | 1.6E+04   | 1.2E+11 |
| Eu154         | 5.4E+08            | 1.2E+10           | 1.8E+09   | 1.5E+10 | 1.5E+08         | 3.5E+09           | 5.2E+08   | 4.1E+09 |
| Eu155         | 1.4E+09            | 2.7E+09           | 2.8E+09   | 6.9E+09 | 1.5E+08         | 2.9E+08           | 3.0E+08   | 7.3E+08 |
| Gd153         | 3.0E+00            |                   | 4.6E-04   | 3.0E+00 | 1.6E-07         |                   | 2.5E-11   | 1.6E-07 |
| Ho163         | 8.1E+02            |                   |           | 8.1E+02 | 8.1E+02         |                   |           | 8.1E+02 |
| Ho166m        | 2.4E+05            |                   | 6.2E-11   | 2.4E+05 | 2.4E+05         |                   | 6.2E-11   | 2.4E+05 |
| Tm170         | 3.7E-03            |                   |           | 3.7E-03 | 7.9E-17         |                   |           | 7.9E-17 |
| Tm171         | 4.7E+05            |                   |           | 4.7E+05 | 1.5E+03         |                   |           | 1.5E+03 |
| Lu174         | 1.4E+03            |                   |           | 1.4E+03 | 4.8E+01         |                   |           | 4.8E+01 |
| Lu176         | 2.6E-01            |                   |           | 2.6E-01 | 2.6E-01         |                   |           | 2.6E-01 |
| Hf182         | 2.7E-01            |                   |           | 2.7E-01 | 2.7E-01         |                   |           | 2.7E-01 |
| Pt193         | 1.3E+07            |                   |           | 1.3E+07 | 1.0E+07         |                   |           | 1.0E+07 |
| Ti204         | 1.6E+07            |                   |           | 1.6E+07 | 8.3E+05         |                   |           | 8.3E+05 |
| Pb205         | 2.8E+08            |                   |           | 2.8E+08 | 2.8E+08         |                   |           | 2.8E+08 |
| Pb210         | 1.1E+08            | 1.2E+09           | 2.3E+01   | 1.3E+09 | 1.5E+09         | 2.9E+09           | 3.6E+02   | 4.3E+09 |
| Bi208         | 1.0E+01            |                   |           | 1.0E+01 | 1.0E+01         |                   |           | 1.0E+01 |
| Bi210m        | 4.5E+04            |                   |           | 4.5E+04 | 4.5E+04         |                   |           | 4.5E+04 |
| Po210         | 5.6E+07            | 1.1E+09           | 2.0E+01   | 1.2E+09 | 1.4E+09         | 2.8E+09           | 3.3E+02   | 4.2E+09 |
| Ra223         | 5.5E+04            | 2.1E+03           | 4.4E+03   | 6.1E+04 | 5.1E+05         | 3.3E+04           | 8.5E+04   | 6.2E+05 |
| Ra225         | 6.6E+04            | 2.6E-04           | 4.6E-01   | 6.6E+04 | 1.2E+05         | 2.3E-02           | 7.8E-01   | 1.2E+05 |
| Ra226         | 3.6E+09            | 5.4E+09           | 1.6E+02   | 9.0E+09 | 3.6E+09         | 5.4E+09           | 1.8E+03   | 8.9E+09 |

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| Radio-nuclide    | LLW1+2             | Existing Facility | Demo. LLW | Total   | LLW1+2          | Existing Facility | Demo. LLW | Total   |
|------------------|--------------------|-------------------|-----------|---------|-----------------|-------------------|-----------|---------|
|                  | Based on DRWI 2009 |                   |           |         | Decayed to 2025 |                   |           |         |
| Ra228            | 3.7E+07            | 5.9E+08           | 4.9E+07   | 6.8E+08 | 8.5E+07         | 8.6E+07           | 9.1E+07   | 2.6E+08 |
| Ac227            | 5.6E+04            | 2.2E+03           | 4.6E+03   | 6.3E+04 | 5.1E+05         | 3.3E+04           | 8.6E+04   | 6.3E+05 |
| Th227            | 5.5E+04            | 2.1E+03           | 4.4E+03   | 6.1E+04 | 5.0E+05         | 3.3E+04           | 8.4E+04   | 6.2E+05 |
| Th228            | 5.8E+07            | 6.5E+08           | 7.5E+07   | 7.8E+08 | 1.3E+08         | 1.3E+08           | 2.1E+08   | 4.7E+08 |
| Th229            | 6.6E+04            | 2.7E-04           | 4.6E-01   | 6.6E+04 | 1.2E+05         | 2.3E-02           | 7.8E-01   | 1.2E+05 |
| Th230            | 4.1E+06            | 4.5E+05           | 8.3E+04   | 4.6E+06 | 2.2E+07         | 1.9E+06           | 3.9E+05   | 2.4E+07 |
| Th232            | 9.3E+07            | 1.7E-01           | 9.8E+07   | 1.9E+08 | 9.3E+07         | 6.9E-01           | 9.8E+07   | 1.9E+08 |
| Th234            | 1.1E+09            | 9.8E+07           | 6.2E+07   | 1.3E+09 | 1.1E+09         | 9.8E+07           | 6.2E+07   | 1.3E+09 |
| Pa231            | 4.4E+05            | 2.9E+04           | 6.4E+04   | 5.3E+05 | 1.8E+06         | 1.2E+05           | 3.3E+05   | 2.3E+06 |
| Pa233            | 1.1E+06            | 1.7E+05           | 3.6E+05   | 1.6E+06 | 2.2E+06         | 8.4E+05           | 4.8E+05   | 3.6E+06 |
| U232             | 5.8E+07            |                   | 1.4E+08   | 2.0E+08 | 4.9E+07         |                   | 1.2E+08   | 1.7E+08 |
| U233             | 3.6E+07            | 1.8E+00           | 2.0E+02   | 3.6E+07 | 3.6E+07         | 3.6E+01           | 2.3E+02   | 3.6E+07 |
| U234             | 1.2E+11            | 9.9E+09           | 2.2E+09   | 1.4E+11 | 1.2E+11         | 9.9E+09           | 2.2E+09   | 1.4E+11 |
| U235             | 4.1E+09            | 2.8E+08           | 7.8E+08   | 5.2E+09 | 4.1E+09         | 2.8E+08           | 7.8E+08   | 5.2E+09 |
| U236             | 1.1E+10            | 6.7E+08           | 2.2E+08   | 1.2E+10 | 1.1E+10         | 6.7E+08           | 2.2E+08   | 1.2E+10 |
| U238             | 1.1E+09            | 9.8E+07           | 6.2E+07   | 1.3E+09 | 1.1E+09         | 9.8E+07           | 6.2E+07   | 1.3E+09 |
| Np237            | 1.1E+06            | 1.7E+05           | 3.6E+05   | 1.6E+06 | 2.3E+06         | 8.4E+05           | 4.9E+05   | 3.6E+06 |
| Pu236            | 8.5E+02            |                   | 1.8E+03   | 2.6E+03 | 1.7E+01         |                   | 3.6E+01   | 5.3E+01 |
| Pu238            | 9.3E+09            | 4.6E+10           | 1.3E+10   | 6.9E+10 | 8.2E+09         | 4.1E+10           | 1.2E+10   | 6.1E+10 |
| Pu239            | 7.7E+09            | 3.1E+11           | 1.4E+10   | 3.3E+11 | 7.7E+09         | 3.1E+11           | 1.4E+10   | 3.3E+11 |
| Pu240            | 7.8E+09            | 1.2E+11           | 1.7E+10   | 1.5E+11 | 7.8E+09         | 1.2E+11           | 1.7E+10   | 1.5E+11 |
| Pu241            | 3.2E+11            | 1.8E+12           | 3.8E+11   | 2.5E+12 | 1.5E+11         | 8.3E+11           | 1.8E+11   | 1.2E+12 |
| Pu242            | 9.3E+06            | 4.7E+07           | 6.0E+06   | 6.2E+07 | 9.3E+06         | 4.7E+07           | 6.0E+06   | 6.2E+07 |
| Am241            | 2.2E+11            | 1.1E+11           | 2.0E+10   | 3.6E+11 | 2.2E+11         | 1.4E+11           | 2.6E+10   | 3.9E+11 |
| Am242m           | 2.2E+08            | 1.5E+09           | 2.2E+08   | 2.0E+09 | 2.0E+08         | 1.4E+09           | 2.1E+08   | 1.8E+09 |
| Am243            | 3.2E+07            |                   | 1.8E+07   | 5.0E+07 | 3.2E+07         |                   | 1.8E+07   | 5.0E+07 |
| Cm242            | 1.8E+08            | 1.3E+09           | 1.8E+08   | 1.6E+09 | 1.7E+08         | 1.2E+09           | 1.7E+08   | 1.5E+09 |
| Cm243            | 7.8E+07            |                   | 7.7E+07   | 1.6E+08 | 5.3E+07         |                   | 5.2E+07   | 1.1E+08 |
| Cm244            | 3.5E+09            |                   | 9.5E+08   | 4.5E+09 | 1.9E+09         |                   | 5.1E+08   | 2.4E+09 |
| Cm245            | 2.5E+06            |                   | 1.5E+05   | 2.7E+06 | 2.5E+06         |                   | 1.5E+05   | 2.7E+06 |
| Cm246            | 4.4E+05            |                   | 1.2E+04   | 4.5E+05 | 4.4E+05         |                   | 1.2E+04   | 4.5E+05 |
| Cm248            | 2.2E+01            |                   | 1.7E-01   | 2.2E+01 | 2.2E+01         |                   | 1.7E-01   | 2.2E+01 |
| Cf249            | 1.2E+03            |                   | 3.6E+02   | 1.6E+03 | 1.2E+03         |                   | 3.5E+02   | 1.5E+03 |
| Cf250            | 2.8E+03            |                   | 2.8E+00   | 2.8E+03 | 1.2E+03         |                   | 1.2E+00   | 1.2E+03 |
| Cf251            | 5.0E+01            |                   | 1.8E-03   | 5.0E+01 | 4.9E+01         |                   | 1.7E-03   | 4.9E+01 |
| Cf252            | 1.4E+02            |                   | 2.0E-04   | 1.4E+02 | 2.1E+00         |                   | 3.0E-06   | 2.1E+00 |
| Other A          |                    |                   |           |         |                 |                   |           |         |
| Other B/G        | 2.3E+10            |                   |           | 2.3E+10 | 2.3E+10         |                   |           | 2.3E+10 |
| Total Alpha      | 4.0E+11            | 6.1E+11           | 6.9E+10   | 1.1E+12 | 3.9E+11         | 6.3E+11           | 7.3E+10   | 1.1E+12 |
| Total Beta/Gamma | 7.1E+12            | 5.3E+12           | 1.3E+12   | 1.4E+13 | 3.9E+12         | 3.2E+12           | 8.0E+11   | 7.8E+12 |



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*Table 39. Forecast Materials Inventory For The Two Currently Built LLW Vaults At Dounreay (LLW1+2) And Existing LLW Storage Facilities. The Equivalent SSW of 'Inorganic IX Materials' Is Highlighted In Yellow (Ref 271).*

| Material                         | LLW 1+2 |       | Existing Facility |       |
|----------------------------------|---------|-------|-------------------|-------|
|                                  | tonnes  | %     | tonnes            | %     |
| Aluminium                        | 34.2    | 0.08% | 21.8              | 0.13% |
| Copper                           | 70.6    | 0.16% | 168.1             | 1.00% |
| Lead                             | 248.6   | 0.56% | 840.4             | 5.00% |
| Zinc                             | 0.2     | 0.00% |                   |       |
| Magnesium/Magnox                 | 0.6     | 0.00% |                   |       |
| Zirconium/Zircaloy               | 0.2     | 0.00% |                   |       |
| Brass - Copper Alloy             | 4.3     | 0.01% |                   |       |
| Bronze - Copper Alloy            | 0.7     | 0.00% |                   |       |
| Inconel - Nickel Alloy           | 0.2     | 0.00% |                   |       |
| Nimonic - Nickel Alloy           | 0.4     | 0.00% |                   |       |
| Stellite - Cobalt-Chromium Alloy | 0.5     | 0.00% |                   |       |
| Boral - Boron Aluminium Alloy    |         |       |                   |       |
| Dural - Aluminium Alloy          | 0.2     | 0.00% |                   |       |
| Monel - Nickel Alloy             | 0.2     | 0.00% |                   |       |
| Other Metals                     | 2.8     | 0.01% | 1.7*              | 0.01% |
| Fluorides                        | 2.3     | 0.01% |                   |       |
| Chlorides                        | 0.2     | 0.00% |                   |       |
| Iodides                          | 0.2     | 0.00% |                   |       |
| Cyanides                         |         |       |                   |       |
| Carbonates                       | 0.2     | 0.00% |                   |       |
| Nitrates                         | 0.9     | 0.00% | 1.7*              | 0.01% |
| Nitrites                         |         |       |                   |       |
| Phosphates                       | 0.9     | 0.00% | 1.7*              | 0.01% |
| Sulphates                        | 0.2     | 0.00% |                   |       |
| Sulphides                        | 0.2     | 0.00% |                   |       |
| Other Anions                     | 0.2     | 0.00% |                   |       |
| Cadmium                          | 0.4     | 0.00% | 1.7*              | 0.01% |
| Mercury                          | 0.9     | 0.00% | 1.7*              | 0.01% |
| Beryllium                        | 0.9     | 0.00% | 1.7*              | 0.01% |
| Selenium**                       |         |       |                   |       |
| Other Toxic Metals               | 0.1     | 0.00% |                   |       |
| Explosive Materials              |         |       |                   |       |
| Low Flash Point Liquids          | 0.5     | 0.00% |                   |       |



**Benchmarking of DFLAW Solid Secondary Wastes and Processes with UK / Europe Counterparts**  
**Document No: DBD/4909/PRJ/RP/001**  
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| Material                           | LLW 1+2 |       | Existing Facility |       |
|------------------------------------|---------|-------|-------------------|-------|
|                                    | tonnes  | %     | tonnes            | %     |
| Strong Oxidising Agents            | 1.3     | 0.00% | 1.7*              | 0.01% |
| Pyrophoric Materials               |         |       |                   |       |
| Materials which react with Water   | 0.4     | 0.00% |                   |       |
| Combustible Metals                 | 0.4     | 0.00% |                   |       |
| Putrescible Wastes                 | 0.7     | 0.00% | 1.7*              | 0.01% |
| Biological or Pathogenic Materials |         |       |                   |       |
| Generating or evolving Toxic Gases |         |       |                   |       |
| Asbestos                           | 29.1    | 0.07% | 361.4             | 2.15% |
| Hydrides                           |         |       |                   |       |
| Phosphorus                         |         |       |                   |       |
| Free Aqueous Liquids               | 0.1     | 0.00% |                   |       |
| Free Non-Aqueous Liquids           |         |       |                   |       |
| Powders                            |         |       |                   |       |
| Pressurised Cylinders/Aerosol Cans | 0.1     | 0.00% |                   |       |
| Complexing Agents                  | 3.2     | 0.01% | 1.7*              | 0.01% |
| Organic IX Materials               |         |       |                   |       |
| Oil & Grease                       | 1.6     | 0.00% | 1.7*              | 0.01% |
| Other Organics                     | 10.5    | 0.02% | 1.7*              | 0.01% |
| Inorganic IX Materials             | 0.1     | 0.00% |                   |       |
| Inorganic Sludges and Flocs        | 57.9    | 0.13% |                   |       |
| Ceramics                           | 8.7     | 0.02% |                   |       |
| Graphite                           | 5.4     | 0.01% |                   |       |
| Water/Aqueous Liquids              |         |       |                   |       |

\* Trace mass, assuming 0.01 wt% of the raw waste.

\*\* Although Se has been detected in contaminated land on the Dounreay site, the DRWI does not give any entries of Se for LLW.