Geological Disposal

Carbon-14 Project - Phase 1 Report

December 2012
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Abstract

Carbon-14 is a key radionuclide in the assessment of the safety of a geological disposal facility for radioactive waste.

NDA RWMD has established an Integrated Project Team, in which the partners will work together to develop a holistic approach to carbon-14 management in a geological disposal system.

The overall aim of the integrated project is:

“To support geological disposal of UK wastes containing carbon-14, by integrating our evolving understanding from current and pre-existing projects, in order to develop a holistic approach to carbon-14 management in the disposal system”.

This report summarises the work that has been completed in Phase 1 of the project which aimed to:

- Summarise the current understanding, identify knowledge gaps and clarify key uncertainties;
- Capture the understanding in a description of the modelling basis that is kept up to date (captured in a set of tables);
- Identify the approaches, models and tools required to support assessments;
- Set out the way forward for Phase 2.

This report incorporates the Roadmap issue 2, which sets out the work that will be undertaken in Phase 2 of this Integrated Project. Phase 2 will last until the end of 2014.
Executive Summary

NDA RWMD has established an integrated project team to develop a holistic approach to carbon-14 management in a geological disposal facility. This report summarises the work carried out in Phase 1 of the project, between April and October 2012. In Phase 1, we aimed to summarise our current understanding, identify knowledge gaps and clarify key uncertainties. We have captured this understanding in a “modelling basis spreadsheet” and carried out scoping assessments that help us to develop our understanding of the potential significance of carbon-14.

There are 9,876 TBq of carbon-14 in the 2010 Baseline inventory (incorporating existing enhancements). In the Phase 1 work, we have calculated that if carbon-14 is released to the biosphere in the form of methane, then the release rate that gives an assessed impact equal to the risk guidance level is ~ 6 x 10^{-4} TBq/year. This means that the wastes containing carbon-14 need to be isolated and contained within the geological disposal system in such a way that spreads any release over a long period of time.

Using the current modelling basis, the calculated release of carbon-14 exceeds the risk guidance level and is dominated by: corrosion of reactive metals (in the operational and early post-closure time frame); corrosion of irradiated stainless steel and leaching of irradiated graphite.

The Phase 1 work has shown, however, that there is considerable scope for improving the calculated radiological consequence for these wastes:

- The inventory is based on assumed material precursor concentrations, which may be overestimated. Work is proposed in Phase 2 that will improve the inventory.
- Some carbon-14 might be lost from wastes before disposal. Work is proposed in Phase 2 that aims to allow these losses to be taken into account.
- The current graphite release model is simple and could be revised to reflect the data and understanding from arising work, with the aim of reducing the graphite source term. Work is proposed in Phase 2 that will update the modelling basis for release of carbon-14 from graphite, based on data arising from the NDA RWMD programme and from other relevant work. It is possible that a significant proportion of the graphite carbon-14 inventory is associated with the graphite matrix and is essentially immobilised. The arguments associated with the long-term stability of graphite will be reviewed.
- There are only very limited data on carbon-14 release from irradiated stainless steels. An experimental programme to gather these data will be undertaken through the proposed collaborative international CAST project and will form part of the Phase 2 work.
- The modelling approach could take into account more appropriate surface area data to calculate the gas produced by corrosion of specific metal wastes (e.g. AGR fuel cladding). This will form part of the Phase 2 work.
- There are no available data on carbon-14 release from irradiated reactive metals. An experimental programme to gather these data has just started and will form part of Phase 2.
- Generation of carbon-14 bearing gases is dependent on water availability and this may be overestimated in the modelling approach. Work is proposed in Phase 2 to consider the impact of water availability, particularly on the corrosion of reactive metals, to investigate whether gas generation is more likely to occur in the operational and early post-closure period (in which case the peak generation rate would be high, but could perhaps be mitigated), or whether it is more likely to be spread out over a longer period.
• There may be microbial metabolism of hydrogen in the near field of the ILW system, which would reduce the amount of bulk gas migrating through the disposal system. Evidence for such microbial processes will be gathered as part of an existing PhD project, which may give some insights during the Phase 2 work.

• The geosphere may have features, such as cap rocks that retard or prevent the breakthrough of gas at the surface. In an evaporite or lower strength sedimentary rock, there is unlikely to be a significant release of carbon-14 bearing gas to the biosphere. In regions of higher groundwater flow, gas may be dissolved. Work is proposed in Phase 2 to develop the geosphere modelling approach for the total system model for carbon-14 in higher strength rocks. If required in the later phases of the project, information will be developed that could inform site characterisation requirements. This would allow a future site-specific model to be developed.

• There may be scope to reduce the calculated radiological consequences in the generic Operational Environmental Safety Assessment, by revising the approach to reflect the expanded knowledge base generated in this project. This will be addressed in Phase 2.

• There may be scope to reduce the calculated post-closure consequences by revising the current assumption that methane is fully converted to carbon dioxide in the soil zone. This will be considered in Phase 2, based on data and understanding from our experimental programme, together with a literature review and participation in an international review project. If justified, the improved understanding will then be reflected in the modelling basis.

• There is some scope for alternative approaches to management of certain waste streams within the disposal system, and these will be investigated further in Phase 2. For example, ILW core graphite could be segregated so that it is located away from waste packages generating significant quantities of bulk gas, and if appropriate, alternative approaches could be considered for wastes containing reactive metals.

We have provided Issue 2 of the Project Roadmap, as part of this Phase 1 report. Phase 2 is expected to last for 2 years until the end of 2014. The proposed programme addresses the above work areas. At key points of the programme, the modelling basis spreadsheet will be updated, and revised assessment calculations will be undertaken.
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1 Introduction

NDA RWMD has established an integrated project team to develop a holistic approach to carbon-14 management in a geological disposal facility. In this Section we describe the objectives of the project, and the structure and management of the Integrated Project Team.

The Nuclear Decommissioning Authority (NDA) has established the Radioactive Waste Management Directorate (RWMD) to manage the delivery of geological disposal for higher activity radioactive wastes as required under UK Government policy, and published in the Managing Radioactive Waste Safely (MRWS) White Paper [1].

Carbon-14 is a key radionuclide in the assessment of the safety of a geological disposal facility (GDF) for radioactive waste. In particular, the radiological consequences of gaseous carbon-14 bearing species is a potential issue and has been recognised as such in Nirex report N/122 [2], in the generic DSSC [3], and in the issues register [4].

NDA RWMD has been carrying out a range of research and assessment tasks on carbon-14 to improve the understanding of the expected evolution of the disposal system and the consequences for the calculated annual risk. Much of this work is summarised in the gas status report [5], the radionuclide behaviour status report [6], and in the R&D Programme Overview document [7]. However, following publication of the DSSC, it has been decided to adopt a collaborative approach to tackling issues related to carbon-14 by establishing an Integrated Project Team, in which the partners work together to develop a holistic approach to carbon-14 management in a geological disposal facility.

This report summarises the work that has been completed in Phase 1 of the project which aimed to:

- Summarise the current understanding, identify knowledge gaps and clarify key uncertainties;
- Capture the understanding in a live list called the “modelling basis”;
- Identify the approaches, models and tools required to support assessments;
- Set out the way forward for Phase 2.

This report incorporates the Roadmap issue 2, which sets out the work that will be undertaken in Phase 2. Phase 2 will last until the end of 2014.

1.1 Objectives of the carbon-14 integrated project

The overall aim of the integrated project is:

“To support geological disposal of UK wastes containing carbon-14, by integrating our evolving understanding from current and pre-existing projects, in order to develop a holistic approach to carbon-14 management in the disposal system. This includes the following sub-objectives:

- To inform strategic decisions on disposal options for specific waste types and inform packaging decisions for specific waste streams;
- To provide data and understanding and, if necessary, develop conceptual and component-level models to support the transport, operational and environmental safety cases;
• To develop options for an integrated waste management approach to disposal of these wastes;
• To establish whether mitigation measures or design solutions are required;
• To develop data and understanding required to inform the siting process that will be undertaken during MRWS stage 5;
• To inform the requirements for site characterisation;
• To deliver value for money.

A successful outcome from this project would be that we understand the envelope of conditions within which disposal of the UK’s wastes containing carbon-14 can be managed."

1.2 Structure and management of the integrated project

Establishing these integrated projects has involved tackling the work in a holistic and integrated way. NDA RWMD has established an integrated project team, which involves a team of people working in partnership to develop a holistic approach to carbon-14 management in the disposal system. The project team includes members from a number of our contracting organisations (representing different “Lots” in our contracting framework) and members from the different technical functions within NDA RWMD. The team incorporates a wide range of expertise, following a “best athlete” approach and includes a number of people with international reputations in their field.

The IPT reports to NDA RWMD’s programme board through the IPT project board, which is chaired by NDA RWMD’s Science Director. The project is managed collaboratively by a representative of NDA RWMD and the Lead Technical Manager (who is a contractor). The IPT also includes relevant pre-existing tasks which have been transferred into the IPT. As the project progresses, we may expand the core project team with additional experts, or alternatively, tasks may be bid through the wider supply chain.

The project has a Roadmap, which sets out the work of the IPT, broken down into two phases; Phase 1, which lasted for six months and is now complete and Phase 2, which is expected to last for a period of around two years. An Issue 1 Roadmap was completed at the end of May 2012 [8], following a project kick-off workshop. It divides the technical work into a number of areas and sets out the current understanding, the work for Phase 1 of the project and an outline of the work expected in Phase 2.

This document reports the Phase 1 work. A revised Roadmap (Issue 2) is included within this report setting out the work for Phase 2. Following our “best athlete approach” tasks will either be carried out within the core team (either by NDA RWMD or by contractors), or bid in the wider supply chain. The key reports and timescales are shown below in Figure 1.

---

1 The lead contracting organisation is AMEC, supported by Poyry, ARUP, the University of Nottingham, Mike Thorne and Associates, and Jacobs.
The following sections describe the outputs of Phase 1 of this project. The overall Technical approach is summarised in Section 2. Then each of Sections 3 to 8 describes our current understanding at the end of Phase 1 in the various technical areas. This understanding is then brought together in the other sections of the document, where we describe the modelling approach (Section 5), the approach to quantitative safety assessment (Section 9), and the approach to evaluating possible alternative treatment, packaging, or design options (Section 10). In Section 11 we provide the Roadmap and way forward for Phase 2, where we summarise the current position for different groups of waste, and describe the proposed work programme for Phase 2, which is expected to last for two years, until the end of 2012.
2 The technical approach summarised

Carbon-14 is a key radionuclide in the assessment of the safety of a geological disposal facility (GDF) for radioactive waste. In particular, the radiological consequences of gaseous carbon-14 bearing species have been recognised as a potential issue. In this Section we summarise previous assessment studies, and the inventories on which they have been based. The key generation and migration processes are well understood, and have been used to form the basis of the integrated technical approach adopted in this project.

The carbon-14 content of the 2010 Baseline Inventory (incorporating existing enhancements) is 9,876 TBq. It is produced by thermal neutron activation of nitrogen-14, carbon-13 and oxygen-17 “precursor” species when nuclear fuel components and reactor core structures are irradiated. The half-life of carbon-14 is 5,730 years, so if it can be retained within the multi-barrier system for sufficient time then it will decay. However, it is possible for carbon-14 to be released as a gas, such as $^{14}$CH$_4$. Using the biosphere model developed in Section 8, we calculate that a release of carbon-14 to the biosphere in the form of methane of $\sim 6 \times 10^4$ TBq/year is equivalent to the regulatory risk guidance level. Therefore if carbon-14 is released in the form of methane gas and this gas is able to migrate quickly to the biosphere, the calculated risk could exceed the regulatory risk guidance level. This means that the wastes containing carbon-14 need to be isolated and contained within the geological disposal system in such a way that spreads any release over a long period of time.

The waste inventory is discussed in detail in Section 3, but in summary, the main components of the carbon-14 inventory are in irradiated graphite, irradiated steels, irradiated reactive metals (Magnox and uranium) and spent fuel. There is also carbon-14 in the form of small organic molecules produced by GE Healthcare. These wastes are in the Baseline inventory, but they are actually planned for incineration rather than disposal.

A summary of the inventory is given in Table 1 below.

<table>
<thead>
<tr>
<th>Waste</th>
<th>Best estimate C-14 inventory (TBq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILW &amp; LLW core graphite</td>
<td>7140</td>
</tr>
<tr>
<td>ILW fuel element graphite</td>
<td>50</td>
</tr>
<tr>
<td>AGR stainless steel fuel cladding and assembly components</td>
<td>530</td>
</tr>
<tr>
<td>ILW stainless steels and other ferrous metals from reactor decommissioning and other ferrous metal reactor wastes</td>
<td>450</td>
</tr>
<tr>
<td>ILW reactive metals (Magnox, uranium)</td>
<td>120</td>
</tr>
<tr>
<td>ILW organics</td>
<td>560* (Not for disposal)</td>
</tr>
<tr>
<td>Spent fuels</td>
<td>930</td>
</tr>
<tr>
<td>Other ILW</td>
<td>110</td>
</tr>
</tbody>
</table>
Certain wastes will be packaged to provide physical containment for many years. However, this is not universally so, and intermediate-level waste packages will generally be vented.

A history of carbon-14 inventories and their usage in different studies is given in Table 2 below. A discussion of how and where the different inventories have been used is presented in the following section.

**Table 2  Inventory history and usage**

<table>
<thead>
<tr>
<th>Inventory name</th>
<th>Carbon-14 inventory,</th>
<th>Used for</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001 Inventory</td>
<td>~3600 TBq</td>
<td>Calculations in the Technical note about carbon-14 [9]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Calculations presented in the Viability report [2]</td>
</tr>
<tr>
<td>2004 UKRWI</td>
<td>7950 TBq (ILW)</td>
<td>Update of the GPA (03) assessment of the consequences of gas [10]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Numerical calculations discussed in the Gas status report [5].</td>
</tr>
<tr>
<td>2007 UKRWI</td>
<td>7,530TBq (Does not include spent fuel)</td>
<td>Used as the basis of the 2007 Reference case derived inventory</td>
</tr>
<tr>
<td>2007 Reference case derived inventory [11, 12]</td>
<td>~9,400 TBq (excluding 6000TBq in HLW now thought to be absent)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Includes enhancements based on packaging assumptions and waste characteristics</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Discussed in the gas status report</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Numerical calculations in the 2012 gas assessment [13]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Calculations in pre-closure to post-closure gas report [14]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Calculations in Section 5 of this report</td>
</tr>
<tr>
<td>2010 UKRWI Baseline inventory [15]</td>
<td>9,683 TBq</td>
<td>Forms the basis of the 2010 Estimated derived inventory</td>
</tr>
<tr>
<td>2010 Estimated Derived Inventory [16]</td>
<td>Captures previous enhancements that remain valid</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9,876 TBq</td>
<td>Discussed in Section 3 of this report.</td>
</tr>
<tr>
<td>2010 UKRWI Upper inventory (includes new build reactor decommissioning and additional reprocessing)</td>
<td>Best estimate of 12,556TBq (going up to 88,754 TBq including consideration of uncertainty bands).</td>
<td>Discussed in Section 3 of this report.</td>
</tr>
</tbody>
</table>
2.1 **Carbon-14 – a brief history of assessments work carried out by NDA RWMD**

The radiological consequences of carbon-14 generated from the degradation of small organic molecules, discharging directly to the biosphere were recognised in the generic post-closure performance assessment published by Nirex in 2003 [17]. It was noted that there were other potential sources of carbon-14 (for example in the form of metal carbides and graphite) that would need to be addressed in future assessments.

This work was taken forward in a technical note on carbon-14 [9] and was also described in [2], where calculations were presented to scope the potential impact of carbon-14. The results of these calculations are reproduced in Figure 2 below.

**Figure 2**  
*Annual individual risk vs. time for carbon-14 dissolved in groundwater and for the scoping calculation for carbon-14 released as gas, from [2]*

These calculations are based on the 2001 inventory and reflect the available understanding of gas generation and release as set out in [9]. Calculations are shown for two scenarios. In the first of these (the blue curve) it is assumed that carbon-14 all dissolves in groundwater and is released to the biosphere in solution; in this case the calculated risk is well below the regulatory risk guidance level. In the second scenario (the yellow curve) it is assumed that methane containing carbon-14 could be generated from irradiated metals, graphite and organic molecules and that any methane generated is released to the biosphere; with the geosphere neither retarding nor retaining the gas. The radiological consequences were calculated using the same biosphere assumptions as in the previously published GPA [17] and the calculated risk from this scenario was significantly above the risk guidance level.

In practice, however, in a multi-barrier system, the geosphere would be expected to play a role and it was recognised [2] that in many geological settings, some degree of gas retardation would be expected. Further work was carried out to investigate the extent to which it might be expected that the geosphere would act to retard or delay the breakthrough of gas at the surface [18] and it was found that for all but one of the variants studied, there was no breakthrough at the surface.
The manner of any release would be site specific, and therefore it was recommended in a regulatory review of gas generation and migration [19] that detailed modelling of any particular geological formation may not be the best use of resources at this stage. The review recommended that, at this stage, NDA RWMD should identify the key gas transport questions that need to be addressed to support the site selection and characterisation process. The NDA RWMD response [20] proposed that such requirements be considered in the light of the conclusions of the forthcoming generic disposal system safety case (DSSC).

The generic DSSC was supported by the gas status report [5], which presented calculations of carbon-14 gas generation based on the 2004 inventory. These calculations again showed that, based on the available understanding of gas generation; direct release of these gases to the biosphere would result in radiological consequences above the risk guidance level.

The calculations presented in the gas status report did not include consideration of the role of the geosphere. Further modelling work has been carried out (based on the 2007 inventory) to investigate the potential impact of coupling between gas generation and groundwater flow in different generic geological environments (higher strength rock, lower strength sedimentary rock and evaporite) [14]. In this work, the model for higher strength rocks shows similar results to the calculations in the gas status report; but in lower strength sedimentary rock and evaporite releases of free gases from the host rock are negligible or zero.

The generic DSSC is mostly based on the 2007 inventory, but no new gas generation calculations were carried out and the calculations presented in the gas status report (which supports the generic DSSC) are based on the 2004 inventory. Further calculations, based on the 2007 inventory, are being carried out in “Updated Gas Assessment 2012” [13] to update those presented in the gas status report. Some of these calculations are presented in Section 5 of this report.

One of the aims of the integrated project on carbon-14 is to consider the assessments that have been carried out together with our evolving understanding of the gas generation and migration processes in a holistic way, to develop an integrated approach to managing wastes containing carbon-14.

Carbon-14 is increasingly being recognised as a safety case issue by other waste management organisations. The European Union Implementing Geological Disposal Technology Platform (IGD-TP) has recognised the carbon-14 source term as a priority within its most recent call for proposals and the proposed project will provide an important forum for benchmarking and agreeing how to represent the source term for carbon-14 in the safety case.

2.2 Key generation and migration processes

The key processes that could result in a significant radiological consequence from carbon-14 are shown in Figure 3 below. Gas can be generated in the near field of a GDF if water is able to interact with the wastes. This is discussed in more detail in Section 4. The main gas generation processes are corrosion of metals, degradation of organic materials and radiolysis. Some of the gas that is produced could contain carbon-14. A discussion about the rates of gas generation required for a separate gas phase is presented in Section 5. Carbon dioxide is likely to be retained within the engineered barrier system through carbonation (see Section 6). However, methane is likely to be either dissolved or entrained within a separate bulk gas phase. Section 7 discusses the features of the geosphere that could prevent or delay migration of gas through the geosphere, but if gas is able to reach the biosphere, it could be released directly as methane or converted to carbon dioxide by microbes in the soil zone. This carbon dioxide would then be taken up by plants and enter the food chain; leading to a consequent dose to any exposed groups or potentially exposed groups (as discussed in Section 8).
From this understanding of the key processes, we have developed our integrated technical approach to the project. We call this integrated technical approach the “AND” approach, as described in Box 1 below.

**Box 1**  
**The integrated technical approach (the **AND** approach)**

For a waste stream containing carbon-14 to be an issue:

- There must be a significant inventory of carbon-14 in the waste stream;  
  **AND**
- That waste stream has to generate carbon-14 bearing gas;  
  **AND**
- A bulk gas phase has to entrain the carbon-14 bearing gas;  
  **AND**
- These gases must migrate through the engineered barriers in significant quantities;  
  **AND**
- These gases must migrate through the overlying geological environment (either as a distinct gas phase or as dissolved gas);  
  **AND**
- These gases must interact with materials in the biosphere (i.e. plants) in a manner that leads to significant doses and risks to exposed groups or potentially exposed groups.

As discussed above, the assessed risk from the migration of carbon-14 in groundwater is generally found to be below the risk guidance level because the ground water travel time is long in comparison with the half-life of carbon-14. However, because there is interaction
between carbon-14 in gas and groundwater, it may be appropriate to consider them together within a total system model².

The integrated project team has used this approach as a way of considering the problem comprehensively and to underpin the prioritisation of the technical work. We have used the “AND” approach for each waste stream in order to break the problem down in a manageable way. We have also used it to underpin our integration activities, in particular the approach to alternative treatment packaging and design options. The steps of the “AND” approach, together with our key integration tools, also frame the structure of the rest of this document and these links are shown in Figure 4.

**Figure 4**  **Schematic showing the steps of the AND approach and where these are discussed in this report**

![Schematic showing the steps of the AND approach and where these are discussed in this report](image)

The AND approach is one of our key integration tools and is used to inform our structured approach to considering alternative treatment, packaging and design options within the IPT. Our other key integration tools are a “modelling basis spreadsheet” and a scoping model. These tools are used to record and communicate our current understanding of the various aspects of the carbon-14 issue and to record how we represent this understanding in the scoping model. The scoping model is used to quantitatively assess alternative options and to develop our understanding of the impact of different components of the overall system.

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² A total system model is a simplified model used to calculate overall performance measures of the geological disposal system, such as radiological dose and risk
3 Inventory

For a waste stream containing carbon-14 to be an issue, there must be a significant inventory of carbon-14 in the waste stream.

In this Section we have documented the current understanding of the carbon-14 inventory and identified knowledge gaps related to the inventory data for each of the key waste types.

There are 9,876 TBq of carbon-14 in the 2010 Baseline inventory (incorporating existing enhancements). The main components of the carbon-14 are in irradiated graphite, irradiated steels, irradiated reactive metals (Magnox and uranium) and spent fuel.

In Phase 2, it is planned to improve the inventory, by carrying out investigations into the basis for the current inventory data and, where possible, by improving the materials data underlying the inventory. The improved inventory will then be used by the IPT.

The 2010 UK Radioactive Waste Inventory (UKRWI) was published in March 2011 [15, 16, 21]. This is the most up-to-date UK national inventory available. As discussed in Section 2 above, this builds on the earlier 2007 UKRWI. However, because more processing of the 2007 UKRWI has been undertaken to develop the Derived Inventory, the 2007 inventory is used in the calculations reported in Section 5 [11, 12].

In this Section, we consider the important waste types in turn, examining the basis of the declared inventories in the most significant streams, focusing in particular on graphite, steels and reactive metals, to identify the important knowledge gaps. This then forms the basis of the work programme for Phase 2.

3.1 Statement of current understanding and knowledge gaps

Carbon-14 in wastes is produced predominantly by the thermal neutron activation of precursor species present in nuclear fuel components and reactor core structures. The principal source of production is nitrogen-14, but carbon-13 and oxygen-17 are also important contributors for certain wastes. Carbon-14 is also produced in fuel from tertiary fission, but this production route makes only a very minor contribution.

The carbon-14 produced in nuclear power reactors can be released directly to the environment in a gaseous form or in much smaller quantities as liquid effluents. The remaining carbon-14 stays in the reactor core until decommissioning or passes to the fuel reprocessing plant in the spent fuel and other fuel element components. Some of the carbon-14 from the spent fuel is released during reprocessing into the off-gases during the dissolution stage. This can be released as CO₂ gas, scrubbed out and discharged as a liquid effluent, or converted to a solid, which is then managed as a waste. The fuel cladding and other fuel element components containing carbon-14 are managed as solid waste.

The dominant production routes for carbon-14 in AGR reactor core components and typical target elemental concentrations are shown in Table 3 and Table 4 below:
Table 3  Dominant nuclear production routes for carbon-14 arising from AGR operation 3

<table>
<thead>
<tr>
<th>Production reaction</th>
<th>Abundance of target isotope</th>
<th>Thermal neutron (2200 ms⁻¹) cross-section (barns)</th>
<th>Proportion of inventory from production route</th>
</tr>
</thead>
<tbody>
<tr>
<td>¹⁴N(n,p)¹⁴C</td>
<td>99.63%</td>
<td>1.76</td>
<td>~100%</td>
</tr>
<tr>
<td>¹⁷O(n,α)¹⁴C</td>
<td>0.04%</td>
<td>0.226</td>
<td>~0%</td>
</tr>
<tr>
<td>¹³C(n,γ)¹⁴C</td>
<td>1.10%</td>
<td>0.0013</td>
<td>~0%</td>
</tr>
<tr>
<td>Tertiary Fission</td>
<td></td>
<td></td>
<td>0%</td>
</tr>
</tbody>
</table>

Table 4  Target element concentrations

<table>
<thead>
<tr>
<th>Target element</th>
<th>Target element concentration in material (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AGR fuel cladding stainless steel</td>
</tr>
<tr>
<td>N</td>
<td>450</td>
</tr>
<tr>
<td>O</td>
<td>250</td>
</tr>
<tr>
<td>C</td>
<td>150</td>
</tr>
</tbody>
</table>

Hence, the results of calculations of the carbon-14 inventory in wastes and spent fuel for geological disposal are critically dependent on assumed material precursor concentrations, and, where measurements of precursor levels have been made, how representative these are. They also depend on how much of the carbon-14 inventory might be released from wastes before disposal.

The other potential major source of carbon-14 in wastes for disposal to the GDF is the manufacturing and development of radiopharmaceuticals and bioscience products by GE Healthcare. Although these wastes are currently in the Baseline inventory, the company plans to incinerate these organic wastes, in which case this source of carbon-14 could be removed from the GDF Inventory. Currently, it is being retained in the inventory as a contingency against failure to meet the regulatory requirements for incineration.

The carbon-14 content of NDA RWMD’s 2007 Derived Inventory Baseline Inventory [11] is about 9,400 TBq (excluding 6,000 TBq in HLW, which is now judged not to be present in the waste) – Table 1. The Upper Inventory contains about 11,500 TBq (Table 2).

The 2010 UK Radioactive Waste Inventory [15] was published in March 2011. Subsequent to the publication of the 2010 UKRWI, NDA RWMD has developed an updated Derived Inventory – the 2010 Estimated Derived Inventory (EDI) to capture the latest data on waste quantities and properties in the 2010 UKRWI as well as retaining enhancements to waste characteristics and packaging that remain valid.

The carbon-14 content of the 2010 EDI Baseline Inventory (incorporating existing enhancements) is 9,683 +193 TBq ⁴. The vast majority originates from nuclear reactors and the reprocessing of spent fuel and other fuel element components. Table 5 below shows the major contributors to the total carbon-14 inventory. The wastes have been divided into

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3 In PWRs the main source of carbon-14 is through the oxygen-17 reaction with water coolant.
4 See Table 5 for an explanation of the +193 TBq.
material categories – graphite, steels, reactive metals (Magnox plus uranium) and other wastes – and within these categories into separate waste groups. The categories and waste stream groups have been informed by discussions within the IPT in other topic areas (see Sections 5.1 and 10.1). To date the work has focused on the major types listed in Table 5; some of the other categories discussed later in the report (e.g. ion-exchange resins) have not been examined in as great a detail to date.

Table 5  Major components of carbon-14 inventory

<table>
<thead>
<tr>
<th>Category – Waste stream group</th>
<th>Total C-14 activity (TBq)</th>
<th>Contribution to total C-14 activity (%) (4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graphite - ILW core graphite</td>
<td>7,132</td>
<td>72.2</td>
</tr>
<tr>
<td>Graphite - ILW AGR fuel element graphite</td>
<td>45</td>
<td>0.5</td>
</tr>
<tr>
<td>Graphite - ILW Magnox fuel element graphite</td>
<td>6</td>
<td>0.1</td>
</tr>
<tr>
<td>Steels - ILW AGR stainless steel fuel cladding</td>
<td>28 (+143)</td>
<td>1.7</td>
</tr>
<tr>
<td>Steels - ILW AGR stainless steel fuel assembly components</td>
<td>356</td>
<td>3.6</td>
</tr>
<tr>
<td>Steels - ILW stainless steels from reactor decommissioning</td>
<td>226</td>
<td>2.3</td>
</tr>
<tr>
<td>Steels - ILW other ferrous metal decommissioning wastes</td>
<td>197</td>
<td>2.0</td>
</tr>
<tr>
<td>Steels - ILW other ferrous metal reactor wastes</td>
<td>28</td>
<td>0.3</td>
</tr>
<tr>
<td>Reactive metals - ILW reactive metals (Magnox and uranium)</td>
<td>66 (+50)</td>
<td>1.2</td>
</tr>
<tr>
<td>Other wastes - ILW organics from GE Healthcare (2)</td>
<td>560</td>
<td>5.7</td>
</tr>
<tr>
<td>Other wastes - Other ILW</td>
<td>67</td>
<td>0.7</td>
</tr>
<tr>
<td>Other wastes - Spent fuels</td>
<td>926</td>
<td>9.4</td>
</tr>
<tr>
<td>Other wastes - LLW core graphite</td>
<td>6</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Other wastes - Miscellaneous not assigned (3)</td>
<td>40</td>
<td>0.4</td>
</tr>
<tr>
<td><strong>Total C-14 in 2010 EDI Baseline Inventory</strong></td>
<td><strong>9,683 (+193)</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

Notes:  
(1) Red figures show the impact of enhancement of the 2010 EDI. These enhancements have been carried forward from the 2007 Derived Inventory.  
(2) ILW organics from GE Healthcare may not be disposed of to the GDF.  
(3) This group comprises those waste streams that contain low concentrations of carbon-14 but do not fit into any of the designated waste stream groups.  
(4) Includes enhancements.

Table 8 to Table 11 show the waste streams that contribute to the carbon-14 activity in the 2010 EDI Baseline Inventory for each material category and waste stream group. These include an indication of the current packaging plans and what information there currently is on how the carbon-14 activity has been calculated for each waste stream. In these tables, wastes that have already been packaged are highlighted in blue; wastes that are currently being packaged are highlighted in green; and wastes with plans reported in the UKRWI for packaging are highlighted in yellow.

The carbon-14 activity is a best estimate that is bounded by lower and upper values of about 1,806 TBq and 88,754 TBq based on waste stream activity “uncertainty bands”. Radionuclide activity uncertainty bands for waste streams in the Derived Inventory are taken from the UKRWI. The factors associated with these bands apply to the best estimate specific activities and are intended to represent the 5th and 95th percentile of the probability distribution. However, it is recognised that, in general, reporting of uncertainty bands may
well be overly cautious, and therefore gives a much greater uncertainty band for carbon-14 activity than is likely in reality.

The best estimate carbon-14 content of NDA RWMD’s 2010 EDI Upper Inventory is 12,556 TBq, with more carbon-14 associated with core graphite (an additional 2,066 TBq as a result of incorporating waste volume uncertainty factors), steels from new build reactor decommissioning (an additional 554 TBq), and organics from GE Healthcare (an additional 168 TBq as a result of incorporating waste volume uncertainty factors), and less overall from spent fuel (637 TBq) because of changes to the reprocessing programme.

Overall, the carbon-14 content of the 2010 EDI Baseline and Upper inventories are about 5% and 10% greater than for the 2007 Derived Inventory. The larger increase in the Upper Inventory is the result of some higher forecast core graphite volumes and activities.

As stated above, carbon-14 activities in NDA RWMD’s Derived Inventories are based on data in the UKRWI. The constraints of the Phase 1 UKRWI exercise means that only superficial assessments of the data provided by the waste producers can be completed. Furthermore, Derived Inventory radionuclide data enhancements have focused on correcting apparent anomalies and filling gaps in the data. An in-depth investigation, assessment and verification of the carbon-14 inventory has not been undertaken in preparing these various inventories. An earlier independent “top-down” assessment did not identify any significant discrepancies, but was limited in scope.

The main categories of waste are discussed in turn in the following Sections. The identifier for the waste streams, as used in the UKRWI, is given in the first column of the tables presented. The first two characters can be used to identify the source of the waste, as detailed in Table 6 below.
Table 6  Waste stream site owners, waste custodian and sites [15]

<table>
<thead>
<tr>
<th>Start of Stream Identifier</th>
<th>Site Owner</th>
<th>Waste Custodian</th>
<th>Site</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A, 1B GE Healthcare Limited</td>
<td>GE Healthcare Ltd</td>
<td></td>
<td>Amersham, Cardiff</td>
</tr>
<tr>
<td>2A NDA</td>
<td>Sellafield Ltd</td>
<td></td>
<td>Calder Hall</td>
</tr>
<tr>
<td>2C NDA</td>
<td>Sellafield Ltd</td>
<td></td>
<td>Chapelcross</td>
</tr>
<tr>
<td>2D, 2F NDA</td>
<td>Sellafield Ltd</td>
<td></td>
<td>Sellafield</td>
</tr>
<tr>
<td>2S NDA</td>
<td>Sellafield Ltd</td>
<td></td>
<td>Windscale</td>
</tr>
<tr>
<td>3J – 3N EDF Energy</td>
<td>British Energy Generation</td>
<td></td>
<td>Dungeness B, Hartlepool, Heysham 1, Heysham 2, Hinkley Point B</td>
</tr>
<tr>
<td>3S EDF Energy</td>
<td>British Energy Generation</td>
<td></td>
<td>Sizewell B</td>
</tr>
<tr>
<td>4B, 4C EDF Energy</td>
<td>British Energy Generation</td>
<td></td>
<td>Hunterston B, Torness</td>
</tr>
<tr>
<td>5B NDA</td>
<td>Dounreay Site Restoration Ltd</td>
<td></td>
<td>Dounreay</td>
</tr>
<tr>
<td>5C NDA</td>
<td>Research Sites Restoration Ltd</td>
<td></td>
<td>Harwell</td>
</tr>
<tr>
<td>5G NDA</td>
<td>Research Sites Restoration Ltd</td>
<td></td>
<td>Winfrith</td>
</tr>
<tr>
<td>7G Ministry of Defence</td>
<td>Babcock and Ministry of Defence</td>
<td></td>
<td>Rosyth &amp; Devonport (Submarines)</td>
</tr>
<tr>
<td>7V Ministry of Defence</td>
<td>Ministry of Defence</td>
<td></td>
<td>Dounreay (Vulcan)</td>
</tr>
<tr>
<td>9A – 9D, 9F NDA</td>
<td>Magnox South Ltd</td>
<td></td>
<td>Berkeley, Bradwell, Dungeness A, Hinkley Point A, Sizewell A</td>
</tr>
<tr>
<td>9E, 9G – 9J NDA</td>
<td>Magnox North Ltd</td>
<td></td>
<td>Oldbury, Trawsfynydd, Wylfa, Hunterston A</td>
</tr>
</tbody>
</table>

\[ M2, M3 \quad AGR \text{ and PWR spent fuel}^5 \]

\[ ^5 \] Spent fuel inventories are not reported in the UKRWI.
3.1.1 Graphite

Information on graphite is provided in Table 8.

Carbon-14 is produced by the $^{13}$C(n,$\gamma^{\prime}$)$^{14}$C and $^{14}$N(n,p)$^{14}$C reactions in the graphite moderators of Magnox and AGR reactors. About 60% of the carbon-14 generated is produced by interaction with the nitrogen impurities in the graphite and 40% by interaction with the carbon-13 in the graphite. Most of the graphite moderator remains in the reactor core and will arise as waste during Final Site Clearance (FSC).

The graphite becomes corroded during reactor operation by a radiolytic reaction in the presence of the CO$_2$ coolant. The rate of the reaction depends on the irradiation level, the coolant composition and the pore structure of the graphite. A large portion of the carbon-14 gaseous releases comes from the clean-up of the CO$_2$ circuits used to cool the reactor and from isotopic exchange between the moderator and CO$_2$ circuit. Estimates of the carbon-14 released from a graphite moderator into the coolant are about 6-7%. The carbon-14 in the coolant is discharged into the atmosphere. Carbon-14 activity in core graphite is based on activation calculations, but it is not known whether any assumptions have been made regarding the loss of some of the carbon-14 to the coolant.

Additional nitrogen contamination of the graphite can arise as a consequence of adsorption of nitrogen from coolant gases onto graphite surfaces (including the open porosity of the graphite). It is not known whether any assumptions have been made regarding the possible increase in nitrogen from this source.

The 2010 UKRWI does not give information on the nitrogen impurity levels in Magnox reactor and AGR graphite. However, Pöyry is aware, from work carried out for Magnox Ltd, that an impurity level of 25 ppm is used in calculations of Magnox core graphite activities. During the 2007 UKRWI exercise, the carbon-14 activities in FSC ILW graphite were revised by EDF Energy following discussions with NDA to be more in line with the Magnox data, but the source of the data was not supplied.

Characterisation of radioactive graphite waste is complicated due to many variables affecting nuclear plant design and operational conditions. Nuclear grade graphite has been sourced from a variety of locations, and the effects of variables such as operational lifetimes, reactor assembly, core temperature, fuel, coolant composition, graphite radiolytic weight loss and shutdown periods on the microstructure and its properties need to be considered. Pile Grade A and Pile Grade B have been used in Magnox reactors and Gilsocarbon graphite in AGRs. It is understood that in general the graphite used in AGR reactors is not as pure as that used in Magnox reactors.

3.1.2 Steels

Information on steels is provided in Table 9. Carbon-14 in steels is produced primarily by the $^{14}$N(n,p)$^{14}$C reaction.

The major contributors to carbon-14 in stainless steel are AGR fuel cladding/assembly components and items from reactor decommissioning. Other ferrous metals comprise mainly mild steel, with the major contributors being items from reactor decommissioning and miscellaneous activated components from reactor operations.

AGR fuel cladding comprises austenitic stainless steel 20Cr/25Ni/Nb and varies in thickness from 0.37mm to 0.46mm. The AGR fuel element grids and braces are made from 20Cr/25Ni/Ti and are of a similar thickness. Some AGR assembly components are identified as comprising 18Cr/9Ni/Nb and Nimonic. The nitrogen impurity levels on which the UKRWI carbon-14 activity calculations are based are unknown.

There is no information in the 2010 UKRWI on the composition of the stainless or mild steels from the PWR at Sizewell or the AGR stations that would be present in FSC wastes. The
waste stream data sheets state that the activity is from the activation of the steel and its impurities and that the major sources of uncertainty are the impurity levels.

Stainless steels from FSC at Magnox stations are made up of a number of grades including BS970-321S12, BS970-EN59, BS970-EN56 and EN58B. Activation calculations for FSC at the Magnox stations are known to use nitrogen impurity levels of 1,000 ppm in EN58B and BS970-321S12 and zero in other steels. These stainless steel wastes will be size reduced for packaging, and thicknesses are likely to vary from a few mm to about 25 mm.

Other ferrous metals from FSC at Magnox stations comprise a wide range of British standards grades. It is known that activation calculations for FSC wastes at the Magnox stations use nitrogen impurity levels of 200 ppm in certain mild steels and zero in other mild steels. These other ferrous metal wastes will be size reduced for packaging, and thicknesses are likely to vary from a few mm to about 100 mm.

3.1.3 Reactive metals

Information on reactive metals is provided in Table 10. Carbon-14 is produced primarily by the $^{14}$N$(n,p)^{14}$C reaction in uranium and Magnox wastes.

The major contributors to carbon-14 in reactive metals are Magnox cladding wastes, generated from decanning Magnox fuel as part of spent fuel reprocessing. The composition of the Magnox is mainly Magnox alloy AL80 used for the fuel element cans, with smaller amounts of alloy MN80 used for the end caps, bottom and top fittings (although at Wylfa the caps and fittings are alloy MN150). The cladding wastes include uranium carry-over from the fuel decanning process.

At Magnox power stations that used the helical fuel type, splitters and braces made from Magnox ZR55 are also present.

All Magnox fuel was manufactured at Springfields. Uranium ore concentrate was chemically processed to uranium tetrafluoride (UF$_4$), which was converted to uranium metal by mixing with magnesium metal. The uranium metal was remelted, cast into rods and inserted into magnesium alloy cans and fitted with end caps.

It is known that the nitrogen content of uranium metal was measured routinely at Springfields, so data should be available in the uranium database. It is not believed that nitrogen was routinely measured in Magnox alloy, so there is a need to access Springfields archives for possible one-off special studies. Of particular importance are studies conducted since the mid-1980s, since some data are available for early material manufactured prior to 1985.

3.1.4 Spent Fuels

Carbon-14 in spent fuel is produced primarily by the $^{14}$N$(n,p)^{14}$C and $^{17}$O$(n,\alpha)^{14}$C reactions.

Spent fuel radionuclide activities are not reported in the UKRWI, but were calculated for the Derived Inventory. AGR spent fuel activities were calculated using a cautious fuel burn-up of 39 GWd/tU and an initial U-235 enrichment of 3.5%. PWR spent fuel activities were calculated using a cautious fuel burn-up of 60 GWd/tU and an initial U-235 enrichment of 4.2%. No upper or lower uncertainty bands were derived.

The calculations used the following material nitrogen concentrations: UO$_2$ fuel (22 ppm); stainless steel AGR fuel cladding (630 ppm); Zircaloy PWR fuel cladding (80 ppm); stainless steel PWR fuel assembly sleeves (395 ppm) and Inconel grids (419 ppm).

3.1.5 Carbon-14 in Sellafield HLW

It is most likely that no carbon-14 is present in vitrified HLW. The addition of carbon-rich sugar solution to the HLW prior to calcination acts as a dispersant for the fission product
oxides, and should act as a carrier gas for the release of any carbon-14 present in the liquid HLW. Hence the carbon-14 is expected in aerial and liquid discharges and in solid process wastes.

NDA has undertaken provisional mass balance spreadsheet calculations for Sellafield spent fuel reprocessing operations in the period from 1995 to 2007. The calculations indicate that the carbon-14 input into the reprocessing plant dissolver approximately accords with what is recorded as discharged in aerial and liquid environmental releases plus what is trapped in the ILW streams arising downstream of the dissolver (i.e. THORP BaCO₃ and EARP floc). These calculations make use of nitrogen precursor data for uranium and UO₂ reported by Nexia Solutions (now NNL).

This position is supported by a Swiss inventory including the HLW produced by COGEMA using a similar vitrification process at Cap de la Hague, which shows only trace quantities of carbon-14 [22].

3.1.6 Methods used to apportion carbon-14 activity for mixed material waste streams

During compilation of NDA RWMD’s 2007 Derived Inventory, factors to apportion activity where there is more than one activated material were derived by assuming that the carbon-14 activity is generated by the thermal neutron activation of the nitrogen impurity content of the material. As a result these factors were derived as the product of three sub-factors:

\[ M = \text{the fraction of waste stream mass associated with the material;} \]

\[ N = \text{the concentration (in ppm) of nitrogen in the material (the assumption was that carbon-14 was primarily produced by the } ^{14}N(n,p)^{14}C \text{ activation reaction);} \]

\[ F = \text{the relative thermal neutron flux to which the material was exposed.} \]

The material mass fractions, M, were obtained from inventory waste stream data. The nitrogen concentration values, N, were largely taken as 50th percentile values derived from the upper and lower bound precursor concentration data [23]. The relative thermal flux data, F, was derived in several ways as follows:

- Where all the waste materials were irradiated in the fuelled region of a reactor core, such as the Magnox and uranium metal from a Magnox fuel element, F was taken as unity for all material types;

- For AGR stringer debris streams that contain Nimonic PE16 tie bars that pass through the fuelled core region and also graphite and steel components from outside the fuelled regions, \(^{35}\text{Cl}(n, \gamma)^{36}\text{Cl}\) activation rates developed for Nirex’s \(^{36}\text{Cl}\) project were used as a surrogate for thermal flux data (such an approach is valid as the energy dependence of the \(^{14}\text{N}(n,p)^{14}\text{C}\) and \(^{35}\text{Cl}(n, \gamma)^{36}\text{Cl}\) activation reactions are very similar);

- For a small number of cases, such as with the SGHWR decommissioning stream, 5G302, detailed flux or activation rate information was not available. However, it was known that some of the activated material, such as the Zircaloy pressure tubes, was irradiated in the fuelled core region, but the mild and stainless steel materials were located just outside this region. For the ex-core materials F was therefore taken as 0.1 and for the in-core materials F was taken as unity.

At this stage, carbon-14 activity has not been apportioned between materials for the 2010 EDI.
3.1.7 Elemental compositions

NDA has compiled a set of spreadsheets containing probability density functions (PDFs) of the elemental precursors for various steels, other metals, graphite, uranium and UO₂. These spreadsheets provide mean, upper uncertainty and lower uncertainty estimates of elemental precursors. The upper uncertainty and lower uncertainty estimates represent the 95% and 5% levels on the cumulative distribution. These spreadsheets were updated with the most recent information for the 2007 Derived Inventory. However, it is known that some of these data are old and may not be representative of current materials.

3.1.8 Potential sources of additional data

NDA has identified potential sources and contacts for additional inventory related data.

Springfields is a source for information on the nitrogen levels in fuel materials, and possible additional data on the specifications for Magnox alloy and AGR cladding stainless steel.

The initial contact for carbon-14 release data from the Magnox fuel element debris (FED) dissolution plant is the Inventory Manager at Magnox Ltd⁶.

Details of the national nuclear archive, including what samples there are and whether they might be available for further analysis will be available from NDA. The NDA strategy team may hold details of possible Magnox samples⁷.

Discussions at an IPT meeting revealed that the IRS database holds details of research reports produced by UKAEA and BNFL. This database may provide a source of further relevant information. NDA will search the database for relevant reports pertaining to carbon-14.

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⁶ Any C-14 measurements made as part of the Magnox dissolution process can be used to confirm the predicted C-14 levels in Magnox alloys. It may be that C-14 is routinely measured in the liquid and aerial discharges from the FED dissolution plant and if not there may be scope for adding in such measurements.

⁷ In the absence of finding additional past measurement data on the nitrogen content of Magnox alloys, new measurements may be needed, requiring access to suitable material samples.
### 3.1.9 Inventory knowledge gaps

Knowledge gaps that have been identified and have been recognised by the IPT as priority areas are listed in Table 7 below:

<table>
<thead>
<tr>
<th>Category</th>
<th>Waste stream group</th>
<th>Knowledge gap</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>All categories</strong></td>
<td></td>
<td>Details of activation calculations that underpin the 2010 UKRWI activities. How the uncertainties have been allocated in the 2010 UKRWI activities. How representative are activities of waste streams as a whole (includes variability). C-14 split for mixed material waste streams.</td>
</tr>
<tr>
<td><strong>Graphite</strong></td>
<td>ILW core graphite</td>
<td>How representative are the calculations, as there is a wide range in graphite elemental compositions? Nitrogen impurity levels used in the AGR core graphite calculations. Whether or not the loss of C-14 to the coolant has been included in the calculations, and whether or not the possible additional nitrogen from the adsorption of nitrogen from coolant gases onto graphite surfaces been accounted for.</td>
</tr>
<tr>
<td></td>
<td>ILW AGR fuel element graphite</td>
<td>Nitrogen impurity levels in the graphite.</td>
</tr>
<tr>
<td></td>
<td>ILW Magnox fuel element graphite</td>
<td>Nitrogen impurity levels in the graphite.</td>
</tr>
<tr>
<td><strong>Steels</strong></td>
<td>ILW AGR stainless steel fuel cladding</td>
<td>Details of the metal thicknesses. Nitrogen impurity levels in the cladding.</td>
</tr>
<tr>
<td></td>
<td>ILW AGR stainless steel fuel assembly components</td>
<td>Details of the metal thicknesses. Nitrogen impurity levels in the grids and braces.</td>
</tr>
<tr>
<td></td>
<td>ILW stainless steels from reactor decommissioning</td>
<td>Details of the metal thicknesses. The stainless steel composition/grade used in the AGR reactors and the PWR reactor at Sizewell, and associated data on nitrogen concentration.</td>
</tr>
<tr>
<td></td>
<td>ILW other ferrous metal decommissioning wastes</td>
<td>Details of the metal thicknesses. The steel composition/grade used in the AGR reactors and the PWR reactor at Sizewell, and associated data on nitrogen concentration.</td>
</tr>
<tr>
<td></td>
<td>ILW other ferrous metal reactor wastes</td>
<td>Details of the metal composition/grades.</td>
</tr>
<tr>
<td><strong>Reactive metals</strong></td>
<td>ILW reactive metals (Magnox and uranium)</td>
<td>Degree of pre-packaging corrosion. Nitrogen impurity levels in Magnox alloys and uranium. Magnox alloy specifications.</td>
</tr>
<tr>
<td><strong>Other wastes</strong></td>
<td>ILW organics from GE Healthcare</td>
<td>In 2012 GE Healthcare advised NDA RWMD that the Environment Agency had given them permission to incinerate their organic wastes. A decision therefore needs to be made about whether such wastes are removed from the Derived Inventory.</td>
</tr>
<tr>
<td></td>
<td>Other ILW</td>
<td>Details of the metal thicknesses. Metal composition/grades.</td>
</tr>
<tr>
<td></td>
<td>Spent fuels</td>
<td>Irradiation history of the spent fuels. Nitrogen impurity levels in the fuels.</td>
</tr>
</tbody>
</table>
3.2 **Objectives and strategy for improving the carbon-14 inventory**

The objectives are to improve the carbon-14 inventory and our understanding of uncertainties by filling the gaps in knowledge identified in the table above.

The strategy will be to engage with waste producers, and identify other organisations that could provide new information of the types described above.

Discussions with waste producers to understand the methodology and data that underpin current inventory estimates will be held. This will determine:

- Details of current inventory calculations;
- If they are representative of the waste to be disposed of at the GDF;
- The extent to which there is waste stream and waste package variability;
- What measurements have been made and how these were undertaken;
- How uncertainties have been allocated, whether they have been subject to rigorous analysis, and how they might be reduced;
- Whether degradation effects have been taken into account during the calculations, i.e. taking into account of loss of carbon-14 in the reactor and in subsequent storage;
- Information on irradiated material samples.

It is expected that discussions will enhance knowledge of carbon-14 precursor concentrations, and provide details of additional documentation and how carbon-14 measurements might be made should they be needed to support an improved inventory.

3.3 **Work for Phase 2**

The action plan proposed is aimed at fulfilling the objectives for the carbon-14 inventory. There are two distinct tasks:

**Task 1: Improving understanding of current inventory data**

We will engage with key current and potential future waste producers to discuss current data and information sources (Sellafield, Magnox Ltd, EDF Energy, RSRL, DSRL and MoD) to address the following points:

- Understanding the basis of the reported carbon-14 activities, and the data that underpin current inventory estimates and LoC submissions (for all relevant categories of waste);
- Understanding how the uncertainties are quantified (for all relevant categories of waste);
- Understanding if potential losses of carbon-14 in the reactor and subsequent storage are accounted for. Investigating carbon-14 levels in reactor coolants and carbon-14 releases made during normal reactor operation, and how they are measured. Investigating carbon-14 discharge models that predict carbon-14 in the coolant (for graphite wastes);
- Obtaining further data on metal thicknesses, the range of metal compositions/grades and the degree of corrosion of reactive metals, also obtaining information on packaging proposals (for steels and reactive metal wastes);
- Identifying what material samples have been measured for carbon-14, if they are representative and what other samples may be available for further investigations (for all relevant categories of waste);
• Reviewing and documenting the justification that there is no carbon-14 remaining in vitrified HLW;
• Obtaining irradiation history data for AGR and PWR spent fuels and carbon-14 precursor concentrations;
• Identifying the sources of data (reports, etc.) and how these might be accessed (for all relevant categories of waste).

Within NDA RWMD, we will ensure we capture any LoC submission data for reactive metal wastes (e.g. nitrogen concentrations in Magnox alloys, AL80 and ZR55).

The output of this task will be a report describing the nature of the investigations undertaken, with the results and a revised radionuclide inventory for use in the other parts of the IPT. This report will be incorporated into the report describing the Phase 2 work of the IPT.

**Task 2: Improving knowledge of materials composition data**

The aim of this task is to enhance the carbon-14 inventory by improving knowledge of materials compositions and carbon-14 precursor concentrations, to investigate what material samples are held and how future carbon-14 measurements might be made and to investigate other potential sources of information. We will also aim to improve knowledge of the carbon-14 inventory that will be disposed of to the GDF with a particular focus on reactive metals.

NDA has developed a set of spreadsheets comprising a database of known elemental composition data for nuclear materials (graphite, steels, Magnox, uranium etc.). One of the aims of this task is to update the information for the materials that are a priority for determining the carbon-14 inventory.

We will engage with Springfields and NDA regarding:

• Nitrogen impurities in uranium (it is understood that Springfields record the nitrogen content of every 10th uranium billet);
• Nitrogen impurities in Magnox alloys (the trace nitrogen content of Magnox alloys is not routinely measured). Note: NDA spreadsheets include only data from 1960 and the early 1980s. Investigate whether there are any other later or earlier studies that report measurements on material from a different part of the manufacturing history. Access a list of all Springfields technical memos/reports in case there is a need to look for any reports that might contain nitrogen data for Magnox alloys;
• Magnox alloy specifications;
• AGR cladding stainless steel specifications;
• Searching the IRS database (this holds details of reports from UKAEA and BNFL, and may include relevant information);
• Obtaining details on the national nuclear archive (NDA also has an archive of Magnox alloy samples from Cl-36 work). We will investigate whether any samples are available, should there be a need to make new nitrogen measurements;
• Capturing any LoC submission or other data on Magnox FED dissolution, and whether the carbon-14 released as liquid and gaseous discharges is measured (this information will help validate nitrogen precursor data).

We will update elemental composition data on material spreadsheets, and identify whether a significant improvement has been made to the nitrogen precursor data.

There would be a hold point in the work after this item. If it is judged that a significant improvement has been made to precursor data, no further work would likely be required. If
improvements to precursor data are limited further work might be carried out to investigate the techniques for how measurements could be carried out to record nitrogen levels down to a few ppm in Magnox and the costs that would be involved. If additional measurements are viable and cost effective, a separate task would be instigated to carry out the measurements required.

The output of this task will be a report describing the nature of the investigations undertaken with the results and a revised materials inventory for use in the other parts of the IPT. Again this will be incorporated into the report describing the Phase 2 work.
### Table 8  Contributors to carbon-14 in graphite

**(a) ILW core graphite**

<table>
<thead>
<tr>
<th>Waste stream identifier</th>
<th>Waste package category</th>
<th>Waste stream description</th>
<th>Packaged volume (m³)</th>
<th>C-14 activity (TBq)</th>
<th>Contribution to total C-14 activity (%)</th>
<th>Uncertainty in C-14 activity (× or / factor of)</th>
<th>Graphite content (%)</th>
<th>Calculation of C-14 activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>2A310</td>
<td>ILW-S</td>
<td>Final Dismantling &amp; Site Clearance : Graphite ILW</td>
<td>5.955</td>
<td>515</td>
<td>7.2</td>
<td>10</td>
<td>100</td>
<td>Neutron activation calculation.</td>
</tr>
<tr>
<td>2C311</td>
<td>ILW-S</td>
<td>Final Dismantling &amp; Site Clearance : Graphite ILW</td>
<td>5.960</td>
<td>362</td>
<td>5.1</td>
<td>10</td>
<td>100</td>
<td>Neutron activation calculation.</td>
</tr>
<tr>
<td>2S302</td>
<td>ILW-U</td>
<td>Windscale Pile1 and Pile 2 Graphite and Aluminium</td>
<td>6.362</td>
<td>16</td>
<td>0.2</td>
<td>3</td>
<td>99.88</td>
<td>Neutron activation calculation.</td>
</tr>
<tr>
<td>3J313</td>
<td>ILW-S</td>
<td>Decommissioning Stage 3: Graphite ILW</td>
<td>4.719</td>
<td>153</td>
<td>2.1</td>
<td>10</td>
<td>100</td>
<td>Neutron activation calculation.</td>
</tr>
<tr>
<td>3K313</td>
<td>ILW-S</td>
<td>Decommissioning Stage 3: Graphite ILW</td>
<td>5.935</td>
<td>436</td>
<td>6.1</td>
<td>10</td>
<td>100</td>
<td>Neutron activation calculation.</td>
</tr>
<tr>
<td>3L313</td>
<td>ILW-S</td>
<td>Decommissioning Stage 3: Graphite ILW</td>
<td>5.935</td>
<td>436</td>
<td>6.1</td>
<td>10</td>
<td>100</td>
<td>Neutron activation calculation.</td>
</tr>
<tr>
<td>3M313</td>
<td>ILW-S</td>
<td>Decommissioning Stage 3: Graphite ILW</td>
<td>5.132</td>
<td>456</td>
<td>6.4</td>
<td>10</td>
<td>100</td>
<td>Neutron activation calculation.</td>
</tr>
<tr>
<td>3N313</td>
<td>ILW-S</td>
<td>Decommissioning Stage 3: Graphite ILW</td>
<td>4.407</td>
<td>380</td>
<td>5.3</td>
<td>10</td>
<td>100</td>
<td>Neutron activation calculation.</td>
</tr>
<tr>
<td>4B313</td>
<td>ILW-S</td>
<td>Decommissioning Stage 3: Graphite ILW</td>
<td>4.407</td>
<td>380</td>
<td>5.3</td>
<td>10</td>
<td>100</td>
<td>No information.</td>
</tr>
<tr>
<td>4C313</td>
<td>ILW-S</td>
<td>Decommissioning Stage 3: Graphite ILW</td>
<td>5.132</td>
<td>456</td>
<td>6.4</td>
<td>10</td>
<td>100</td>
<td>No information.</td>
</tr>
<tr>
<td>5B304c</td>
<td>ILW-S</td>
<td>Dounreay Fast Reactor ILW</td>
<td>458</td>
<td>5</td>
<td>0.1</td>
<td>3</td>
<td>100</td>
<td>Neutron activation calculation.</td>
</tr>
<tr>
<td>5B310a</td>
<td>ILW-S</td>
<td>Materials Test Reactor ILW</td>
<td>20</td>
<td>0.01</td>
<td>0.0001</td>
<td>3</td>
<td>18% graphite, 22% lead, 14% stainless steel, 14% mild steel.</td>
<td>Neutron activation calculation.</td>
</tr>
<tr>
<td>5C302a</td>
<td>ILW-S</td>
<td>BEPO Research Reactor ILW</td>
<td>827</td>
<td>7</td>
<td>0.1</td>
<td>3</td>
<td>100</td>
<td>Specific activities are based on a sampling campaign and calculations on the operational life of the reactor.</td>
</tr>
<tr>
<td>Waste stream identifier</td>
<td>Waste package category</td>
<td>Waste stream description</td>
<td>Packaged volume (m³)</td>
<td>C-14 activity (TBq)</td>
<td>Contribution to total C-14 activity (%)</td>
<td>Uncertainty in C-14 activity (× or / factor of)</td>
<td>Graphite content (%)</td>
<td>Calculation of C-14 activity</td>
</tr>
<tr>
<td>------------------------</td>
<td>------------------------</td>
<td>--------------------------</td>
<td>----------------------</td>
<td>-------------------</td>
<td>----------------------------------------</td>
<td>---------------------------------------------</td>
<td>---------------------</td>
<td>----------------------------</td>
</tr>
<tr>
<td>5C306a</td>
<td>ILW-U</td>
<td>Dido Reactor Decommissioning ILW</td>
<td>35</td>
<td>0.07</td>
<td>0.001</td>
<td>10</td>
<td>16% graphite, 11% stainless steel, 1.2% cast iron.</td>
<td>Neutron activation calculation.</td>
</tr>
<tr>
<td>5C306b</td>
<td>ILW-U</td>
<td>Dido Reactor Decommissioning ILW</td>
<td>37</td>
<td>0.07</td>
<td>0.001</td>
<td>10</td>
<td>Neutron activation calculation.</td>
<td></td>
</tr>
<tr>
<td>5C308a</td>
<td>ILW-U</td>
<td>Pluto Reactor Decommissioning ILW</td>
<td>27</td>
<td>0.06</td>
<td>0.001</td>
<td>10</td>
<td>9% graphite, 15% steel/other metals.</td>
<td>Neutron activation calculation.</td>
</tr>
<tr>
<td>5C308b</td>
<td>ILW-U</td>
<td>Pluto Reactor Decommissioning ILW</td>
<td>29</td>
<td>0.06</td>
<td>0.001</td>
<td>10</td>
<td>Neutron activation calculation.</td>
<td></td>
</tr>
<tr>
<td>9A321</td>
<td>ILW-S</td>
<td>Graphite ILW</td>
<td>3,858</td>
<td>229</td>
<td>3.2</td>
<td>10</td>
<td>100</td>
<td>Neutron activation calculation.</td>
</tr>
<tr>
<td>9B312</td>
<td>ILW-S</td>
<td>Graphite ILW</td>
<td>3,739</td>
<td>300</td>
<td>4.2</td>
<td>10</td>
<td>100</td>
<td>Neutron activation calculation.</td>
</tr>
<tr>
<td>9C312</td>
<td>ILW-S</td>
<td>Graphite ILW</td>
<td>4,233</td>
<td>476</td>
<td>6.7</td>
<td>10</td>
<td>100</td>
<td>Neutron activation calculation.</td>
</tr>
<tr>
<td>9D312</td>
<td>ILW-S</td>
<td>Graphite ILW</td>
<td>4,395</td>
<td>388</td>
<td>5.4</td>
<td>10</td>
<td>100</td>
<td>Neutron activation calculation.</td>
</tr>
<tr>
<td>9E319</td>
<td>ILW-S</td>
<td>Final Dismantling &amp; Site Clearance: Graphite ILW</td>
<td>4,083</td>
<td>656</td>
<td>9.2</td>
<td>10</td>
<td>100</td>
<td>Neutron activation calculation.</td>
</tr>
<tr>
<td>9F312</td>
<td>ILW-S</td>
<td>Graphite ILW</td>
<td>4,458</td>
<td>466</td>
<td>6.5</td>
<td>10</td>
<td>100</td>
<td>Neutron activation calculation.</td>
</tr>
<tr>
<td>9G311</td>
<td>ILW-S</td>
<td>Final Dismantling &amp; Site Clearance: Graphite ILW</td>
<td>4,243</td>
<td>340</td>
<td>4.8</td>
<td>10</td>
<td>100</td>
<td>Neutron activation calculation.</td>
</tr>
<tr>
<td>9H311</td>
<td>ILW-S</td>
<td>Final Dismantling &amp; Site Clearance: Graphite ILW</td>
<td>6,790</td>
<td>437</td>
<td>6.1</td>
<td>10</td>
<td>100</td>
<td>Neutron activation calculation.</td>
</tr>
<tr>
<td>9J301</td>
<td>ILW-S</td>
<td>Final Dismantling &amp; Site Clearance: Graphite ILW</td>
<td>4,245</td>
<td>238</td>
<td>3.3</td>
<td>10</td>
<td>100</td>
<td>Neutron activation calculation.</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>ILW-S</strong></td>
<td></td>
<td><strong>88,930</strong></td>
<td><strong>7,116</strong></td>
<td><strong>99.8</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>ILW-U</strong></td>
<td></td>
<td><strong>6,978</strong></td>
<td><strong>16</strong></td>
<td><strong>0.2</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### (b) ILW AGR fuel element graphite

<table>
<thead>
<tr>
<th>Waste stream identifier</th>
<th>Waste package category</th>
<th>Waste stream description</th>
<th>Packaged volume (m³)</th>
<th>C-14 activity (TBq)</th>
<th>Contribution to total C-14 activity (%)</th>
<th>Uncertainty in C-14 activity (× or / factor of)</th>
<th>Graphite content (%)</th>
<th>Calculation of C-14 activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>2F07</td>
<td>ILW-U</td>
<td>AGR Graphite Fuel Assembly Components</td>
<td>13,883</td>
<td>45</td>
<td>88.0</td>
<td>10</td>
<td>100</td>
<td>No information.</td>
</tr>
</tbody>
</table>

### (c) ILW Magnox fuel element graphite

<table>
<thead>
<tr>
<th>Waste stream identifier</th>
<th>Waste package category</th>
<th>Waste stream description</th>
<th>Packaged volume (m³)</th>
<th>C-14 activity (TBq)</th>
<th>Contribution to total C-14 activity (%)</th>
<th>Uncertainty in C-14 activity (× or / factor of)</th>
<th>Graphite content (%)</th>
<th>Calculation of C-14 activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>9A31</td>
<td>ILW-U</td>
<td>FED Graphite</td>
<td>206</td>
<td>0.1</td>
<td>2.4</td>
<td>10</td>
<td>99</td>
<td>Neutron activation calculations and experimental measurements of the contamination of Magnox.</td>
</tr>
<tr>
<td>9A32</td>
<td>ILW-U</td>
<td>FED Graphite</td>
<td>307</td>
<td>0.4</td>
<td>7.2</td>
<td>10</td>
<td>99</td>
<td>Neutron activation calculations and experimental measurements of the contamination of Magnox.</td>
</tr>
<tr>
<td>9A33</td>
<td>ILW-U</td>
<td>FED Graphite</td>
<td>362</td>
<td>0.5</td>
<td>8.4</td>
<td>10</td>
<td>99</td>
<td>Neutron activation calculations and experimental measurements of the contamination of Magnox.</td>
</tr>
<tr>
<td>9A34</td>
<td>ILW-U</td>
<td>FED Graphite</td>
<td>213</td>
<td>0.5</td>
<td>7.4</td>
<td>10</td>
<td>99</td>
<td>Neutron activation calculations and experimental measurements of the contamination of Magnox.</td>
</tr>
<tr>
<td>9A35</td>
<td>ILW-U</td>
<td>FED Graphite</td>
<td>89</td>
<td>0.2</td>
<td>3.1</td>
<td>10</td>
<td>99</td>
<td>Neutron activation calculations and experimental measurements of the contamination of Magnox.</td>
</tr>
<tr>
<td>9J18</td>
<td>ILW-U</td>
<td>FED Graphite</td>
<td>5</td>
<td>0.01</td>
<td>0.2</td>
<td>10</td>
<td>100</td>
<td>Neutron activation calculations with assumptions for contamination.</td>
</tr>
<tr>
<td>9J19</td>
<td>ILW-U</td>
<td>FED Graphite</td>
<td>619</td>
<td>1.5</td>
<td>23.9</td>
<td>10</td>
<td>100</td>
<td>Neutron activation calculations with assumptions for contamination.</td>
</tr>
<tr>
<td>9J20</td>
<td>ILW-U</td>
<td>FED Graphite</td>
<td>569</td>
<td>1.4</td>
<td>21.9</td>
<td>10</td>
<td>100</td>
<td>Neutron activation calculations with assumptions for contamination.</td>
</tr>
<tr>
<td>9J21</td>
<td>ILW-U</td>
<td>FED Graphite</td>
<td>552</td>
<td>1.3</td>
<td>21.3</td>
<td>10</td>
<td>100</td>
<td>Neutron activation calculations with assumptions for contamination.</td>
</tr>
<tr>
<td>9J22</td>
<td>ILW-U</td>
<td>FED Graphite</td>
<td>107</td>
<td>0.3</td>
<td>4.1</td>
<td>10</td>
<td>100</td>
<td>Neutron activation calculations with assumptions for contamination.</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>ILW-U</strong></td>
<td></td>
<td><strong>3,028</strong></td>
<td><strong>6.2</strong></td>
<td><strong>100.0</strong></td>
<td><strong>100</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Key to colours at the end of Table 11
### Table 9  Contributors to carbon-14 in steels

#### (a) ILW AGR stainless steel fuel cladding

<table>
<thead>
<tr>
<th>Waste stream identifier</th>
<th>Waste package category</th>
<th>Waste stream description</th>
<th>Packaged volume (m³)</th>
<th>C-14 activity (TBq)</th>
<th>Contribution to total C-14 activity (%)</th>
<th>Uncertainty in C-14 activity (× or / factor of)</th>
<th>Stainless steel (%) and description</th>
<th>Calculation of C-14 activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>2F03/C</td>
<td>ILW-U</td>
<td>Encapsulated AGR Cladding</td>
<td>1,944</td>
<td>28 (+143)</td>
<td>7.3</td>
<td>3</td>
<td>22%; 20Cr/25Ni/Nb, 77% concrete.</td>
<td>The activities are calculated, based on characteristics of AGR fuel reprocessed to date for stocks and that yet to be reprocessed for arisings.</td>
</tr>
</tbody>
</table>

Red figure shows the impact of enhancement of 2010 EDI for the waste stream.

Key to colours at the end of Table 11.

#### (b) ILW AGR stainless steel assembly components

<table>
<thead>
<tr>
<th>Waste stream identifier</th>
<th>Waste package category</th>
<th>Waste stream description</th>
<th>Packaged volume (m³)</th>
<th>C-14 activity (TBq)</th>
<th>Contribution to total C-14 activity (%)</th>
<th>Uncertainty in C-14 activity (× or / factor of)</th>
<th>Stainless steel (%) and description</th>
<th>Calculation of C-14 activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>2F08 ILW-U</td>
<td>AGR Stainless Steel Fuel Assembly Components</td>
<td>1,609</td>
<td>236</td>
<td>66.3</td>
<td>10</td>
<td>100%; 18Cr/9Ni/Nb</td>
<td>No information.</td>
<td></td>
</tr>
<tr>
<td>3J21 ILW-U</td>
<td>Fuel Stringer Debris</td>
<td>867</td>
<td>30</td>
<td>8.3</td>
<td>10</td>
<td>49.7%; 18Cr/9Ni/Nb, 4.3% Nimonic, 46%</td>
<td>Theoretical assessments.</td>
<td></td>
</tr>
<tr>
<td>3K25 ILW-U</td>
<td>Fuel Stringer Debris - Graphite &amp; Associated Metals</td>
<td>296</td>
<td>7</td>
<td>2.0</td>
<td>10</td>
<td>90% stainless steel; 10% graphite.</td>
<td>Theoretical assessments.</td>
<td></td>
</tr>
<tr>
<td>3L22 ILW-U</td>
<td>Fuel Stringer Debris - Graphite and Associated Metals</td>
<td>281</td>
<td>5.4</td>
<td>1.5</td>
<td>10</td>
<td>60% graphite, 40% stainless steel.</td>
<td>Theoretical assessments.</td>
<td></td>
</tr>
<tr>
<td>3M07 ILW-U</td>
<td>Fuel Stringer Debris - Steel and Nimonic</td>
<td>187</td>
<td>10</td>
<td>2.9</td>
<td>10</td>
<td>92%; 18Cr/9Ni/Nb, 8% Nimonic.</td>
<td>Theoretical assessments.</td>
<td></td>
</tr>
<tr>
<td>3N10 ILW-U</td>
<td>Fuel Stringer Debris: Steel and Nimonic</td>
<td>416</td>
<td>28</td>
<td>8.0</td>
<td>10</td>
<td>90%; 18Cr/9Ni/Nb, 10% Nimonic.</td>
<td>Theoretical assessments.</td>
<td></td>
</tr>
<tr>
<td>4B11 ILW-U</td>
<td>Miscellaneous Activated Components</td>
<td>1,017</td>
<td>16</td>
<td>4.5</td>
<td>10</td>
<td>85%; 18Cr/9Ni/Nb, 5% Nimonic, 10%</td>
<td>No information.</td>
<td></td>
</tr>
<tr>
<td>4C12 ILW-U</td>
<td>Miscellaneous Activated Items</td>
<td>515</td>
<td>23</td>
<td>6.6</td>
<td>10</td>
<td>85%; 18Cr/9Ni/Nb, 5% Nimonic, 10%</td>
<td>No information.</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>ILW-U</td>
<td></td>
<td>5,187</td>
<td>356</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### (c) ILW stainless steel decommissioning wastes

<table>
<thead>
<tr>
<th>Waste stream identifier</th>
<th>Waste package category</th>
<th>Waste stream description</th>
<th>Packaged volume (m³)</th>
<th>C-14 activity (TBq)</th>
<th>Contribution to total C-14 activity (%)</th>
<th>Uncertainty in C-14 activity (× or / factor of)</th>
<th>Stainless steel (%) and description</th>
<th>Calculation of C-14 activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>2A312 ILW-U</td>
<td>Final Dismantling &amp; Site Clearance : Stainless Steel (Reactor) ILW</td>
<td>115</td>
<td>8</td>
<td>3.5</td>
<td>10</td>
<td>100%; BS970-EN58B and BS970-EN56.</td>
<td>Neutron activation calculation.</td>
<td></td>
</tr>
<tr>
<td>2C313 ILW-U</td>
<td>Final Dismantling &amp; Site Clearance : Stainless Steel (Reactor) ILW</td>
<td>114</td>
<td>7</td>
<td>3.2</td>
<td>10</td>
<td>100%; BS970-EN58B and BS970-EN56.</td>
<td>Neutron activation calculation.</td>
<td></td>
</tr>
<tr>
<td>3J311 ILW-S</td>
<td>Decommissioning Stage 3: Stainless Steel (Reactor) ILW</td>
<td>34</td>
<td>0.03</td>
<td>0.01</td>
<td>10</td>
<td>100%; No details.</td>
<td>Neutron activation calculation.</td>
<td></td>
</tr>
<tr>
<td>3K311 ILW-S</td>
<td>Decommissioning Stage 3: Stainless Steel (Reactor) ILW</td>
<td>472</td>
<td>3</td>
<td>1.3</td>
<td>10</td>
<td>100%; No details.</td>
<td>Neutron activation calculation.</td>
<td></td>
</tr>
<tr>
<td>3L311 ILW-S</td>
<td>Decommissioning Stage 3: Stainless Steel (Reactor) ILW</td>
<td>360</td>
<td>3</td>
<td>1.3</td>
<td>10</td>
<td>100%; No details.</td>
<td>Neutron activation calculation.</td>
<td></td>
</tr>
<tr>
<td>3M311 ILW-U</td>
<td>Decommissioning stage 3: Stainless Steel (Reactor) ILW</td>
<td>204</td>
<td>2</td>
<td>1.0</td>
<td>10</td>
<td>100%; No details.</td>
<td>Neutron activation calculation.</td>
<td></td>
</tr>
<tr>
<td>3N311 ILW-U</td>
<td>Decommissioning Stage 3: Stainless Steel (Reactor) ILW</td>
<td>280</td>
<td>3</td>
<td>1.4</td>
<td>10</td>
<td>100%; No details.</td>
<td>Neutron activation calculation.</td>
<td></td>
</tr>
<tr>
<td>3S306 ILW-U</td>
<td>Decommissioning: Stainless Steel ILW</td>
<td>210</td>
<td>120</td>
<td>53.0</td>
<td>10</td>
<td>100%; No details.</td>
<td>No information.</td>
<td></td>
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<tr>
<td>4B311 ILW-U</td>
<td>Decommissioning Stage 3: Stainless Steel (Reactor) ILW</td>
<td>280</td>
<td>3</td>
<td>1.4</td>
<td>10</td>
<td>100%; No details.</td>
<td>No information.</td>
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</tr>
<tr>
<td>4C311 ILW-S</td>
<td>Decommissioning Stage 3: Stainless Steel (Reactor) ILW</td>
<td>304</td>
<td>2</td>
<td>1.0</td>
<td>10</td>
<td>100%; No details.</td>
<td>No information.</td>
<td></td>
</tr>
<tr>
<td>5B302b ILW-U</td>
<td>Prototype Fast Reactor ILW</td>
<td>983</td>
<td>12</td>
<td>5.4</td>
<td>3</td>
<td>41.6%; 316L, 50% concrete.</td>
<td>Neutron activation calculation.</td>
<td></td>
</tr>
<tr>
<td>7G104 ILW-U</td>
<td>Long-Lived ILW from Decommissioned Submarines</td>
<td>741</td>
<td>28</td>
<td>12.6</td>
<td>1.5/3</td>
<td>90%; Austenitic and low alloy steels.</td>
<td>Neutron activation calculation.</td>
<td></td>
</tr>
</tbody>
</table>
### (c) ILW stainless steel decommissioning wastes

<table>
<thead>
<tr>
<th>Waste stream identifier</th>
<th>Waste stream description</th>
<th>Packaged volume (m³)</th>
<th>C-14 activity (TBq)</th>
<th>Contribution to total C-14 activity (%)</th>
<th>Uncertainty in C-14 activity (× or / factor of)</th>
<th>Stainless steel (%) and description</th>
<th>Calculation of C-14 activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>7V24 ILW-U</td>
<td>Metallic ILW from Vulcan</td>
<td>146</td>
<td>10</td>
<td>4.3</td>
<td>100</td>
<td>99%; Steel alloys 304 and 316</td>
<td>No information.</td>
</tr>
<tr>
<td>9A310 ILW-S</td>
<td>Stainless Steel (Reactor) ILW</td>
<td>85</td>
<td>3</td>
<td>1.5</td>
<td>10</td>
<td>100%; BS970-321S12, BS970-EN59, BS970-EN56 and EN58B.</td>
<td>Neutron activation calculation.</td>
</tr>
<tr>
<td>9B310 ILW-S</td>
<td>Stainless Steel (Reactor) ILW</td>
<td>358</td>
<td>5</td>
<td>2.1</td>
<td>10</td>
<td>100%; BS980-CDS20, BS970-EN59, BS1631/1950 and EN58B.</td>
<td>Neutron activation calculation.</td>
</tr>
<tr>
<td>9C310 ILW-U</td>
<td>Stainless Steel (Reactor) ILW</td>
<td>205</td>
<td>1</td>
<td>0.6</td>
<td>10</td>
<td>100%; EN58B and BS1631/1950.</td>
<td>Neutron activation calculation.</td>
</tr>
<tr>
<td>9D310 ILW-S</td>
<td>Stainless Steel (Reactor) ILW</td>
<td>131</td>
<td>1</td>
<td>0.5</td>
<td>10</td>
<td>100%; BS970-EN59F, BS970-EN59 and EN58B.</td>
<td>Neutron activation calculation.</td>
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<tr>
<td>9E310 ILW-U</td>
<td>Final Dismantling &amp; Site Clearance : Stainless Steel (Reactor) ILW</td>
<td>116</td>
<td>2</td>
<td>0.7</td>
<td>10</td>
<td>100%; BS1631/1950 and EN58B.</td>
<td>Neutron activation calculation.</td>
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<tr>
<td>9F310 ILW-U</td>
<td>Stainless Steel (Reactor) ILW</td>
<td>27</td>
<td>1</td>
<td>0.5</td>
<td>10</td>
<td>100%; BS970-EN59F and EN58B.</td>
<td>Neutron activation calculation.</td>
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<tr>
<td>9G309 ILW-S</td>
<td>Final Dismantling &amp; Site Clearance : Stainless Steel (Reactor) ILW</td>
<td>111</td>
<td>5</td>
<td>2.3</td>
<td>10</td>
<td>100%; BS970-321S12, BS980-CDS20, BS1508-821, BS970-EN59 and EN58B.</td>
<td>Neutron activation calculation.</td>
</tr>
<tr>
<td>9H309 ILW-U</td>
<td>Final Dismantling &amp; Site Clearance : Stainless Steel (Reactor) ILW</td>
<td>97</td>
<td>5</td>
<td>2.1</td>
<td>10</td>
<td>100%; EN58B and BS970-EN58B.</td>
<td>Neutron activation calculation.</td>
</tr>
<tr>
<td>9J306 ILW-S</td>
<td>Final Dismantling &amp; Site Clearance : Stainless Steel (Reactor) ILW</td>
<td>83</td>
<td>1</td>
<td>0.6</td>
<td>10</td>
<td>100%; EN58B</td>
<td>Neutron activation calculation.</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>1,938</strong></td>
<td><strong>23</strong></td>
<td><strong>10.3</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>ILW-S</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ILW-U</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Waste stream identifier</td>
<td>Waste package category</td>
<td>Waste stream description</td>
<td>Packaged volume (m³)</td>
<td>C-14 activity (TBq)</td>
<td>Contribution to total C-14 activity (%)</td>
<td>Uncertainty in C-14 activity (× or / factor of)</td>
<td>Mild steel (%) and description</td>
</tr>
<tr>
<td>-------------------------</td>
<td>------------------------</td>
<td>--------------------------</td>
<td>---------------------</td>
<td>-------------------</td>
<td>----------------------------------------</td>
<td>-----------------------------------------------</td>
<td>-----------------------------</td>
</tr>
<tr>
<td>2A311</td>
<td>ILW-S</td>
<td>Final Dismantling &amp; Site Clearance : Mild Steel (Reactor) ILW</td>
<td>1,402</td>
<td>7</td>
<td>3.0</td>
<td>10</td>
<td>100%; MEEHANITE and COHLO (PV).</td>
</tr>
<tr>
<td>2C312</td>
<td>ILW-S</td>
<td>Final Dismantling &amp; Site Clearance : Mild Steel (Reactor) ILW</td>
<td>1,278</td>
<td>8</td>
<td>3.6</td>
<td>10</td>
<td>100%; MEEHANITE and COHLO (PV).</td>
</tr>
<tr>
<td>2S308/C</td>
<td>ILW-S</td>
<td>Conditioned WAGR Decommissioning ILW</td>
<td>1,263</td>
<td>4</td>
<td>1.7</td>
<td>1.5</td>
<td>30%: a variety of steels, 11% graphite, 58% cement grout.</td>
</tr>
<tr>
<td>2S313</td>
<td>ILW-U</td>
<td>Windscale Piles Miscellaneous ILW</td>
<td>5,481</td>
<td>3</td>
<td>1.4</td>
<td>3</td>
<td>96.2%: a variety of steels.</td>
</tr>
<tr>
<td>3J312</td>
<td>ILW-S</td>
<td>Decommissioning Stage 3: Mild Steel (Reactor) ILW</td>
<td>662</td>
<td>1.2</td>
<td>0.6</td>
<td>10</td>
<td>100%: a variety of steels.</td>
</tr>
<tr>
<td>3K312</td>
<td>ILW-S</td>
<td>Decommissioning Stage 3: Mild Steel (Reactor) ILW</td>
<td>450</td>
<td>2</td>
<td>0.7</td>
<td>10</td>
<td>100%: a variety of steels.</td>
</tr>
<tr>
<td>3L312</td>
<td>ILW-S</td>
<td>Decommissioning Stage 3: Mild Steel (Reactor) ILW</td>
<td>343</td>
<td>2</td>
<td>0.7</td>
<td>10</td>
<td>100%: a variety of steels.</td>
</tr>
<tr>
<td>3M312</td>
<td>ILW-S</td>
<td>Decommissioning Stage 3: Mild Steel (Reactor) ILW</td>
<td>1,256</td>
<td>7</td>
<td>3.1</td>
<td>10</td>
<td>100%: a variety of steels.</td>
</tr>
<tr>
<td>3N312</td>
<td>ILW-U</td>
<td>Decommissioning Stage 3: Mild Steel (Reactor) ILW</td>
<td>853</td>
<td>7</td>
<td>3.4</td>
<td>10</td>
<td>100%: a variety of steels.</td>
</tr>
<tr>
<td>3S302</td>
<td>ILW-U</td>
<td>Decommissioning: Mild Steel ILW</td>
<td>1,889</td>
<td>0.4</td>
<td>0.2</td>
<td>10</td>
<td>100%: a variety of steels.</td>
</tr>
<tr>
<td>4B312</td>
<td>ILW-S</td>
<td>Decommissioning Stage 3: Mild Steel (Reactor) ILW</td>
<td>1,274</td>
<td>7</td>
<td>3.4</td>
<td>10</td>
<td>100%: a variety of steels.</td>
</tr>
<tr>
<td>4C312</td>
<td>ILW-S</td>
<td>Decommissioning Stage 3: Mild Steel (Reactor) ILW</td>
<td>1,144</td>
<td>6</td>
<td>2.9</td>
<td>10</td>
<td>100%: a variety of steels.</td>
</tr>
<tr>
<td>5B304b</td>
<td>ILW-U</td>
<td>Dounreay Fast Reactor ILW</td>
<td>944</td>
<td>6</td>
<td>2.6</td>
<td>3</td>
<td>41.2%: a variety of steels, 37.8% stainless steel.</td>
</tr>
<tr>
<td>5G302</td>
<td>ILW-U</td>
<td>SGHWR Decommissioning ILW</td>
<td>2,915</td>
<td>62</td>
<td>29.0</td>
<td>3</td>
<td>72.3%: none specified, 21% stainless steel.</td>
</tr>
<tr>
<td>5G304</td>
<td>ILW-U</td>
<td>Dragon Reactor Decommissioning ILW</td>
<td>489</td>
<td>3</td>
<td>1.3</td>
<td>Upper/3</td>
<td>62.1%: none specified, 33.8% graphite.</td>
</tr>
</tbody>
</table>
### (d) ILW other ferrous metal decommissioning wastes

<table>
<thead>
<tr>
<th>Waste stream identifier</th>
<th>Waste package category</th>
<th>Waste stream description</th>
<th>Packaged volume (m³)</th>
<th>C-14 activity (TBq)</th>
<th>Contribution to total C-14 activity (%)</th>
<th>Uncertainty in C-14 activity (× or / factor of)</th>
<th>Mild steel (%) and description</th>
<th>Calculation of C-14 activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>9A311</td>
<td>ILW-S</td>
<td>Mild Steel (Reactor) ILW</td>
<td>334</td>
<td>2</td>
<td>0.7</td>
<td>10</td>
<td>100%: a variety of steels.</td>
<td>Neutron activation calculation.</td>
</tr>
<tr>
<td>9A312</td>
<td>ILW-S</td>
<td>Miscellaneous Metal (Reactor) ILW</td>
<td>150</td>
<td>1.1</td>
<td>0.5</td>
<td>10</td>
<td>34%: a variety of steels, 60% Magnox, 6% Zircaloy.</td>
<td>Neutron activation calculation.</td>
</tr>
<tr>
<td>9B311</td>
<td>ILW-S</td>
<td>Mild Steel (Reactor) ILW</td>
<td>673</td>
<td>24</td>
<td>11.1</td>
<td>10</td>
<td>100%: BS970(1955)-EN3A, BS592, RPV STEEL, BS1501 and BS15.</td>
<td>Neutron activation calculation.</td>
</tr>
<tr>
<td>9B313</td>
<td>ILW-S</td>
<td>Miscellaneous Metal (Reactor) ILW</td>
<td>11</td>
<td>1.3</td>
<td>0.6</td>
<td>10</td>
<td>65%: boron steel, 33% zirconium, 2% Nimonic.</td>
<td>Neutron activation calculation.</td>
</tr>
<tr>
<td>9C311</td>
<td>ILW-S</td>
<td>Mild Steel (Reactor) ILW</td>
<td>590</td>
<td>9</td>
<td>4.2</td>
<td>10</td>
<td>100%: BS1501, PV steel and BS970(1955)-EN3A.</td>
<td>Neutron activation calculation.</td>
</tr>
<tr>
<td>9D311</td>
<td>ILW-S</td>
<td>Mild Steel (Reactor) ILW</td>
<td>628</td>
<td>11</td>
<td>5.2</td>
<td>10</td>
<td>100%: BS970(1955)-EN3A, BS970(1955)-EN5, BS1501, BS14 and BS15.</td>
<td>Neutron activation calculation.</td>
</tr>
<tr>
<td>9E311</td>
<td>ILW-S</td>
<td>Final Dismantling &amp; Site Clearance : Mild Steel (Reactor) ILW</td>
<td>605</td>
<td>5</td>
<td>2.3</td>
<td>10</td>
<td>100%: BS15.</td>
<td>Neutron activation calculation.</td>
</tr>
<tr>
<td>9F311</td>
<td>ILW-S</td>
<td>Mild Steel (Reactor) ILW</td>
<td>492</td>
<td>7</td>
<td>3.3</td>
<td>10</td>
<td>100%: BS15.</td>
<td>Neutron activation calculation.</td>
</tr>
<tr>
<td>9G310</td>
<td>ILW-S</td>
<td>Final Dismantling &amp; Site Clearance : Mild Steel (Reactor) ILW</td>
<td>1,431</td>
<td>5</td>
<td>2.1</td>
<td>10</td>
<td>100%: BS1504-101A, BS4360-40E, BS4360-40A, BS1501 and BS15.</td>
<td>Neutron activation calculation.</td>
</tr>
<tr>
<td>9G312</td>
<td>ILW-S</td>
<td>Final Dismantling &amp; Site Clearance : Miscellaneous Metal (Reactor) ILW</td>
<td>22</td>
<td>0.3</td>
<td>0.1</td>
<td>10</td>
<td>82%: boron steel. 18% Magnox incorporating zirconium.</td>
<td>Neutron activation calculation.</td>
</tr>
<tr>
<td>9H310</td>
<td>ILW-S</td>
<td>Final Dismantling &amp; Site Clearance : Mild Steel (Reactor) ILW</td>
<td>211</td>
<td>2</td>
<td>0.8</td>
<td>10</td>
<td>100%: BS15.</td>
<td>Neutron activation calculation.</td>
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</tbody>
</table>
(d) ILW other ferrous metal decommissioning wastes

<table>
<thead>
<tr>
<th>Waste stream identifier</th>
<th>Waste package category</th>
<th>Waste stream description</th>
<th>Packaged volume (m³)</th>
<th>C-14 activity (TBq)</th>
<th>Contribution to total C-14 activity (%)</th>
<th>Uncertainty in C-14 activity (× or / factor of)</th>
<th>Mild steel (%) and description</th>
<th>Calculation of C-14 activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>9H319</td>
<td>ILW-U</td>
<td>Final Dismantling &amp; Site Clearance : Miscellaneous Metals (Reactor) ILW</td>
<td>32</td>
<td>4</td>
<td>2.0</td>
<td>10</td>
<td>100%: a variety of steels includes 4% Boron Cr steel, MgO, Chromel (NiCr) and Alumel (Ni Al).</td>
<td>Neutron activation calculation.</td>
</tr>
<tr>
<td>9J303</td>
<td>ILW-S</td>
<td>Final Dismantling &amp; Site Clearance : Mild Steel (Reactor) ILW</td>
<td>304</td>
<td>2</td>
<td>1.1</td>
<td>10</td>
<td>100%: HSS soft grade iron, PV steel, BS1501 and BS15.</td>
<td>Neutron activation calculation.</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>ILW-S</strong></td>
<td></td>
<td><strong>14,522</strong></td>
<td><strong>111</strong></td>
<td><strong>56.5</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td><strong>ILW-U</strong></td>
<td></td>
<td><strong>12,604</strong></td>
<td><strong>86</strong></td>
<td><strong>43.5</strong></td>
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(e) ILW other ferrous metal reactor wastes

<table>
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<th>Waste stream identifier</th>
<th>Waste package category</th>
<th>Waste stream description</th>
<th>Packaged volume (m³)</th>
<th>C-14 activity (TBq)</th>
<th>Contribution to total C-14 activity (%)</th>
<th>Uncertainty in C-14 activity (× or / factor of)</th>
<th>Mild steel (%) and description</th>
<th>Calculation of C-14 activity</th>
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<tr>
<td>3N09</td>
<td>ILW-U</td>
<td>Miscellaneous Activated Components</td>
<td>129</td>
<td>4</td>
<td>2.1</td>
<td>10</td>
<td>90%: a variety of steels.</td>
<td>Neutron activation calculation.</td>
</tr>
<tr>
<td>9H18</td>
<td>ILW-U</td>
<td>Miscellaneous Activated Components</td>
<td>380</td>
<td>5</td>
<td>2.4</td>
<td>10/100</td>
<td>&gt;90%: none specified.</td>
<td>Theoretical assessment.</td>
</tr>
<tr>
<td>9H19</td>
<td>ILW-U</td>
<td>Miscellaneous Activated Components</td>
<td>380</td>
<td>5</td>
<td>2.4</td>
<td>10/100</td>
<td>&gt;90%: none specified.</td>
<td>Theoretical assessment.</td>
</tr>
<tr>
<td>9H20</td>
<td>ILW-U</td>
<td>Miscellaneous Activated Components</td>
<td>425</td>
<td>6</td>
<td>2.7</td>
<td>10/100</td>
<td>&gt;90%: none specified.</td>
<td>Theoretical assessment.</td>
</tr>
<tr>
<td>9J36</td>
<td>ILW-U</td>
<td>FED Fuel Channel Components</td>
<td>33</td>
<td>3</td>
<td>1.2</td>
<td>10</td>
<td>67% cast iron, 33% zirconium.</td>
<td>Neutron activation calculation.</td>
</tr>
<tr>
<td>9J37</td>
<td>ILW-U</td>
<td>FED Fuel Channel Components</td>
<td>31</td>
<td>2</td>
<td>1.1</td>
<td>10</td>
<td>67% cast iron, 33% zirconium.</td>
<td>Neutron activation calculation.</td>
</tr>
<tr>
<td>9J38</td>
<td>ILW-U</td>
<td>FED Fuel Channel Components</td>
<td>29</td>
<td>2</td>
<td>1.0</td>
<td>10</td>
<td>67% cast iron, 33% zirconium.</td>
<td>Neutron activation calculation.</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>ILW-U</strong></td>
<td></td>
<td><strong>5,187</strong></td>
<td><strong>28</strong></td>
<td><strong>100</strong></td>
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Key to colours at the end of Table 11.
Table 10 Contributors to carbon-14 in reactive metals (Magnox and uranium)

<table>
<thead>
<tr>
<th>Waste stream identifier</th>
<th>Waste package category</th>
<th>Waste stream description</th>
<th>Packaged volume (m³)</th>
<th>C-14 activity (TBq)</th>
<th>Contribution to total C-14 activity (%)</th>
<th>Uncertainty in C-14 activity (× or / factor of)</th>
<th>Metals (%)</th>
<th>Calculation of C-14 activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D07</td>
<td>ILW-U</td>
<td>Pile Fuel Cladding and Miscellaneous Solid Waste</td>
<td>8,164</td>
<td>15</td>
<td>12.6</td>
<td>3</td>
<td>23.9% Magnox, 3.6% uranium metal, 6.5% aluminium, 2.4% lead, 22.5% steel, stainless steel scrap.</td>
<td>No information.</td>
</tr>
<tr>
<td>2D08</td>
<td>ILW-U</td>
<td>Magnox Cladding and Miscellaneous Solid Waste</td>
<td>12,695</td>
<td>11</td>
<td>9.5</td>
<td>1.5/3</td>
<td>&lt;5% Magnox, &lt;1% uranium metal, 10% stainless steel and &lt;1% mild steel.</td>
<td></td>
</tr>
<tr>
<td>2D09</td>
<td>ILW-U</td>
<td>Magnox Cladding and Miscellaneous Solid Waste</td>
<td>10,487</td>
<td>16</td>
<td>13.5</td>
<td>1.5</td>
<td>~6% Magnox, &lt;2% uranium metal, &lt;10% stainless steel and &lt;1% mild steel.</td>
<td></td>
</tr>
<tr>
<td>2D22</td>
<td>ILW-U</td>
<td>Magnox Cladding and Miscellaneous Solid Waste</td>
<td>3,827</td>
<td>8</td>
<td>6.7</td>
<td>1.5</td>
<td>~21.3% Magnox and ~4.3% uranium metal.</td>
<td></td>
</tr>
<tr>
<td>2D24</td>
<td>ILW-U</td>
<td>Magnox Cladding and Miscellaneous Solid Waste</td>
<td>5,041</td>
<td>11</td>
<td>9.4</td>
<td>1.5</td>
<td>~25.3% Magnox and ~7.9% uranium metal.</td>
<td></td>
</tr>
<tr>
<td>2D35</td>
<td>ILW-U</td>
<td>Magnox Cladding and Miscellaneous Solid Waste</td>
<td>2,716</td>
<td>0.15 (+10.5)</td>
<td>9.2</td>
<td>3</td>
<td>79.4% Magnox and ~4% uranium metal.</td>
<td></td>
</tr>
<tr>
<td>2D35/C</td>
<td>ILW-U</td>
<td>Encapsulated Retrieved Magnox Cladding</td>
<td>1,408</td>
<td>5</td>
<td>4.1</td>
<td>3</td>
<td>16% Magnox and 0.6% uranium metal.</td>
<td></td>
</tr>
<tr>
<td>2D38/C</td>
<td>ILW-U</td>
<td>Encapsulated Magnox Cladding</td>
<td>12,090</td>
<td>1 (+37.1)</td>
<td>32.8</td>
<td>3</td>
<td>16% Magnox and 0.55% uranium metal.</td>
<td></td>
</tr>
<tr>
<td>2D45</td>
<td>ILW-U</td>
<td>Magnox Fuel End Crops</td>
<td>55</td>
<td>0.03 (+0.76)</td>
<td>0.7</td>
<td>1.5</td>
<td>25% Magnox, 60% uranium metal and 8% zirconium.</td>
<td></td>
</tr>
<tr>
<td>2D17</td>
<td>ILW-U</td>
<td>Cemented Wastes in Skips</td>
<td>124</td>
<td>0 (+1.6)</td>
<td>1.4</td>
<td>-</td>
<td>1% Magnox, 40% uranium metal and 2% Zircaloy.</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>ILW-U</strong></td>
<td></td>
<td><strong>56,607</strong></td>
<td><strong>66 (+50)</strong></td>
<td><strong>100.0</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Red figures show the impact of enhancement of 2010 EDI for the waste stream.

Key to colours at the end of Table 11.
### Table 11  Contributors to carbon-14 in other wastes

<table>
<thead>
<tr>
<th>Waste stream identifier</th>
<th>Waste package category</th>
<th>Waste stream description</th>
<th>Packaged volume (m³)</th>
<th>C-14 activity (TBq)</th>
<th>Contribution to total C-14 activity (%)</th>
<th>Uncertainty in C-14 activity (× or / factor of)</th>
<th>Description</th>
<th>Calculation of C-14 activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A07</td>
<td>ILW-U</td>
<td>ILW</td>
<td>272</td>
<td>23</td>
<td>4.2</td>
<td>1.5</td>
<td>Glassware (10%), cellulosics (31%), absorbed liquids (15%), metals (7%), rubber (3%), plastics (33%).</td>
<td>No information.</td>
</tr>
<tr>
<td>1B05</td>
<td>ILW-U</td>
<td>ILW Containing Carbon-14 Excluding Free Liquid</td>
<td>58</td>
<td>194</td>
<td>34.6</td>
<td>10</td>
<td>Glass (40%), cellulose (0.5%), metals (5%), water (39.5%), oil (2.5%), ion-exchange resins (2.5%), vermiculite/silica (10%).</td>
<td>Activity is either measured (absorbed liquids) or assessed following specific operations from radioactivity balance data.</td>
</tr>
<tr>
<td>1B07</td>
<td>ILW-U</td>
<td>ILW Containing Tritium and Carbon-14</td>
<td>157</td>
<td>320</td>
<td>57.1</td>
<td>10</td>
<td>Glass (40%), paper (0.5%), metals (15%), absorbed liquid (32%), ion-exchange resins (2.5%), vermiculite/silica (10%)</td>
<td>No information.</td>
</tr>
<tr>
<td>1B10</td>
<td>ILW-U</td>
<td>ILW Containing Carbon-14 Free Liquid</td>
<td>17</td>
<td>23</td>
<td>4.1</td>
<td>10</td>
<td>Industrial methylated spirits, ethanol and acetonitrile</td>
<td>The waste contains C-14 only and is either measured or assessed following specific operations from radioactivity balance data.</td>
</tr>
<tr>
<td>Total</td>
<td>ILW-U</td>
<td></td>
<td>504</td>
<td>560</td>
<td>100.0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### (b) Other ILW

<table>
<thead>
<tr>
<th>Waste stream identifier</th>
<th>Waste package category</th>
<th>Waste stream description</th>
<th>Packaged volume (m³)</th>
<th>C-14 activity (TBq)</th>
<th>Contribution to total C-14 activity (%)</th>
<th>Uncertainty in C-14 activity (× or / factor of)</th>
<th>Description</th>
<th>Calculation of C-14 activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>2F06/C</td>
<td>ILW-U</td>
<td>Encapsulated Barium Carbonate Slurry/MEB Crud</td>
<td>575</td>
<td>30</td>
<td>49.3</td>
<td>3</td>
<td>Concrete (70%), water (19.6%), barium carbonate (7.8%), NaNO₂/NaNO₃ (2.1%), NaOH (0.5%), Ba(NO₃)₂, Ba(OH)₂, BaI₂ and Ba(IO₃)₂.</td>
<td>The activities are a combination of measurements and calculated activities, based on characteristics of fuel reprocessed to date for stocks and that still to be reprocessed for arisings.</td>
</tr>
<tr>
<td>2F04/C</td>
<td>ILW-U</td>
<td>Encapsulated LWR Cladding</td>
<td>1,915</td>
<td>27</td>
<td>44.2</td>
<td>3</td>
<td>Zircaloy (26.9%), Inconel (0.6%), stainless steel (4.5%), concrete (68%), UO₂ (TR).</td>
<td>The activities are calculated, based on characteristics of LWR fuel reprocessed.</td>
</tr>
<tr>
<td>2D27/C</td>
<td>ILW-U</td>
<td>Encapsulated Floc from Effluent Treatment</td>
<td>14,616</td>
<td>4</td>
<td>6.5</td>
<td>10</td>
<td>Ferric and alumino-ferric hydroxide floc, with adsorbed actinide ions (51%), PFA/OPC cement (49%).</td>
<td>The various feeds (SEC, MAC, Bulks and retrieved floc) are sampled prior to treatment in EARP. The samples are analysed for the quoted species. The permeate from the floc due to dewatering is sampled and analysed. The amount in the floc is calculated from the difference between the feed and permeate inventories.</td>
</tr>
<tr>
<td>9D322 ILW-U Reactor Neutron Sources R1</td>
<td>ILW-U</td>
<td>Reactor Neutron Sources R1</td>
<td>0.7</td>
<td>3</td>
<td>4.4</td>
<td>10</td>
<td>Antimony (49%), beryllium (14%) and stainless steel 79 EN58B (37%).</td>
<td>No information.</td>
</tr>
<tr>
<td>9D323 ILW-U Reactor Neutron Sources R2</td>
<td>ILW-U</td>
<td>Reactor Neutron Sources R2</td>
<td>0.7</td>
<td>3</td>
<td>4.4</td>
<td>10</td>
<td>Antimony (49%), beryllium (14%) and stainless steel 79 EN58B (37%).</td>
<td>No information.</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>ILW-U</strong></td>
<td></td>
<td><strong>17,107</strong></td>
<td><strong>67</strong></td>
<td><strong>100.0</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Key to colours at the end of Table 11.
### (c) Spent fuels

<table>
<thead>
<tr>
<th>Waste stream identifier</th>
<th>Waste package category</th>
<th>Waste stream description</th>
<th>Packaged volume (m³)</th>
<th>C-14 activity (TBq)</th>
<th>Contribution to total C-14 activity (%)</th>
<th>Uncertainty in C-14 activity (× or / factor of)</th>
<th>Description</th>
<th>Calculation of C-14 activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>M2D100</td>
<td>SF</td>
<td>AGR Spent Fuel</td>
<td>4,786</td>
<td>853</td>
<td>92.1</td>
<td>-</td>
<td>82.5% UO₂, 16.9% 20Cr/25Ni/Nb.</td>
<td>Activation calculations. (16% activity from the fuel, 84% from the cladding)</td>
</tr>
<tr>
<td>M3S100</td>
<td>SF</td>
<td>PWR Spent Fuel</td>
<td>1,636</td>
<td>73</td>
<td>7.9</td>
<td>-</td>
<td>78.8% UO₂, 17.8% Zircaloy, 1% Inconel.</td>
<td>Activation calculations. (49% activity from the fuel, 51% from the cladding, grids and sleeves)</td>
</tr>
<tr>
<td>Total</td>
<td>SF</td>
<td></td>
<td>6,422</td>
<td>926</td>
<td>100.0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Key:** Table 8 to Table 11

Wastes that have already been packaged are highlighted in blue.

Wastes that are currently being packaged are highlighted in green.

Wastes with plans reported in the UKRWI for packaging are highlighted in yellow.

---

8 This is the total activity for all the FSC LLW graphite waste streams.

### (d) LLW core graphite

<table>
<thead>
<tr>
<th>Waste stream identifier</th>
<th>Waste package category</th>
<th>Waste stream description</th>
<th>Packaged volume (m³)</th>
<th>C-14 activity (TBq)</th>
<th>Contribution to total C-14 activity (%)</th>
<th>Uncertainty in C-14 activity (× or / factor of)</th>
<th>Description</th>
<th>Calculation of C-14 activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 LLW-S</td>
<td>FSC Graphite</td>
<td></td>
<td>13,358</td>
<td>6</td>
<td>0.6</td>
<td>10</td>
<td>100% graphite.</td>
<td>Neutron activation calculations.</td>
</tr>
</tbody>
</table>
4 Experiments on the generation of gases containing carbon-14

Once the waste streams containing significant inventories of carbon-14 have been identified, the next step is to understand whether there is the potential for these streams to generate gases bearing carbon-14.

In Phase 1 of the project we have reviewed and captured the current understanding of gas generation, drawing on work undertaken as part of the UK programmes and the programmes of overseas radioactive waste management organisations. We have then identified where further data or process understanding is required and developed a plan to address these needs in Phase 2.

In Phase 2, it is planned to:

- Complete experiments to measure release and speciation of carbon-14 release from graphite;
- Continue experiments to measure release and speciation of carbon-14 release from irradiated reactive metals;
- Carry out experiments to measure release and speciation of carbon-14 release from irradiated stainless steels.

Together these will provide improved data for use in gas generation models.

In the subsections below, we describe the current understanding for each category of waste and how it is captured in the modelling basis spreadsheet. We then discuss the justification of the data and process understanding, whether these require improvement and, if so, whether these requirements are being addressed through current work, require further work in Phase 2 or may be addressed in the potential Carbon-14 Source Term (CAST\textsuperscript{9}) international project that is being led by NDA RWMD \textsuperscript{10}.

A significant amount of work on the release of carbon-14 from irradiated graphite and metal wastes has been undertaken in Japan, although there has been a relative lack of detailed information, suitable for critical review, published in English. As a result of a consultation with representatives from RWMC and Toshiba on 12 September 2012, we have gained a clearer understanding of these work programmes, the methods used and some of the key findings, including more recent results for Zircaloy, stainless steel and graphite. A summary of the work programmes undertaken by RWMC and the key results are presented in Table 12 and Table 13. The findings of these programmes are referred to, where appropriate, in the subsections below.

4.1 Graphite

Assessment approach

In the absence of a mechanistic understanding of carbon-14 release from irradiated graphite, a simple empirical approach has been used in the 2012 gas assessment model [13]. The approach and the parameters used are the same as those used in the 2007 GPA (03) update [10].

\textsuperscript{9} CAST stands for C\textsuperscript{A}rbon-14 S\textsuperscript{O}urce T\textsuperscript{E}rm
\textsuperscript{10} The proposal was submitted to the EU in November 2012.
A simple empirical model of the release of carbon-14 from graphite is implemented in SMOGG [24]. The release rate, $q_c$ [TBq a\(^{-1}\)], of carbon-14 is modelled as:

$$q_c = k_c A_c(t) M_g$$  \hspace{1cm} (4.1)

where:

- $k_c$ is a rate constant for the release of carbon-14 from the graphite [a\(^{-1}\)];
- $A_c(t)$ is the activity of the carbon-14 in the graphite at time $t$ [TBq kg\(^{-1}\)]; and
- $M_g$ is the mass of graphite present [kg].

The production of carbon-14 from the graphite decreases with time as the amount of carbon-14 left in the graphite is reduced as a result both of release from the graphite and of radioactive decay, so that the rate of release at time $t$ after the initial time is:

$$q_c = k_c A_c(0) M_g e^{-(k_c + \lambda_c)t}$$  \hspace{1cm} (4.2)

where:

- $\lambda_c$ is the radioactive decay constant for carbon-14 [a\(^{-1}\)].

It is assumed in the model that the possible release products can be represented by \(^{14}\)CH\(_4\) and \(^{14}\)CO\(_2\), with the proportion of each specified by the model user.

The parameter values being used in the current assessment were based on two sources of leaching data: a review by Marsden \textit{et al.} [25] and an experimental study by Handy [26].

According to reference [10] the selected value for $k_c = 5 \times 10^{-4}$ a\(^{-1}\) was based on UK graphite leach tests, although it is unclear how this value has been derived from the data presented in reference [25]. In addition, there is some ambiguity concerning the units of the results of the Magnox graphite leaching tests presented (it appears that tabulated cumulative fractional release data are presented in units of %). It should be noted that the data concerned are measurements of dissolved releases of carbon-14; no measurements were made of carbon-14 releases to the gas phase.

The partitioning of the carbon-14 releases has been set as 1% methane, 99% carbon dioxide and is based on a conclusion from the study of irradiated graphite from the Windscale Advanced Gas-cooled reactor (WAGR) by Handy [26]:

“Bounding values have been estimated for the fraction of the total C-14 inventory that could be released as a hydrocarbon. The range was from 0.001% to 1%.”

However, this conclusion is based on an experimental data set with only one positive measurement (out of 18) of gaseous carbon-14 over the 31-week timescale of the leaching experiments. It is not stated by Handy, but the upper bound value of 1% for release of carbon-14 as hydrocarbon appears to be based on the ratio of the upper limit for carbon-14 release measured in the gas phase, <6 Bq (assumed to be hydrocarbon, based on the sum of limits of detection for individual measurements), to the dissolved release, 500 Bq (assumed to be CO\(_2\)) from an intact sample. Nearly 1% of the inventory of carbon-14 was released during the experiments.

Thus the two parameter values for carbon-14 release from graphite used in the current assessment model are based on a limited amount of data, which are not from a coherent set of experiments.

\textbf{Status of data}

Release rate data in the literature for total carbon-14 releases to the solution phase from graphite leaching experiments up to 2002 (with one exception [27]) were reviewed by Marsden [25]. None of the studies made measurements of gas phase releases or of the
speciation of the carbon-14 released to solution. In general these experiments, undertaken under aerobic conditions, observed a decrease in the rate of total carbon-14 release with time over a period of 50-100 days. The results suggest a fast initial release of readily mobilised surface species on contact with water, followed by a slower long-term release that may be controlled by the rate of out-diffusion of carbon-14 species from the porosity of the graphite. Total fractional releases (i.e. the total release as a fraction of the sample carbon-14 inventory) vary by several orders of magnitude, reflecting the different sources, irradiation histories and irradiation conditions of the graphites as well as differences in geometries and porosities of leached samples.

More recent leaching studies of moderator and reflector graphite samples from the Tokai (Magnox) reactors in Japan [28, 29] (see Table 12 and Table 13) have included separation of the organic carbon-14 species in solution from $^{14}$C-carbonate and attempts to identify the nature of these organic species (there are no gas phase measurements) [30]. About 0.1% of the carbon-14 inventory of graphite samples was released over three years, with the majority of the release occurring in the first month. The organic leachate components were separated into fractions by High Performance Liquid Chromatography (HPLC) and the fractions analysed individually for carbon-14. In addition, the strength of sorption of the released carbon-14 species was assessed. Although the leached organic carbon-14 species eluted at similar times to small organic molecules, they were found to be more strongly sorbing than small organic species (methanol, formate, acetate, etc). As a result, the identities of the leached organic carbon-14 species have yet to be confirmed.

Work on the NDA RWMD programme has focused on measurements of gas-phase carbon-14 releases. An initial study by Serco confirmed that some carbon-14 was released to the gas phase on leaching of WAGR graphite [31], and this was followed by a series of leaching experiments on WAGR and British Experimental Pile 0 (BEP0) graphites to measure the gaseous carbon-14 releases with time and to discriminate between organic/hydrocarbon and inorganic gaseous forms of carbon-14 [26, 32].

The latter of these experiments (by Serco) was undertaken with periodic sampling of volatile carbon-14 releases from BEP0 graphite leached in alkaline solution under aerobic conditions over a period of 14 months [32]. The estimated initial content of the graphite was 2.1 MBq. At the conclusion of the 14 month experiment, 112 Bq of carbon-14 had been released into the gaseous phase (corresponding to 0.005% of the carbon-14 inventory, with 80% as inorganic species (assumed to be $^{14}$CO) and 20% as organic species (assumed to be $^{14}$CH$_4$)), with a further 2.1 kBq into solution (corresponding to 0.1% of the carbon-14 inventory). The rate of $^{14}$C release generally decreased with time (see Figure 5) and was found to correspond fairly well the first-order function:

$$a(t) = fA(1 - e^{-kt})$$

(4.1)

where

- $a$ is the total activity released up to time $t$
- $A$ is the initial activity in the graphite
- $f$ and $k$ are fitted parameters.

Differentiation of equation (4.1) gives the rate:

$$\frac{da}{dt} = fAke^{-kt}$$

(4.2)

Fitting of the experimental data to the exponential function of equation (4.1) gave a reasonable fit as shown in Figure 5. The model represents a first-order reaction for the release. $f$ can be thought of as the fraction of total activity that is potentially released to the gas phase. It may be simply a proportion of the total, or it may depend on other factors, for example, if the $^{14}$C release measured in the experiment was predominantly from that on the
graphite surface, then the surface area may be a factor. \( k \) is a rate constant for the release of \(^{14}\text{C} \). It may also be dependent on the ease with which the graphite porosity can be accessed by the solution.

**Figure 5**  Cumulative \(^{14}\text{CO} \) and \(^{14}\text{C}-\text{organic} \) release from BEP0 graphite under alkaline (pH 13), aerobic conditions, with fitting of a simple release model (\(^{14}\text{CO} \) model parameters: \( f = 4.2 \times 10^{-4} \) [dimensionless], \( k = 3.8 \times 10^{-4} \text{ hr}^{-1} \); \(^{14}\text{C}-\text{organic} \) model parameters: \( f = 1.2 \times 10^{-5} \) [dimensionless], \( k = 4.1 \times 10^{-4} \text{ hr}^{-1} \) ) [32]

---

Work is currently ongoing in the NDA RWMD programme to measure the rates of gaseous release of carbon-14 from irradiated Magnox carrier graphite from Oldbury. The effects of anaerobic compared to aerobic conditions, pH, temperature and the form of the graphite on gaseous carbon-14 releases are being investigated and the work being managed under this IPT. The experimental design has been extended to discriminate between inorganic gas-phase releases as \(^{14}\text{CO}_2\) or \(^{14}\text{CO} \). Results to date have confirmed that under both aerobic and anaerobic conditions the principal gas-phase inorganic species is \(^{14}\text{CO} \) (the majority of \(^{14}\text{CO}_2\) release is retained as carbonate in solution) [33]. However, rates of release are about one order of magnitude lower than for the BEP0 graphite and (under aerobic conditions\(^{11}\)) decrease with time (Figure 6). In the case of the Magnox graphite, under aerobic conditions, the ratio of \(^{14}\text{CO} \) to \(^{14}\text{C}-\text{organic} \) species is close to 50:50. Initial results (up to 7 days leaching) under anaerobic conditions may indicate a higher proportion of gas phase \(^{14}\text{C}-\text{organic} \) species.

---

\(^{11}\) Sufficient data are not yet available for anaerobic conditions to enable conclusions to be drawn
Some work on graphite leaching is also being undertaken on the CARBOWASTE programme. This will be evaluated under the CAST project once the final report is available during 2013.

In addition, work is in progress on the C-14 BIG project [34], a collaborative programme involving the Universities of Huddersfield, Bristol and Central Lancashire (jointly funded by the NDA and the Research Councils UK Energy programme) which will include studies of the behaviour and partitioning of graphite-associated carbon-14 under GDF conditions.

Data/modelling needs

The ongoing programmes of experimental work to measure both dissolved and gaseous releases from irradiated Oldbury (Magnox) graphite and work on the C-14 BIG project are addressing current data needs and developing understanding of carbon-14 association with, and release from, irradiated graphites. In addition, the proposed CAST project is planned to include a review task on the understanding of carbon-14 release from irradiated graphite. Thus, it is considered that additional programmes of experimental work on graphite during the timescale of this IPT are not required.

However, it is envisaged that future work may be required (beyond 2014) to characterise releases from other types of reactor graphites (e.g. Gilsonite AGR graphites) with different irradiation histories and under site-specific environmental conditions. Some forward planning for the identification and potential acquisition of suitable samples is an activity for Phase 2 of this IPT (although this has been assigned a low priority).

The current assessment model for carbon-14 release from graphite overestimates the release of carbon-14 and the release model and associated parameters used will be re-evaluated based on the results of recent and on-going studies that are providing new data and increased understanding of carbon-14 release processes from graphite. In particular, the development of a more realistic conceptual model for the release of carbon-14 from graphite that better reflects the behaviour observed experimentally is an objective for Phase 2 of this IPT. This will draw on data from recent and ongoing programmes and should take account of the review work on graphite that is proposed within the international CAST project.
It is possible that a significant proportion of the graphite carbon-14 inventory is associated with the graphite matrix and is essentially immobilised. An activity for Phase 2 of this IPT is to review the arguments associated with the long-term stability of graphite and the potential for taking credit from the immobilisation of a significant fraction of the carbon-14 inventory in the graphite matrix.
<table>
<thead>
<tr>
<th>Study</th>
<th>Material</th>
<th>Abstract</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Activated Zircaloy</td>
<td>Organic C-14. Not detected in gas phase. In analysis, organic C-14 was oxidized by KMnO₄. Most of organic C-14 was neutral species (organic C-14 passes through anion exchange paper).</td>
<td>[35]</td>
</tr>
<tr>
<td>2</td>
<td>BWR Zry-2 STEP I</td>
<td>Detected in gas and liquid phases. Amount of C-14 leaching out from Zircaloy with oxide film was more than that from Zircaloy metal. The same amounts of inorganic and organic C-14 were detected by the leaching test of 30 months. In the leaching test conducted by a stepwise sampling method, decreases of C-14 in summarising samples were observed. Formate, formaldehyde and acetate were isolated by HPLC.</td>
<td>[39]</td>
</tr>
<tr>
<td>3</td>
<td>BWR Zry-2 STEP III</td>
<td>More than 40% of C-14 was organic carbon. Detected in gas phase, however not detected in gas phase of leaching sample for 12 months. Leaching test continuing.</td>
<td>[40]</td>
</tr>
<tr>
<td>4</td>
<td>Stainless steel</td>
<td>Not measured in gas phase. 66 ~ 75% of C-14 in liquid phase was organic carbon, oxidized by KMnO₄. C-14 chromatograph was measured by HPLC + LSC, some peaks were obtained and associated with formate, formaldehyde, acetate, methanol.</td>
<td>[37]</td>
</tr>
<tr>
<td>5</td>
<td>BWR Shroud</td>
<td>25% of C-14 in gas phase, 38% of organic C-14 and 37% of inorganic C-14 in the liquid phase were detected. Organic carbon in liquid phase was separated by anion exchange resin to obtain neutral and anion species. Of organic C-14, neutral species were 18%, anion species were 82%.</td>
<td>[41]</td>
</tr>
<tr>
<td>6</td>
<td>Graphite</td>
<td>Not measured in gas phase. 80% of C-14 in liquid phase was organic carbon. In analysis, organic C-14 was oxidized by KMnO₄. C-14 chromatograph was measured by HPLC + LSC to obtain peaks at the same positions as for formate, acetate, and methanol. The $K_d$ value of OPC for total C-14 was 69 cm$^3$g$^{-1}$. The $K_d$ values of organic carbon to be assigned to the peaks of the C-14 chromatograph were more than 30 cm$^3$g$^{-1}$, and were not consistent with that of C-14 bearing compounds for OPC. It was suggested that organic carbon leaching out from the graphite is not formate, acetate or methanol.</td>
<td>[28]</td>
</tr>
<tr>
<td>7</td>
<td>Non-activated Fe₃C, ZrC, Zr, carbon steel</td>
<td>Not measured in gas phase. C-14 detected in liquid phase was inorganic and organic carbon. Ratio of organic was more than that of inorganic. C.f. studies 2 and 5.</td>
<td>[43]</td>
</tr>
</tbody>
</table>

Key: BWR Boiling water reactor; HPLC High performance liquid chromatography; $K_d$ Sorption distribution ratio (units: cm$^3$g$^{-1}$); LSC Liquid scintillation counting; OPC Ordinary Portland cement.
Table 13  Outline of results of speciation studies of carbon-14 releases from irradiated metals and graphite undertaken in Japan [30]; refers to studies listed in Table 12

<table>
<thead>
<tr>
<th>Study</th>
<th>Material</th>
<th>Analysis method</th>
<th>Gas phase</th>
<th>Liquid phase</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Inorganic C-14</td>
<td>Organic C-14</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Inorganic C-14</td>
<td>Organic C-14</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Zircaloy</td>
<td>PWR Zry-4</td>
<td>Wet oxidation + LSC</td>
<td>N.D.(CO₂, CO)</td>
<td>11 months : N.D. 5.5 months : 21%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Base metal</td>
<td></td>
<td>N.D.(CH₄)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Zircaloy</td>
<td>BWR Zry-2 STEP I</td>
<td>Wet oxidation + LSC</td>
<td>Inorganic + Organic ; N. D. (0%) ~76% 30 months : 71%</td>
<td>Inorganic + Organic : 24% ~ 100% 30 months : Inorganic 17%; Organic 12% [39]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Base metal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Zircaloy</td>
<td>BWR Zry-2 STEP III</td>
<td>Wet oxidation + LSC</td>
<td>Inorganic + organic 6 ~ 9 months: 50% 12 months : N.D.(0%)</td>
<td>6 ~ 9 months : 18<del>20% 12 months: 72% 6 ~ 9 months : 30</del>31% 12 months: 28% [40]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Base metal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Activated</td>
<td>PWR Zry-4</td>
<td>Wet oxidation + LSC</td>
<td>N.D.(CO₂,CO)</td>
<td>11 months : N.D. 11 months : 100%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Oxide film</td>
<td></td>
<td>N.D.(CH₄)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Activated</td>
<td>BWR Zry-2 STEP I</td>
<td>Wet oxidation + LSC</td>
<td>Inorganic + Organic ; N. D. (0%) ~76% 30 months : 8%</td>
<td>Inorganic + Organic : 5% ~ 70% 30 months : Inorganic 30%; Organic 62% [39]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Oxide film</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Stainless steel</td>
<td>BWR Upper grid</td>
<td>Wet oxidation, HPLC+LSC</td>
<td>Not measured</td>
<td>Total 23 ~ 34%</td>
</tr>
<tr>
<td>5</td>
<td>Stainless steel</td>
<td>BWR Shroud</td>
<td>Ion exchange + LSC</td>
<td>Inorganic + Organic; 42 months 25%</td>
<td>42 months : 37%</td>
</tr>
<tr>
<td>6</td>
<td>Graphite</td>
<td>Moderator Reflector</td>
<td>HPLC + LSC</td>
<td>Not measured</td>
<td>~ 20%</td>
</tr>
<tr>
<td>7</td>
<td>Non-activated</td>
<td>Fe₃C</td>
<td>HPLC</td>
<td>Not measured</td>
<td>35~45%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ZrC</td>
<td>HPLC</td>
<td>Not measured</td>
<td>10~12%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Carbon steel</td>
<td>HPLC</td>
<td>Not measured</td>
<td>~0.01%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Zr</td>
<td>HPLC</td>
<td>Not measured</td>
<td>~0.01%</td>
</tr>
</tbody>
</table>

Key: see footnote to Table 12; N.D. Not detected
4.2 Irradiated steels, Zircaloy (and other ferrous metals)

Assessment approach

Metals corrode, and under appropriate environmental conditions will generate hydrogen gas. Typically there is an initial short-term period of rapid (acute) corrosion followed by a long-term period of slower (chronic) corrosion. This is represented in the current gas generation model, as implemented in SMOGG [24] by the sum of two terms, each of which decays exponentially with time. Each contribution is the product of a rate constant, a time-varying exponential factor and an exponential (Arrhenius) factor describing the temperature dependence. The release of carbon-14 is assumed to occur at the rate of corrosion as fresh metal surface is exposed.

Options are available in SMOGG to specify the distribution of carbon-14 through a bulk metal. However, in assessments to date (and in the absence of information on carbon-14 distribution), the distribution is assumed to be homogeneous.

The carbon-14 could be released as a variety of chemical forms and it is assumed in SMOGG that these forms can be represented by $^{14}$CH$_4$ and $^{14}$CO$_2$, with the proportion of each specified by the model user. In the GPA (03) gas update and the 2012 gas assessment, the cautious assumption is made that all carbon-14 is released from metals as methane.

Status of data

Speciation and rate of carbon-14 releases

Most of the work to date on irradiated ferrous metals and Zircaloy has been undertaken in Japan, with most information being available on studies of Zircaloy [35, 36]. Some work on stainless steel and Inconel (nickel alloy) was presented at a Nagra/NDA RWMD workshop on carbon-14 in 2003 [37, 38]. There are currently no reports available on the latter studies in English that provide sufficient details of the materials used, the experimental methodologies or the results, suitable for critical review. However, we have gained a clearer understanding of ongoing work programmes [39, 40], and some of the analytical methods used, from a meeting held with representatives from RWMC and Toshiba on 12 September 2012. The work programmes are summarised in Table 12 and Table 13. In particular, there appears to be one recent experiment that has measured gaseous carbon-14 release from irradiated stainless steel [41].

The current understanding of carbon-14 releases from corrosion-resistant metals can be summarised as follows:

- In experiments where the metal was first acid-cleaned to remove the passivating oxide film, carbon-14 is released from Zircaloy, Inconel and stainless steel into solution at rates that are consistent with metal corrosion rates [38].

- Gaseous carbon-14 releases were below the detection limit of 0.1 Bq from Zircaloy leached in a synthetic groundwater for up to 5.5 months [35, 36]; however, some gas phase release of carbon-14 has been detected in more recent leaching experiments on Zircaloy-2 in pH 12.5 sodium hydroxide solution (see Table 12 and Table 13).

- In one test, 25% of the carbon-14 released from irradiated stainless steel plate over 42 months is reported to be released as gaseous species [41].

- Carbon-14 is released to the solution phase as a mixture of inorganic (carbonate) and organic forms. Formic acid, acetic acid, formaldehyde, methanol, ethanol, and an unidentified species are reported from activated stainless steel at pH 10 [37]; at pH 12.5 the ratio of organic to inorganic species released from stainless steel is.
reported to be close to one, with 80% of the organic species present as anionic forms (e.g. carboxylates) [41].

- Results from inactive analogue studies tend to support the above conclusions concerning speciation of dissolved release, but with varying proportions of inorganic and organic species [42, 43, 44]: thus carbon-14 may be released as soluble species, both organic and inorganic; gaseous species may be a smaller component.

Thus, there appears to be one single test on the leaching of irradiated stainless steel under high pH conditions, which has measured a very small release of gaseous carbon-14 (~1.2 Bq1241) [41]. Unfortunately, full details of the experiment are not available for critical review. Clearly such findings need to be corroborated and more data are required concerning the rate and speciation of release of carbon-14, to build confidence in the understanding of carbon-14 releases from irradiated stainless steel and also from Zircaloy.

A work package to determine the rate and speciation of carbon-14 release from irradiated stainless steel is planned within CAST. A number of organisations will participate in this work package including NDA RWMD and AMEC from the UK.

**Corrosion rates**

Data on the corrosion rates of carbon steels, stainless steels and Zircaloy under disposal conditions were reviewed in 2007 [45]. Based on these reviews, recommendations were made regarding the corrosion rates to be used in SMOGG. The recommended corrosion rates are summarised in Sections 4.4, 6.3 and 8.3 of reference [45]. The same values are being used in the 2012 gas assessment [13].

Compared with the reactive metals, steels and Zircaloy are corrosion resistant. In particular, Zircaloy and stainless steels have very low corrosion rates under alkaline, anaerobic disposal conditions (in fact under all conditions for Zircaloy) and this makes them difficult to measure. For example, in experiments to measure the gas generation from anaerobic corrosion of stainless steel under alkaline conditions over a 10-year period, it was not possible to measure any hydrogen generation [46]. This indicated that the anaerobic corrosion rate of stainless steel was less than 0.01 μm yr⁻¹, the estimated detection limit for the gas cell technique. The difficulties of measuring the very low corrosion rates of Zircaloy by gas generation are compounded by the absorption of the resulting hydrogen into the metal to form hydrides [47].

As a result of these experimental difficulties, there are significant uncertainties concerning the long-term corrosion rates of stainless steels and Zircaloy that will control carbon-14 releases from these materials in the longer term. The value of 0.01 μm yr⁻¹ was selected [45] as the long-term anaerobic corrosion rate for stainless steel in gas assessments based on the upper limit estimated in reference [46] and some comparable, independent Japanese work [48,49]. In comparison the long-term corrosion rate of mild steel under anaerobic alkaline conditions is taken to be 0.005 μm yr⁻¹ [45].

**Data/modelling needs**

The review of current information has highlighted the lack of robust data on gaseous carbon-14 releases from irradiated stainless steel and Zircaloy, and a lack of any data for irradiated mild steel. Although there is some evidence for the release of gaseous carbon species from both inactive and irradiated steels, and from irradiated Zircaloy under alkaline leaching conditions, these results require corroboration. Work packages on the speciation and release of carbon-14 from steels and from Zircaloy are included within the proposed

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12 The total release of carbon-14 after 42 months was 4.76 Bq, of which 1.2 Bq was in the gas phase. The original sample contained 2.93 MBq of carbon-14 and was leached in sodium hydroxide at pH 12.5.
international CAST project. These work packages would, over a 4 year period, starting in mid-2013, address the key gaps in data and understanding concerning carbon-14 releases from these metals.

Owing to the low corrosion rates of stainless steel and Zircaloy, (which is due to the formation of a passivating surface layer), the long-term corrosion rate of these materials is difficult to measure. The value for stainless steel in the current gas assessment may be an upper limit, but improved data are not considered to be a priority for Phase 2 of the IPT. We understand that some work on Zircaloy corrosion is being undertaken in Japan [50].

About 70% of the carbon-14 associated with metal waste in the UK inventory is associated with stainless steel (see Table 5) and therefore of the corrosion-resistant metal wastes, carbon-14 releases from stainless steels are the highest priority. Improved understanding of the rate and speciation of associated carbon-14 releases are needed to better parameterise assessment models. There is a work package within the proposed CAST project to specifically address this need. This work package will include a programme of work by AMEC/NRG, which is currently on hold. The Justification for re-starting this work programme has been developed as part of the work during Phase 1 of this IPT. The findings are summarised in the following subsection. An initial task within the AMEC programme of work for CAST is an up-to-date review of the release of carbon and carbon-14 from steels by corrosion, which in particular will seek to draw together all the knowledge on this topic held (but not necessarily published) by contributors to CAST.

Zircaloy wastes contribute only a small fraction of the carbon-14 inventory (see Table 14). Therefore, carbon-14 releases from Zircaloy are considered to be a low priority. Maintaining knowledge of the results from the work package on Zircaloy under the CAST project will be sufficient to meet our current data needs.

**Justification for restarting the carbon-14 release from steels experiments**

In view of the identified data gap, the justification for restarting the AMEC/NRG programme of work on carbon-14 release from stainless steels (within the CAST project) has been developed.

The approach adopted was to consider the five criteria (see Box 1) that need to be met for C-14 gases released from steel wastes to contribute significantly to radiological risk in the biosphere, and to test whether each of the criteria could be met given current uncertainties concerning the location of a GDF, the host rock environment and the design of the engineered barriers. Information on the carbon-14 inventory of waste metals was provided by Pöyry. Information on the rates of gas generation were taken from the 2012 gas assessment calculations [13].

The findings of the review can be summarised as follows.

- There is a significant inventory of carbon-14 associated with stainless steel waste streams (70% of the inventory of metal wastes).
- There is uncertainty concerning speciation of carbon-14 derived from neutron activation compared with bulk carbon in steels and thus uncertainty concerning the speciation (e.g. CH₄, CO₂, CO, C₂H₂) of carbon-14 releases from irradiated materials compared with carbon-12 and carbon-13.
- Experiments on inactive steel suggest that carbon may be released from stainless steel primarily as water soluble organic species [42, 43]; but there is some evidence for the release of volatile species including methane.
- One experiment has been reported in which a small amount of carbon-14 was released to the gas phase on leaching irradiated stainless steel in alkaline solution for 42 months; however, these findings require corroboration.
• In current assessments, irradiated stainless steel is predicted to be the predominant long-term source of gaseous carbon-14 from metal wastes after reactive metals have corroded away (by 2160 in current SMOGG calculations).

• There is a likelihood that there will be a bulk gas phase in a GDF, which may persist for a long time (up to 100,000 years).

• Gaseous organic carbon-14 species would partition preferentially into the bulk gas phase.

• Depending on the geology of the site, bulk gas may migrate to the surface (in higher strength rock in the absence of mitigating overlying geological features).

If the short-term release of carbon-14 from reactive metals were managed by, for example, thermal treatment, alternative packaging or by mitigation of operational releases, then the remaining release of carbon-14 would be dominated by irradiated stainless steel. Given the lack of data and understanding of the rate and speciation of the release of carbon-14 from irradiated stainless steels, it is recommended that experimental measurements are made. The proposed CAST project includes a work package that should deliver these data on a timescale of 3-5 years. It is proposed that this will include the proposed AMEC/NRG programme.

4.3 Irradiated reactive metals

Assessment approach
The mathematical treatment of carbon-14 releases from irradiated reactive metals is as outlined above in Section 4.2 for irradiated steels and other less reactive metals.

Both the GPA (03) update and 2012 gas assessments include the release of gaseous carbon-14 from irradiated Magnox and uranium but not aluminium [10,13]; only a small carbon-14 inventory is thought to be associated with aluminium wastes.

Status of data

Corrosion data

Data on the corrosion rates of the reactive metals under disposal conditions were reviewed in 2007 [51]. In the case of uranium, the review drew heavily on a previous international review [52]. Based on these reviews, recommendations were made regarding the corrosion rates to be used in SMOGG. The recommended corrosion rates are summarised in Table 3.10 of reference [10]. The same values are being used in the 2012 gas assessment [13].

A further review of metal corrosion rates related to the encapsulation of waste metals (including Magnox, uranium and aluminium) in cementitious grout was undertaken by NNL in 2010 [53]. This review included data from extensive trials undertaken by BNFL that were not available for the 2007 review [51].

Reactive metals corrode relatively rapidly, and therefore their corrosion rates are readily measurable and have been determined under a range of conditions.

Magnox

In the case of Magnox, the rate of corrosion is independent of the oxygen concentration, so there is no distinction between aerobic and anaerobic conditions but continuing corrosion is determined by the availability of water. There was found be a good accord between the corrosion rates derived for Magnox for use in SMOGG, and the findings of the NNL review.
Thus, in general, the Magnox corrosion parameters used in the assessments are considered to be well-founded. One possible exception concerns the effect of salinity on the chronic corrosion rate of Magnox. A value two orders of magnitude higher than the chronic corrosion rate is used in SMOGG for saline conditions, based on results from Winfrith PETF tests to which salt was added [54, 55] as shown in Figure 7. However, replicate studies have not been undertaken to corroborate these results and relate them to the expected conditions in a GDF.

**Figure 7** Corrosion rates for Magnox encapsulated in grout in 500 litre scale experiments [54] (reproduced from [51])

It is noted here that in the 2012 gas assessment [13], the assumption is made that the groundwater infiltrating the GDF will be saline. Consequently, it is the anaerobic corrosion rate under saline conditions that is used for to calculate the gas generation rate following resaturation of the GDF and this leads to a large increase in the rate of gas generation following resaturation.

**Uranium**

There is a very significant body of literature concerning the corrosion behaviour of uranium in aqueous systems as outlined in reference [51]. There is considered to be no identifiable acute phase of uranium corrosion. Corrosion under anaerobic conditions (generating hydrogen) is between 30 and 100 times faster than under aerobic conditions (no hydrogen production); the reaction of uranium with water is inhibited by the presence of dissolved oxygen (>10 ppm) [53]. Overall, the chronic aerobic and anaerobic corrosion rates derived for use in SMOGG (based on corrosion in aqueous systems) and their temperature dependence are considered to be well-founded. It is notable that the NNL review [53] found that corrosion rates measured for grouted uranium over a range of temperatures lie between the anaerobic (higher) and aerobic (lower) corrosion rates predicted by SMOGG. This difference is likely to be due to variability in the conditions in the packages, the extent to which they are anaerobic, and possibly due to the extent to which water was available. It is noted here that in the base case for the 2012 gas assessment, the aerobic and anaerobic corrosion rates for uranium are used for the operational and post-closure phases of a GDF, respectively. This may lead to an underestimate of carbon-14 and hydrogen...
releases from uranium during the operational phase if regions of waste packages are anaerobic and consequently to an overestimate of these releases on GDF closure.

**Aluminium**

In the case of aluminium, the corrosion rates under alkaline conditions for use in SMOGG were derived [51] by fitting experimental data from grout encapsulation trials with limited test durations (<90 days). It was recognised in reference [51] that the value obtained for the chronic corrosion rate may be cautiously high. Additional studies of grouted aluminium outlined in the NNL review [53], indicate that the corrosion rate continues to decrease even after 900 days curing. The NNL reviewers suggest that the long-term rates used in SMOGG are likely to be too high, possibly by orders of magnitude, highlighting a data gap concerning the chronic rate of aluminium corrosion under grouted conditions, which is being addressed by the current NNL programme.

**Understanding of carbon-14 release**

There are currently no published data on carbon-14 releases from the corrosion of reactive metals to either gas or solution phases.

**Data/modelling needs**

The data gap concerning carbon-14 releases from reactive metals is being addressed by a new programme of NDA RWMD funded work, beginning in September 2012, with the aims of measuring gaseous and dissolved carbon-14 releases from three types of irradiated reactive metals: Magnox, uranium and aluminium. The project is being undertaken by NNL and is being managed as part of the carbon-14 IPT. The initial work is to recover suitable samples and determine their carbon-14 content prior to undertaking the corrosion experiments. It is possible that irradiated aluminium may contain little carbon-14 (no carbon-14 is associated with irradiated aluminium in the derived inventory) and, if so, study of this metal would be curtailed. The corrosion experiments are designed to discriminate between gaseous carbon-14 releases as $^{14}$CO, $^{14}$CO$_2$ and $^{14}$C-hydrocarbons. The programme of work is scheduled to run until March 2014.

In terms of corrosion rate data, further consideration needs to be given to the anaerobic corrosion rate of Magnox under saline conditions to establish whether a two orders of magnitude increase in corrosion rate compared with non-saline conditions is justified. The sensitivity of the model outputs to the uranium corrosion rate could be considered in the light of the NNL review described above.

**4.4 Other wastes**

Three additional types of carbon-14 containing wastes were identified in Section 3:

- Organic wastes;
- Ion-exchange materials; and
- Carbonate wastes (primarily barium carbonate).

Although a significant proportion of the total carbon-14 inventory is associated with organic wastes (small organic molecules), this is associated primarily with GE Healthcare waste streams that are currently anticipated to undergo incineration and would not be disposed to a GDF (see Table 7).
Assessment approach
The gaseous releases of carbon-14 from ion-exchange materials and carbonate wastes are not included in the current gas assessment models.

Status of data
Although, in general, carbonates are expected to be inert, there is some evidence that organic species may be produced from the irradiation of inorganic carbonate salts \[56, 57\]. Gamma irradiation of solid \( \text{Ca}^{14}\text{CO}_3 \), for instance, is reported to give rise to quantities of formic and other carboxylic acids \[56\]. It is currently assumed that cementitious grouts and backfill will act as sinks for bulk carbon and carbon-14 released from wastes as \( \text{CO}_2 \) and \( ^{14}\text{CO}_2 \) and that this prevents conversion of carbon dioxide to methane in the presence of hydrogen. We are supporting a PhD study at the University of Manchester, commencing this year, which includes work on the utilisation of hydrogen and coupling to microbial processes in high pH environments. In addition, barium carbonate wastes generated by treatment of off-gases (e.g. from Thorp) will contain \( \text{Ba}^{14}\text{CO}_3 \). If irradiation of carbonates was to give rise to \( ^{14}\text{C} \)-bearing organic species, there is the potential for these to be converted, by microbial action, into volatile hydrocarbons \[58\].

Some work has been undertaken by NDA RWMD on the gamma-irradiation of inactive \( \text{BaCO}_3 \), both in a dry state and in slurries with water (pH 7) and \( \text{Ca(OH)}_2 \) solution (pH 12), to assess the potential production of organic compounds \[59\], but was inconclusive.

There is also a possibility that carbon-14 may be associated with ion-exchange materials (organic or inorganic) and could be susceptible to ion exchange, microbial action and/or radiolysis. It is noted that some work on ion-exchange resins (organic materials) is ongoing in the Swedish (SKB) and Swiss (Nagra) programmes. Work on the speciation and release of carbon-14 from ion exchange materials will also form a work package within the proposed CAST project.

Data needs
Owing to the relatively small fractions of the carbon-14 waste inventory associated with ion-exchange materials and carbonate wastes, these are not considered to be priorities for further work at this stage of the MRWS process. We will draw on work undertaken as part of the CAST project to meet data needs and the development of understanding required at this stage.

4.5 Work for Phase 2
Phase 2 of the IPT will include three experimental programmes to measure carbon-14 releases from irradiated materials:

- A project to measure carbon-14 release from irradiated Oldbury graphite (currently underway);
- A project to measure carbon-14 release from irradiated reactive metals (currently underway);
- A programme of work within CAST to measure carbon-14 release from irradiated stainless steel.

The CAST proposal is due for submission in November 2012 and will be evaluated by April 2013. The start date for work under the CAST proposal, if successful, would be around September 2013.

During Phase 2, the carbon-14 IPT will also engage with other UK (e.g. C-14 BIG) and overseas projects on carbon-14 releases to ensure that the latest understanding and data are available as inputs to modelling activities. Engagement with overseas work would be
facilitated primarily through the proposed international CAST project, which includes work packages on carbon-14-containing gas generation from steels, Zircaloy, graphite and ion-exchange resins.

The main desk-based activities to be undertaken in the carbon-14 gas generation area during Phase 2 of this IPT can be summarised as follows:

- Collation and review of data and scientific understanding obtained from recent and ongoing programmes of work (in the UK and overseas) concerned with carbon-14 releases from graphite, reactive metals and stainless steel, in preparation for model development and data elicitation exercises. In particular, an up-to-date review of carbon and carbon-14 releases from steels by corrosion will be undertaken to underpin the CAST project work package on steels.

- Keeping abreast of international best practice, in particular developments in carbon-14 speciation analysis and, where appropriate and practicable, facilitating the transfer of best practice to and from UK work programmes on carbon-14 releases from irradiated materials.

- A review of the arguments associated with the long-term stability of graphite and the potential for taking credit from the immobilisation of a significant fraction of the associated carbon-14 inventory in the graphite matrix.

- Forward planning concerning the identification and potential acquisition of suitable samples that may be required for future experimental programmes on graphite (e.g. AGR graphite) and possibly other irradiated materials (e.g. mild steel), beyond the timescales of this IPT.

- Further consideration of the effect of water availability and salinity on the rate of Magnox corrosion, which will impact the timing of carbon-14 release from these wastes.

- Leadership and coordination of the proposed international CAST project will provide access to information relevant to topics regarded as lower priority in the UK context, in particular:
  o corrosion studies and carbon-14 release studies from Zircaloy; and
  o studies of radiolysis and carbon-14 releases from ion-exchange resins.
5 Modelling generation of carbon-14 bearing gases and bulk gases

In Phase 1 of the project, we have processed the most recent gas generation assessment results to determine the contributions to the generation rates of carbon-14 containing gas and bulk gas from different types of waste. We do this to identify the main contributions. The release is dominated by the corrosion of reactive metals in the operational and early post-closure time frame, and by the corrosion of irradiated stainless steel and leaching of irradiated graphite later in the post-closure period.

These calculations will be updated at key points during Phase 2, as new data and models become available.

In Phase 1 of the project, we have processed the most recent gas generation assessment results to determine the contributions to carbon-14 containing gas and bulk gas generation from different types of waste to identify the main contributions. Uncertainties in the data and the modelling approach have also been considered. The aim has been to understand the most significant waste streams, and the most important parameters and the uncertainties in them. This allows future work in this and other areas of the work of the IPT to be focused on the most important impacts.

Calculations are presented for ILW and not for HLW and spent fuel because:

- Radioactive gases will be released from vented ILW containers.
- Carbon-14 is not expected to be present in HLW (see Table 2).
- For spent fuel, it is expected that a high integrity container would be used, and therefore carbon-14 would have decayed significantly before the container were breached. To contain the carbon-14 for ten half-lives would require a container life of around 50,000 years [5, 60].

5.1 Summary of results from 2012 gas generation assessment

To enable better understanding of the generation of carbon-14 and bulk gases from ILW it is appropriate to analyse in more detail the results generated as part of the assessment of gas generation from a GDF.

In 2007 an update to the GPA (03) assessment was published [10]. This assessment used data from the 2004 UKRWI. An updated gas assessment [13] is currently being undertaken for higher strength rock (HSR) using data from the 2007 DI in reference [12]. This assessment is being undertaken using the SMOGG tool [24, 61] to perform the gas generation calculations. Although these are still not the latest inventory data that are available, the 2010 UKRWI has not yet been analysed and processed to include the additional information needed to carry out gas generation calculations. Using the 2007 DI has the additional benefits of bringing the gas assessments in line with the rest of the generic DSSC documentation [3] and provides a consistent bench mark for Letter of Compliance assessments.

Results from the current assessment are used to provide the baseline gas generation data for the work reported here. There has also been a recently published study on the implications for gas generation of the transition from the operational to the post-closure phase [14].

The following gas generating processes are included in the gas generation modelling presented in the 2012 gas assessment [13]:

- Radioactive gases will be released from vented ILW containers.
- Carbon-14 is not expected to be present in HLW (see Table 2).
- For spent fuel, it is expected that a high integrity container would be used, and therefore carbon-14 would have decayed significantly before the container were breached. To contain the carbon-14 for ten half-lives would require a container life of around 50,000 years [5, 60].
• Corrosion of metal wastes, generating hydrogen and releasing radioactive gases (e.g. tritium and carbon-14) trapped in the metal as the metal corrodes;
• Corrosion of metal containers and stillages generating hydrogen\textsuperscript{13};
• Degradation of cellulosic materials to small organic molecules, followed by microbial degradation of small organic molecules, generating carbon dioxide and methane and releasing carbon-14 substituted molecules of these gases;
• Radiolysis of water in the waste packages, water in the vaults and some organic waste materials, generating a range of gases;
• The release of \textsuperscript{222}Rn by radioactive decay of radium and its parents;
• The release of radioactive gases containing tritium and carbon-14 from graphite containing these radionuclides;
• The release of tritium by solid state diffusion from metals has also been considered in a separate empirical model.

More details of the modelling approach are found in [13].

A summary of the “base case” gas generation assessment results is presented below. In line with the methodology of the assessment, gas generation rate results are presented separately for the UILW vaults in Figure 8 and the SILW/LLW vaults in Figure 9. Results are presented for bulk hydrogen and methane, carbon-14 containing methane, tritiated hydrogen and radon. The last two of these are not relevant to the work of the IPT, and so are not discussed further.

These calculations adopt a modelling basis that is described later in the report in Section 9.1. There is considerable scope for reducing the calculated radiological consequence of carbon-14 release from these wastes as described in the Roadmap for Phase 2 of the project.

\textsuperscript{13} Other metallic components in the GDF vaults are not included in the current calculations.
Figure 8  Results from assessment of gas generation from the 2007 DI for UILW\textsuperscript{14} – plotted on two time scales. The bulk gases (i.e. H\textsubscript{2} and CH\textsubscript{4}) are plotted vs. the left-hand axis, and the active gases (i.e. \textsuperscript{3}HH, \textsuperscript{14}CH\textsubscript{4} and \textsuperscript{222}Rn) are plotted vs. the right-hand axis. Any CO\textsubscript{2} generated reacts with cement (i.e. the carbonation reaction takes place) and therefore is not shown on the plots.

\textsuperscript{14} In the assessment, the UILW includes some organic waste from GE Healthcare that, in practice, is unlikely to be disposed in its current form. This results in an overestimate of the C-14 generation rate in the assessment at some times.
Figure 9  Results from assessment of gas generation from the 2007 DI for SILW/LLW – plotted on two time scales. The bulk gases (i.e. $H_2$ and $CH_4$) are plotted vs. the left-hand axis, and the active gases (i.e. $^3HH$, $^{14}CH_4$ and $^{222}Rn$) are plotted vs. the right-hand axis. Any $CO_2$ generated reacts with cement (i.e. the carbonation reaction takes place) and therefore is not shown on the plots.
The main features of the gas generation results can be related to the stages of the GDF life-cycle as follows:

- Between 2040 and 2090 it is assumed that waste is emplaced in the vaults. This results in gradual increases in the bulk hydrogen and $^{14}$CH$_4$ generation rates. No bulk methane is generated as the conditions are assumed to be aerobic.

- Between 2090 and 2140 the vaults are assumed to be full of waste and to remain open. In this period the bulk hydrogen and $^{14}$CH$_4$ generation rates are therefore constant.

- Between 2140 and 2150 it is assumed that the vaults are backfilled. The temperature is assumed to increase during backfilling, which increases the rate of some gas generating reactions. This results in step increases in the bulk hydrogen and $^{14}$CH$_4$ generation rates.

- At 2150 it is assumed that the vaults are closed, and that groundwater can begin to flow into the waste packages. This increases certain reaction rates further, resulting in the bulk hydrogen and $^{14}$CH$_4$ generation rates peaking soon after closure.

- A few years after closure the vaults become anaerobic, resulting in the initiation of bulk methane generation.

- At 2155 it is assumed that the vaults are fully resaturated with saline groundwater, allowing reactions to proceed without being limited by the amount of water available.

- A few decades after closure the reactive metals become completely corroded. This results in a substantial reduction in the bulk hydrogen and $^{14}$CH$_4$ generation rates. In the case of carbon-14 containing methane, the reduction occurs earlier, as there is no carbon-14 associated with aluminium in the current inventory. $^{15}$

- In the longer-term, the bulk methane generation rate reduces as the inventory of cellulose reduces, the bulk hydrogen generation rate remains reasonably constant due to a significant contribution from the continuing corrosion of steels, and the $^{14}$CH$_4$ generation rate reduces largely due to decay of the carbon-14.

5.2 Breakdown of 2012 assessment results by waste group

In order to gain understanding of the important sources of carbon-14 in the ILW, the gas generation assessment results presented in Section 5.1 must be broken down into the generation rates for different parts of the waste inventory. Such a breakdown of the results is presented in this section.

Data for waste groups

If the carbon-14 generation rate from a particular waste is considered to be a potential issue, one way of reducing this may be to consider alternative options for managing this waste, as discussed in Section 10. The alternative options available depend on the type of waste. This leads to a natural division of the waste inventory into groups for which particular options can be considered. It is appropriate to consider the breakdown in terms of these groups; therefore the waste groups identified in Section 10.1 are used as the basis of the breakdown of the gas generation results.

To calculate the fraction of the gas generation associated with each waste group, certain data for the waste groups are required. By default, SMOGG provides a breakdown of the

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$^{15}$ There is no carbon-14 associated with aluminium in the current inventory. There is a current programme in place to measure whether there is any carbon-14 associated with irradiated aluminium, see Section 4.3.
gas generation results by process and substrate. So, for example, carbon-14 release from graphite in the waste, and hydrogen generation from stainless steels in the waste are given. However, some of the waste groups identified are more specific than this. For example, graphite in the UILW is divided into core graphite, Magnox fuel element graphite and AGR fuel element graphite. To calculate a breakdown for such waste groups the activity of carbon-14 and the mass of the relevant material in that group (relative to the totals for the relevant material) are required, to divide the carbon-14 and bulk gas generation rates respectively. In addition, the volume of the waste group (relative to the total volume of the waste in the corresponding vaults) is required to estimate the division of the bulk gas generation rate from the containers between the waste groups. The relevant data that have been used in this work are presented in Table 14 and Table 15 for the UILW and SILW/LLW respectively.

**Table 14 Waste group data for UILW used in the breakdown of gas generation rates**

<table>
<thead>
<tr>
<th>Waste group</th>
<th>Carbon-14 activity (TBq) (^{16,17})</th>
<th>Material mass (tonnes) (^{17})</th>
<th>Packaged volume (m(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core graphite</td>
<td>16 (22%)</td>
<td>3870 (33%)</td>
<td>6980 (2.3%)</td>
</tr>
<tr>
<td>Magnox fuel element graphite</td>
<td>6.2 (8.6%)</td>
<td>2290 (20%)</td>
<td>3030 (1.0%)</td>
</tr>
<tr>
<td>AGR fuel element graphite</td>
<td>50 (69%)</td>
<td>4670 (40%)</td>
<td>14200 (4.7%)</td>
</tr>
<tr>
<td>AGR SS fuel cladding</td>
<td>171 (24%)</td>
<td>876 (4.3%)</td>
<td>1940 (0.7%)</td>
</tr>
<tr>
<td>AGR SS assembly components</td>
<td>350 (48%)</td>
<td>1220 (5.9%)</td>
<td>4910 (1.6%)</td>
</tr>
<tr>
<td>SS decommissioning waste</td>
<td>193 (27%)</td>
<td>2860 (14%)</td>
<td>3370 (1.1%)</td>
</tr>
<tr>
<td>Other SS waste</td>
<td>10 (1.4%)</td>
<td>160 (0.8%)</td>
<td>146 (0.05%)</td>
</tr>
<tr>
<td>Other ferrous metal waste (plate)</td>
<td>100 (90%)</td>
<td>9310 (51%)</td>
<td>14000 (4.7%)</td>
</tr>
<tr>
<td>Other ferrous metal waste (sphere)</td>
<td>11 (10%)</td>
<td>296 (1.6%)</td>
<td></td>
</tr>
<tr>
<td>Zircaloy waste</td>
<td>27 (100%)</td>
<td>1150 (86%)</td>
<td>1920 (0.6%)</td>
</tr>
<tr>
<td>Reactive metals (Magnox)</td>
<td>88 (100%)</td>
<td>5890 (83%)</td>
<td>56600 (19%)</td>
</tr>
<tr>
<td>Reactive metals (uranium plate)</td>
<td>16 (59%)</td>
<td>212 (28%)</td>
<td></td>
</tr>
<tr>
<td>Reactive metals (uranium sphere)</td>
<td>12 (41%)</td>
<td>384 (51%)</td>
<td></td>
</tr>
</tbody>
</table>

\(^{16}\) There are minor differences between these values and the values in Table 5 due to slight differences in the interpretation of the waste groupings when calculating the values.

\(^{17}\) The percent values quoted are relative to the total for that material (indicated by the alternating shading).
Table 15 Waste group data for SILW/LLW used in the breakdown of
gas generation rates

<table>
<thead>
<tr>
<th>Waste group</th>
<th>Carbon-14 activity (TBq)</th>
<th>Material mass (tonnes)</th>
<th>Packaged volume (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core graphite</td>
<td>7116 (100%)</td>
<td>68900 (84%)</td>
<td>88900 (70%)</td>
</tr>
<tr>
<td>Other graphite</td>
<td>6 (0.08%)</td>
<td>Unknown</td>
<td>13400 (11%)</td>
</tr>
<tr>
<td>SS decommissioning waste</td>
<td>23 (100%)</td>
<td>1390 (94%)</td>
<td>1940 (1.5%)</td>
</tr>
<tr>
<td>Other ferrous metal waste</td>
<td>111 (100%)</td>
<td>11700 (70%)</td>
<td>14500 (11%)</td>
</tr>
</tbody>
</table>

The data for carbon-14 activity and packaged volume given in the tables are based on data from the 2010 UKRWI, with some enhancements, as discussed in Section 3. The data for material mass were separately collated from 2010 UKRWI data, by cross-referencing the waste stream IDs comprising each waste group.

To allow application to the gas generation data, some of the waste groups had to be subdivided into the divisions in the SMOGG results. This included dividing data for the UILW other ferrous metal waste group into a fraction represented as plate and a fraction represented as spheres for the purpose of the SMOGG modelling. Also, for the UILW reactive metals waste group, data were divided so they could be associated with either Magnox metal or uranium, and in the case of uranium these were sub-divided as for other ferrous metal. These divisions could not be defined exactly, so were approximated by:

- Assuming the data for metal geometries available in the 2007 DI could be applied to the waste streams in the 2010 UKRWI where the same waste stream was present in both inventories;
- Assuming waste streams only present in the 2010 UKRWI that are similar to other waste streams had the same geometry as those other waste streams;
- Estimating the geometry for the remaining waste streams based on the descriptions of the waste in the 2010 UKRWI;
- Assuming data for the split of carbon-14 between the Magnox and uranium in the reactive metals waste streams in the 2007 DI could be applied to the corresponding waste streams in the 2010 UKRWI.

It should also be noted that the data presented above are derived from the latest data from the 2010 UKRWI (with a few enhancements), whereas the gas generation assessment results are calculated from data from the 2007 DI. This means that there is not an exact correspondence between the inventory data in the two cases. To allow the results to be broken down into the contributions from different types of waste, the fractions of the carbon-14 and materials inventory given above were applied to the assessment results; that is it was effectively assumed that these fractions were the same in the two cases.
**Breakdown of carbon-14 containing gas generation rate**

Using the waste groups and data for associated fractions of the inventory presented above, the gas assessment results for the carbon-14 containing gas generation rate can be broken down into the generation rate due to each waste group as shown in Figure 10 for the UILW and in Figure 11 for the SILW/LLW. The following abbreviations are used in these figures:

<table>
<thead>
<tr>
<th>Corr</th>
<th>Corrosion</th>
<th>Deg</th>
<th>Degradation</th>
<th>Rad</th>
<th>Radiolysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS</td>
<td>Stainless steel</td>
<td>MS</td>
<td>Mild steel</td>
<td>Mx</td>
<td>Magnox</td>
</tr>
<tr>
<td>U</td>
<td>Uranium</td>
<td>Al</td>
<td>Aluminium</td>
<td>Zr</td>
<td>Zircaloy</td>
</tr>
<tr>
<td>P</td>
<td>Plates</td>
<td>S</td>
<td>Spheres</td>
<td>Cont</td>
<td>Containers</td>
</tr>
<tr>
<td>Clad</td>
<td>Cladding</td>
<td>Ass</td>
<td>Assembly components</td>
<td>Decommm</td>
<td>Decommissioning wastes</td>
</tr>
<tr>
<td>fe</td>
<td>Fuel element</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In the assessment, the UILW includes some organic waste from GE Healthcare that is proposed for incineration and is not expected to be disposed in its current form. This provides the contribution to the C-14 generation rate from degradation of organics, which is not expected. This corresponds to a significant overestimate of the C-14 generation rate in the assessment between 2160 and ~3500.
Figure 11  Breakdown by waste group of results for carbon-14 containing gas generation rate from assessment of gas generation from the 2007 DI for SILW/LLW – plotted on two time scales.
For the UILW, the breakdown of the results indicates that the main sources of carbon-14 containing gas generation are:

- Corrosion of Magnox and uranium during the operational and early post-closure periods (until these metals are all fully corroded, which occurs by 2161 in the assessment calculation);
- Microbial degradation of small organic molecules (for several thousand years), corrosion of stainless steels (in particular the AGR assembly components, but also the decommissioning waste and the AGR fuel cladding) during the remainder of the post-closure period until the carbon-14 has decayed to an insignificant level.

Carbon-14 containing gas is generated from degradation of small organic molecules because the assessment includes some of the carbon-14 contaminated GE Healthcare organic waste. In practice it is expected that this waste will be incinerated before disposal, so the fraction of the carbon-14 containing gas generation from this waste is not expected to occur. This means that the stainless steel wastes are expected to be the main sources of carbon-14 containing gas generation in the longer term post-closure.

For the SILW/LLW, the breakdown of the results indicates that the main source of carbon-14 containing gas generation is degradation of core graphite during all periods until the carbon-14 has decayed to an insignificant level.

These results are used in the assessments of consequences reported in Section 9.2, where they are presented in a tabular form.

The results above depend on the accuracy of the assumptions and the effects of simplifications used in the assessment model, so should be treated only as a first estimate of the wastes that are important sources of carbon-14 containing gas generation. This is discussed further below.

**Breakdown of bulk gas generation rates**

For carbon-14 containing gas generated in the GDF to be a potential issue outside of the GDF after it has closed, it must migrate away from the GDF. The carbon-14 containing gas generated corresponds to only a very small volume of gas. Therefore, for the carbon-14 containing gas to migrate requires bulk gas generation to occur at a significant rate, so as to act as a carrier. This means it is important to also understand the breakdown of the bulk gas generation rate.

Using the waste groups and data for associated fractions of the inventory presented above, the gas assessment results for the bulk gas generation rate can be broken down into the generation rate due to each waste group, as shown in Figure 12 and Figure 13 for the UILW and the SILW/LLW, respectively.
Figure 12  Breakdown by waste group of results for bulk gas generation rates from assessment of gas generation from the 2007 DI for UILW – plotted on two time scales
Figure 13  Breakdown by waste group of results for bulk gas generation rates from assessment of gas generation from the 2007 DI for SILW/LLW – plotted on two time scales
For the UILW, the breakdown of the results indicates that the main sources of bulk gas generation are:

- Corrosion of Magnox and aluminium during the operational and early post-closure periods (until these metals are all fully corroded, which occurs by 2161 and 2174 respectively in the assessment calculation);
- Microbial degradation of cellulose (for several thousand years), radiolysis of water and polymers, and corrosion of stainless steels (in particular the containers and the fraction of the stainless steel waste not containing a significant inventory of carbon-14) during the remainder of the post-closure period modelled.

For the SILW/LLW, the breakdown of the results indicates that the main sources of bulk gas generation are:

- Corrosion of Magnox (in particular the fraction represented as spheres) and aluminium during the operational and early post-closure periods (until these metals are all fully corroded, which occurs by 2167 in the assessment calculation);
- Corrosion of stainless steels (in particular the containers) during the remainder of the post-closure period modelled.

The results above depend on the accuracy of the assumptions and the effects of simplifications used in the assessment model, so should be treated only as a first estimate of the wastes that are important sources of bulk gas generation. This is discussed further below.

5.3 Effects of uncertainties, assumptions and model simplifications

As noted above, the breakdown of the results presented is dependent on the assumptions and simplifications made in order to carry out the modelling for the gas generation assessment, as well as the assumptions made in using data from the 2010 UKRWH to calculate the breakdown of the results generated using 2007 DI data. Therefore there are significant uncertainties in the results breakdown presented.

In some cases these uncertainties may be sufficient that sources of carbon-14 containing gas or bulk gas other than those identified above could be important. To identify other potentially important sources it is necessary to consider the different uncertainties, assumptions, etc. that affect the different processes modelled. To provide a guide to the magnitudes of the different uncertainties, indicative values are provided below. These use judgement based on the information available on the quantification of the process rates and understanding of the assumptions and simplifications made in the modelling.

**Carbon-14 release from graphite**

For carbon-14 release from graphite, the detailed process is not well understood, so the model implemented in SMOGG is very simple. The release rate is determined by the inventory of carbon-14 (or the inventory available for release), a rate constant and a fraction released as methane (i.e. as gas). There are substantial uncertainties in all of these parameters, although some of the values assumed are expected to be cautious. Therefore it is judged possible that carbon-14 containing gas generation from graphite could differ from the base case results by one or two orders of magnitude.

**Corrosion of metals**

For corrosion of metals (including irradiated steel waste, steels used for packaging and irradiated reactive metals), the main uncertainties/assumptions that will affect the gas generation are the corrosion rates, the geometry, availability of water (for reactive metals), the inventory of carbon-14 and its distribution (in waste metals), and the fraction of carbon-14 released that forms gas (for waste metals).
• The corrosion rates are reasonably well justified, but depend on assumptions about the conditions. For steels, rates may vary between different grades, and the rates assumed may be upper bound values in some cases. For Magnox there is significant uncertainty in the rate in the presence of chloride, but in practice very rapid corrosion is likely to be limited by the rate of supply of water. Therefore it is expected that corrosion rates assumed would be correct within an order of magnitude, and should be significantly closer in many cases.

• Geometries of the metals are simplified in the assessment, averaging over the geometries for different wastes, so that a single plate and sphere dimension are defined for each metal. Thus, for some wastes there may be a discrepancy of up to an order of magnitude in the geometry. A notable example is AGR fuel cladding, which has a plate-like geometry of less than 0.5 mm thickness, but is included in the assessment for UILW as part of the stainless steel plate, with an assumed thickness of 3.84 mm.

• The way water availability is accounted for is a key assumption in the model for the corrosion of reactive metals. Differing assumptions could reduce the post-closure corrosion rates of the reactive metals substantially.

• The carbon-14 inventory for many wastes has an uncertainty of an order of magnitude. The inventory is currently assumed to be uniformly distributed throughout the metals. For certain waste metals, it is possible that the carbon-14 may be predominantly near to the metal surface. This could increase the release rate substantially.

• There is substantial uncertainty in the form of the carbon-14 when released from metals. If only a small fraction of the carbon-14 released forms gaseous molecules this will reduce the carbon-14 containing gas generation substantially.

Overall it is judged possible that bulk gas generation from metal wastes could differ from the base case results by up to an order of magnitude, and carbon-14 containing gas generation could differ by somewhat more. These changes could also affect the timing of carbon-14 release from reactive metals, possibly leading to a lower peak release over a longer time.

**Radiolysis**

For radiolysis, the main uncertainties/assumptions that will affect the gas generation are the radionuclide inventory, its distribution between different waste components, and the G-values that define the amount of gas generation per unit energy absorption by each material.

• For many wastes the uncertainty in the radionuclide inventory is given as an order of magnitude.

• The assessment assumes a homogeneous mixture of the wastes. If substantial fractions of the radionuclide inventory are associated with wastes containing materials that can or cannot be radiolysed this could increase or decrease gas generation from radiolysis, respectively. Radiolysis of water will be less affected by such heterogeneity, since it is assumed to be present throughout the waste.

• G-values have been selected to be broadly representative of (or slightly cautious for) general categories of radiolysable materials. However, G-values will differ for each specific material and could also vary with the conditions. The uncertainty in the G-values could be more than an order of magnitude for specific wastes, but should be much less overall.

Overall it is judged possible that bulk gas generation from radiolysis could differ from the base case results by up to an order of magnitude.
Degradation of cellulose

For degradation of cellulose, the main uncertainties/assumptions that will affect the gas generation are the rate constants for the degradation processes, the amounts of nitrate and sulphate present and the effectiveness of the carbonation reaction.

- There is substantial uncertainty, perhaps one or two orders of magnitude, in the rate constants, particularly under alkaline conditions.
- It is assumed in this assessment that there is no sulphate or nitrate in the vicinity of the cellulose waste. If present this would delay and reduce methane generation from cellulose degradation.
- It is assumed that all the carbon dioxide generated is retained by carbonation by the cementitious materials in the packages and vaults. If this does not occur, the total rate of bulk gas generation would be increased. However, methanogenesis of hydrogen may then occur, which could reduce the total gas generation rate overall.

Overall it is judged possible that bulk gas generation from degradation of cellulose could differ from the base case results by around an order of magnitude.

Potentially important sources of gas generation

Based on the above potential differences from the base case assessment results for the gas generation rates for the various processes, it is possible to consider which other sources of carbon-14 containing gases and bulk gas generation could be important in addition to those identified in the previous subsections. From above, possible differences in the gas generation rates are generally up to an order of magnitude, with the exception of generation of carbon-14 containing gas from graphite, which may be more.

Applying this analysis to the results breakdown in Figure 10, the following additional sources of carbon-14 containing gas in UILW are identified as potentially important:

- Corrosion of both stainless steel and mild steel waste during the operational period. These sources are over an order of magnitude lower than corrosion of Magnox and uranium. A combination of the possible underestimation of carbon-14 containing gas generation from these processes and the overestimation of carbon-14 containing gas generation from corrosion of Magnox and uranium would be required for these streams to lead to higher generation rates than the Magnox and uranium during the operational period.
- Allowing for the uncertainties, corrosion of Magnox and uranium remain the only important sources during the early post-closure period.
- Corrosion of mild steel waste in the longer term post-closure. This source is over an order of magnitude lower than corrosion of stainless steel waste. A combination of the possible underestimation of carbon-14 containing gas generation from this process and the overestimation of carbon-14 containing gas generation from corrosion of stainless steel would be required for these streams to lead to higher generation rates than the stainless steel wastes.

Applying this to the results breakdown in Figure 11, the following additional source of carbon-14 containing gas generation in SILW/LLW is identified as potentially important:

- Corrosion of mild steel waste during the operational and early post-closure periods. This source is over an order of magnitude lower than degradation of core graphite. A combination of the possible underestimation of carbon-14 containing gas generation from this process and the overestimation of carbon-14 containing gas generation from degradation of core graphite would be required for these streams to lead to higher generation rates than the core graphite.
Allowing for the uncertainties, degradation of core graphite remains the only important source in the longer term post-closure.

Applying this to the results breakdown in Figure 12, the following additional sources of bulk gas generation in UILW are identified as potentially important:

- Radiolysis of both water and polymers during the operational period. These sources are about an order of magnitude lower than the corrosion of Magnox and aluminium, so either the possible underestimation of bulk gas generation from these processes or the overestimation of bulk gas generation from corrosion of Magnox and aluminium (or a combination of the two) would be required for this to be significant.
- Corrosion of uranium during the early post-closure period. This source is about an order of magnitude lower than the corrosion of Magnox and aluminium at certain times, so either the possible underestimation of bulk gas generation from this process or the overestimation of bulk gas generation from corrosion of Magnox and aluminium (or a combination of the two) would be required for this to be significant.
- Corrosion of mild steel (plate) waste in the longer term post-closure. This source is around an order of magnitude lower than both the corrosion of stainless steel containers and certain wastes and the radiolysis of water, so either the possible underestimation of bulk gas generation from this process or the overestimation of bulk gas generation from corrosion of the stainless steels and radiolysis of water (or a combination of the two) would be required for this to be significant.

Applying this to the results breakdown in Figure 13, the following additional source of bulk gas generation in SILW/LLW is identified as potentially important:

- Allowing for the uncertainties, corrosion of Magnox and aluminium remain the only important sources during the operational and early post-closure periods.
- Corrosion of mild steel waste in the longer term post-closure. This source is over an order of magnitude lower than the corrosion of stainless steel containers, so a combination of the possible underestimation of bulk gas generation from this process and the overestimation of bulk gas generation from corrosion of stainless steel containers would be required. Corrosion of stainless steel waste also generates bulk gas at a similar rate, but is unlikely to be important as some of the uncertainties will be the same for stainless steel waste as for stainless steel containers.

5.4 Work for Phase 2

In the light of the above discussions, combined with the updated understanding of the potential consequences of carbon-14 containing gas generation given by the assessments in Section 9.2, the Phase 1 gas generation modelling has enabled a number of priorities to be identified for work in Phase 2, as described below. We believe it is appropriate at this stage to focus on generation of carbon-14 containing gas rather than bulk gas, but we note that there is significant overlap in the understanding required.

As graphite is the dominant source of carbon-14 containing gas from SILW/LLW:

- Completion of the experimental work (as described in Section 4.1) should improve our understanding of the rate of leaching of carbon-14 from graphite and how this evolves over time, as well as the speciation of the carbon-14 released.
- Using the experimental data, we will be able to evaluate the simple model that is currently used for calculating carbon-14 containing gas generation for this process and develop and implement an improved model if appropriate.
As irradiated steel is the dominant source of carbon-14 containing gas from UILW in the long term post-closure:

- Experimental work (as described in Section 4.2) should improve our understanding of the rate and speciation of the release of carbon-14 from steels (particularly stainless steels).
- More detailed information on the geometry and associated carbon-14 inventory and distribution for different irradiated steel waste streams should be collated so that we can better represent the likely distribution of release rates in the modelling.

As irradiated reactive metals are the dominant sources of carbon-14 containing gas from UILW in the operational and early post-closure periods:

- Experimental work (as described in Section 4.3) should improve our understanding of the rate and speciation of the release of carbon-14 from reactive metals.
- A better understanding of the water that will be available to support the corrosion of reactive metals, and the rate at which additional water may flow through vaults, into containers and through wasteforms post-closure is required so that we can improve the representation of the control that water availability provides on corrosion in the modelling if appropriate.
- Improved data on the potential enhancement of the corrosion rate of Magnox in the presence of chloride would be beneficial.
- More detailed information on the geometry and associated carbon-14 inventory and distribution for different irradiated reactive metal waste streams should be collated so that we can better represent the likely distribution of release rates in the modelling.
- Given the relatively rapid corrosion rates of reactive metals, it may be important to account for corrosion and associated generation of carbon-14 containing gas that occurs before emplacement in a GDF.

The calculations that have been reported in this Section will be updated at key points during Phase 2, as new data and models become available. This will inform the prioritisation of the ongoing Phase 2 work programme.
6 Interaction of carbon-14 bearing gases with engineered materials

If carbon-14 bearing gas is generated, the next step is to understand whether it will be entrained within a bulk gas phase, and whether it is able to migrate through the engineered barriers. These have been reviewed as part of Phase 1, and we have concluded that:

- A gas phase is likely to form.
- Carbon dioxide will undergo a carbonation reaction with the cementitious materials, and will therefore not migrate out of the GDF. However, in competition with this, carbon dioxide could be converted to methane by methanogenesis, and would then be able to migrate out of the GDF.
- Whether gas migrates out of the engineered barrier system can be influenced by specific features, including voidage in the crown space, the use of a low permeability liners and the presence of an excavation disturbed zone.

In Phase 2, it is planned to incorporate the evolving understanding from relevant near-field projects in the modelling basis spreadsheet.

In Phase 1 of the work we have reviewed understanding from previous and ongoing studies.

6.1 Review of current understanding

The work in this section is concerned mostly with packages of intermediate level / low level wastes in a higher strength host rock, because:

- Although packages of spent fuel could release carbon-14 bearing gases [60], a high integrity container would be used, and therefore carbon-14 would have decayed significantly before the container were breached. To contain the carbon-14 for ten half-lives would require a container life of around 50,000 years.
- In either lower strength sedimentary or evaporite host rocks, the geology would be a significant barrier to gas migration (see Section 7).

The illustrative disposal concept for a higher strength host rock assumes that packages of intermediate level / low level wastes will be surrounded by a cementitious backfill. A number of processes will occur in the cementitious near-field that could affect the migration of the carbon-14 bearing gases (including $^{14}\text{CO}_2$ and $^{14}\text{CH}_4$) from a GDF:

- A gas phase is likely to form in a GDF. Carbon-14 bearing gases will partition between the gas and aqueous phases according to Henry’s Law.
- Carbon dioxide will undergo a “carbonation” reaction with cements, which will have an impact on the volume of bulk gas released from the engineered barrier system but will only have a minor effect on the predicted risk from the carbon-14 bearing gases, because there is unlikely to be significant generation of $^{14}\text{CO}_2$. $^{14}\text{CO}_2$ could arise from the degradation of wastes containing organic carbon-14, but these wastes are not intended for disposal in a GDF. Limited experimental evidence suggests that irradiated metals are not a direct source of $^{14}\text{CO}_2$ under alkaline conditions (although it is possible that carbon-14 species released from the metal could participate in subsequent microbial reactions; see below).
- Competing with the carbonation reaction, a methanogenesis reaction, which is mediated by microbes under anaerobic conditions (strictly in the absence of other
terminal electron acceptors, such as oxygen, nitrate and sulphate), could convert carbon dioxide to methane.

- A number of engineering solutions to reduce the release of carbon-14 bearing gases from the near-field have been investigated [62]. For example, the presence of the cementitious backfill, as well as a lining to the vaults, could reduce the flows of groundwater to, and gas from, a GDF.

6.1.1 Speciation of carbon-14 bearing gases

As described previously, the gas generation processes occurring in a GDF will lead to the formation of both bulk gases (hydrogen, carbon dioxide and methane) and radioactive gases (including carbon-14 bearing carbon dioxide and methane).

In the case of the bulk gases, the modelling basis used within SMOGG is that:

- Before conditions become anaerobic, any bulk carbon dioxide which may form as a result of the microbial degradation of organic wastes will react with cementitious materials in a GDF (i.e. the carbonation reaction).
- After conditions become anaerobic, equi-molar quantities of bulk carbon dioxide and bulk methane will form from the degradation of organic wastes (this is based on a consideration of the network of microbial processes that will occur), but the bulk carbon dioxide will react with cementitious materials in a GDF. Note that the start of methane production would be delayed if there were nitrate or sulphate present.

In the case of the radioactive gases, the modelling basis used within SMOGG is:

- Carbon-14 released from the irradiated metal wastes will be in the form of methane, and so will be able to migrate away from a GDF.
- Less than half of the carbon-14 released from the organic wastes will be in the form of methane; the remainder will be in the form of carbon dioxide that will react with the cementitious materials in the GDF. However, these wastes are not expected to be disposed in a GDF.
- One percent of the carbon-14 leached from the graphite wastes will be in the form of volatile organic gases (e.g. methane). However, experimental data obtained for aerobic conditions show that a larger percentage of the carbon-14 (~4%) could be in the form of other volatile inorganic gases (e.g. carbon monoxide). The modelling basis for anaerobic conditions is that only the volatile organic gases (i.e. methane) will form and migrate away from the GDF.
- Carbon-14 gases, other than $^{14}$CO$_2$, do not undergo further reaction in the Engineered Barrier System (EBS), or the host rock and overlying formations.
- Carbon-14 gases, other than $^{14}$CO$_2$, are entrained in the bulk gas stream.

6.1.2 Solubility of gases

Some of the gas that will be generated in a GDF [13] will dissolve in the porewater. If there is sufficient volume of porewater, then a gas phase will not form. It is of interest to know

---

Preliminary indications from experiments under anaerobic, alkaline conditions are that both methane and carbon monoxide form, but that methane is present in a larger quantity than carbon monoxide. A brief review as part of this work found no evidence to support the hypothesis that carbon monoxide would be retained within the EBS.
how quickly the porewater in the vaults would have to be flushed through in order to prevent a gas phase forming.

To a good approximation, the solubility of a gas in water is linear (Henry’s Law) in the partial pressure, $p_g$, of the gas:

$$c = H p_g$$

where:

- $c$ is the concentration of the dissolved gas; and
- $H$ is Henry’s constant.

Note that:

- Henry’s Law gives the concentrations in solution for a mixture of gases in equilibrium with water at a given pressure.
- The solubility of one component of the mixture will be less than would be the case if it were the only gas present at the given pressure (because its partial pressure will be less than the total pressure).

The significance of this is that it is necessary to consider the total quantity of gas involved (mainly hydrogen for gas generated in a GDF), not just the component of particular interest (methane in the present case) in deciding whether a free gas phase (containing the component of particular interest) will be present at a given pressure.

Actually, Henry’s “constant” varies with both temperature and salinity (the “salting out” effect), decreasing as the temperature and salinity increase. In the calculations reported below, it is assumed that at the repository the temperature is 20°C and the salinity is 0 (hence, the dissolution of gas is maximised). For these conditions, the Henry’s constants are given in Table 16.

### Table 16  Henry’s constants for gases of interest at 20°C and 0 salinity [63]

<table>
<thead>
<tr>
<th>Gas</th>
<th>Henry’s constant mol L$^{-1}$ Pa$^{-1}$</th>
<th>Henry’s constant m$^3$ at STP m$^{-3}$ Pa$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>$7.95 \times 10^{-9}$</td>
<td>$1.78 \times 10^{-7}$</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>$3.84 \times 10^{-7}$</td>
<td>$8.60 \times 10^{-6}$</td>
</tr>
<tr>
<td>Methane</td>
<td>$1.41 \times 10^{-8}$</td>
<td>$3.15 \times 10^{-7}$</td>
</tr>
</tbody>
</table>

A rough estimate$^{20}$ of the gas pressure can be obtained by equating it to the hydrostatic pressure at the depth of the GDF. The hydrostatic pressure could be of the order of $10^7$ Pa if the GDF were situated at a depth of 1,000m. Hence, rough estimates of the maximum concentrations of gas in solution in the GDF are obtained (see Table 17).

The recent assessment of gas generation in a GDF (see Section 5.1) assumes that the UILW vaults in a higher strength rock will have a pore volume (accounting for the porosity of both the wasteform grouts and the cementitious backfill) of about $4 \times 10^5$ m$^3$, while the SILW/LLW vaults will have a pore volume of about $2 \times 10^5$ m$^3$. (Because similar conditioning factors are likely to be used in a lower strength sedimentary rock, these

---

$^{20}$ This estimate is good for a higher strength rock, where the pressure in the GDF is predicted to return to the ambient hydrostatic pressure soon after closure. However, it could be an underestimate (by several MPa) for a lower strength sedimentary rock, where the vaults are likely to pressurise.
numbers also can be used for this geological environment.) It follows that the amounts of
gas that could dissolve in the porewater of the GDF can be estimated (see Table 17).

Table 17  Estimates of concentrations and amounts in solution for
gases of interest

<table>
<thead>
<tr>
<th>Gas</th>
<th>Concentrations (expressed as m³ at STP m⁻³)</th>
<th>Amount in solution for UILW vaults (expressed as m³ at STP)</th>
<th>Amount in solution for SILW/LLW vaults (expressed as m³ at STP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>1.78</td>
<td>7.1×10⁵</td>
<td>3.6×10⁵</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>86</td>
<td>3.4×10⁷</td>
<td>1.7×10⁷</td>
</tr>
<tr>
<td>Methane</td>
<td>3.15</td>
<td>1.3×10⁶</td>
<td>6.3×10⁵</td>
</tr>
</tbody>
</table>

The values in Table 16 are presented at STP, to allow comparison with the gas generation
rates presented in the Figures in Section 5. In practice the volumes would be much
smaller. For comparison, 10³ m³ at STP is equivalent to 10 m³ at a pressure of 10⁷ Pa.

For the UILW vaults, the recent assessment of gas generation predicted (see Section 5.1)
that during the early post-closure period hydrogen will be formed at a rate of about
10⁶ m³ a⁻¹ (at STP), while in the long term hydrogen will be formed at a rate of about
10³ m³ a⁻¹ (at STP) and methane will be formed at a rate that declines gradually from about
8×10² m³ a⁻¹ (at STP). For the SILW vaults, during the early post-closure period hydrogen
will be formed at a rate of about 10⁴ m³ a⁻¹ (at STP), while in the long term hydrogen will be
formed at a rate of about 10² m³ a⁻¹ (at STP) and methane will be formed at a rate that
decreases gradually from about 2 m³ a⁻¹ (at STP).

Considering only the long term rates of gas generation, the flow of water through the GDF
would have to be greater than about 6×10² m³a⁻¹ in order to prevent a gas phase from
forming. This is considered implausible for the low permeability geological environments
that potentially could host a GDF. However, an order of magnitude decrease in the overall
gas generation rate would require a volumetric flow rate of only 60 m³ a⁻¹ to prevent the
formation of a free gas phase. This flow rate conceivably could occur in a relatively
permeable higher strength rock, but would not occur in either a lower strength sedimentary
rock or an evaporite. However, in these environments, the gas generation rates could be
limited by water availability.

6.1.3  Carbonation

Of the identified gases, it is currently assumed that only carbon dioxide will react chemically
with materials in the GDF. In particular, carbon dioxide (CO₂) could react with calcium
hydroxide (Ca(OH)₂) in the cement to form calcium carbonate (CaCO₃) as follows:

\[ \text{CO}_2 + \text{Ca(OH)}_2 \rightarrow \text{CaCO}_3 + \text{H}_2\text{O} \]

The carbonation reaction\(^{21}\) is potentially an important process, both during operations
(when it is argued that \(^{14}\text{CO}_2\) will react with wasteform grouts) and post-closure (when
\(^{14}\text{CO}_2\) can react also with the cementitious backfill material). However, it has a minor effect
on the predicted doses from carbon-14 bearing gases, because, as discussed above, only
a small fraction of these radioactive gases may be in the form of \(^{14}\text{CO}_2\).

\[^{21}\text{Although Ca(OH)}_2\text{ plays a dominant role in the carbonation process, other constituents (e.g. CSH gel)}\]
\[^{21}\text{in the cement can react as well. Carbonation also will affect the transport properties, the strength, and}
\[^{21}\text{the alkalinity of the backfill.}\]

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It should be emphasised that carbonation is a well-understood process, at least for partially saturated concrete. The mechanism involves the following steps [64]:

- Diffusion of CO$_2$(g) through the gas phase into the concrete.
- Dissolution of CO$_2$(g) in the pore water lining the smaller pores in the concrete.
- Hydration of CO$_2$(aq) to form H$^+$, HCO$_3^-$ and CO$_3^{2-}$.
- Dissolution of calcium-containing phases from the concrete to form Ca$^{2+}$.
- Nucleation of CaCO$_3$(s) and precipitation of solid phases.

For partially saturated concrete, the diffusion of CO$_2$(g) through the gas phase is the rate controlling step. Based on this understanding, both simple, empirical models (which fit the depth of carbonation to the square root of exposure time) and detailed, process models (which solve transport equations) have been developed and validated. However, under saturated conditions carbonation is less well understood and similar models do not exist.

NDA RWMD has commissioned a number of studies of carbonation:

- During 1998/1999 a preliminary study of the carbonation of the NRVB and a wasteform grout was performed [65]. During 2000/2001 this was followed by a more detailed study of the carbonation of NRVB [66]. The work distinguished between carbonation of unsaturated NRVB (which could be explained using models from the literature) and saturated NRVB (where the models did not apply, and the rate of carbonation may be affected by the changing properties of the carbonated material).
- There have been recent PhD studies at University College London [67] and at the University of Leeds [68]. The former thesis, in particular, has provided confirmation of the earlier work (described in references 65 and 66). It reports the carbonation capacity of the NRVB as 5,437 mol m$^{-3}$ (the earlier work quotes 5,200±100 mol m$^{-3}$), compared with a theoretical capacity of 7,516 mol m$^{-3}$.
- Currently NNL is performing work to determine how effectively CO$_2$(g) released from waste packages will react with the NRVB to form carbonates.
- BGS are carrying out work within the EC FORGE project to investigate the reaction of carbon dioxide as gas, as a supercritical fluid, and in solution with the NRVB, and the impact of the reaction on the evolution of permeability [69].

A key conclusion that can be drawn from these studies is that the NRVB has a very large carbonation capacity, which will be capable of reacting with all of the CO$_2$ that is expected to be formed in a GDF. The recent assessment of gas generation in a GDF (see Section 5.1) predicts that in the case of the UILW vaults 3.5×10$^7$ mol of carbon dioxide will be produced. This would require only 6.6×10$^3$ m$^3$ of NRVB for the carbonation reaction, compared to 1.25×10$^4$ m$^3$ of NRVB present in the current conceptual design for a GDF in a higher strength rock [70]. In the case of the SILW/LLW vaults, 7.2×10$^4$ mol of carbon dioxide will be produced, which will require only 14 m$^3$ of NRVB for the carbonation reaction.

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22 The subscripts (g) refers to gaseous species, (aq) to aqueous species and (s) to the solid phase.

23 Other reactions also may ‘consume’ NRVB.

24 This value is the combined value for UILW and SILW/LLW vaults for the baseline inventory.
There is the possibility that CO$_2$(g) could migrate through preferential pathways (i.e. cracks) in the NRVB. That might mean the CO$_2$(g) would “see” much less of the NRVB, and potentially could allow migration through the EBS.

### 6.1.4 Microbial processes

Both hydrogen and methane are reactive gases that may undergo reaction as they migrate through the host rock. It is also likely that microbial processes could occur in regions of a GDF [71].

A possible microbial process, which could compete with the carbonation reaction, is methanogenesis:

\[
\text{CO}_2(g) + 4\text{H}_2(g) \rightarrow \text{CH}_4(g) + 2\text{H}_2\text{O}
\]

This reaction could substantially reduce the amount of bulk gas that is released from the GDF (5 moles of gas on the left hand side of the reaction are converted to 1 mole of gas on the right hand side). Conversely, it could increase the amount of carbon-14 bearing methane that is released from the GDF.

Another microbial process that could consume hydrogen is the reaction of sulphate in the groundwater (the wastes themselves are thought to contain little sulphate) with hydrogen to form hydrogen sulphide:

\[
4\text{H}_2(g) + \text{H}_2\text{SO}_4 \rightarrow \text{H}_2\text{S}(g) + 4\text{H}_2\text{O}
\]

Although these processes have been proposed, there are challenges in demonstrating whether potential benefits will occur with sufficient confidence to be taken into account in safety case arguments.

- For example, in the ILW/LLW vaults of a GDF the high pH environment will be relatively hostile for microbes (particularly at early times, when the pH is expected to be above 13). It is possible that microbes may not be active in such an environment [71], but it is likely that micro-niches and regions of lower pH would occur in some parts of the GDF.
- In the case of the sulphate reduction reaction, the source of sulphate would most likely be the groundwater (as an example of a saline groundwater from a higher strength rock, Sellafield Borehole RCF3 DET5 had a SO$_4^{2-}$ concentration of $1.2 \times 10^{-2}$ M). However, the sulphate could react with the NRVB. Thus the sulphate reaction may be more likely to occur as any hydrogen gas migrates from a GDF through the overlying rocks and comes into contact with the groundwater.

Conversely, it may be necessary to re-examine the assumption that carbonation of cements prevents the conversion of carbon dioxide to methane in the presence of high concentrations of hydrogen. NDA RWMD are currently considering how its research programme on microbial processes should be developed, and is represented on the advisory panel to the BIGRAD project.

### 6.1.5 Engineering solutions

The GDF will be an engineered system that could provide a number of barriers to gas migration. Some aspects of the engineered barrier system that could influence the migration of gas are:

- The possibility of incorporating an open “crown space” in the vaults;
- The possibility of adding a low-permeability liner around the vaults;
- The presence and extant of an excavation disturbed zone (EDZ) around the vaults;
• The possibility of introducing a material that will sorb methane (e.g. anthracite) into the vaults (although this is unlikely to be practicable).

For the case of a higher strength host rock (which is the host rock that will provide the least effective barrier to gas migration), these aspects of the GDF have been considered in previous work [62]. The conclusions of the previous work are summarised below. Design mitigation measures are considered in Section 10.

The presence of a crown space
The previous modelling [62], which was for a vault in a higher strength host rock, showed that in the absence of an open “crown space”, the vault will resaturate more quickly and gas will start to migrate out of the vault sooner. This could have implications for the release of gases from the GDF.

The presence of a low-permeability liner
The previous modelling [62] also considered the effect of a low-permeability liner; this is similar in concept to a hydraulic cage applied at the Richard repository in the Czech Republic [72].

For the case of a higher strength rock, it was shown that the presence of a low-permeability liner around a vault would reduce the extent and magnitude of the drawdown in the surrounding rocks, and it would greatly increase the times for the waste stack and the GDF to resaturate. The liner could therefore reduce the rate of gas generation by delaying resaturation. It would then delay the time at which gas first starts to migrate out of a vault, and it could reduce the flux of gas out of the vault.

In a lower strength sedimentary rock, a low-permeability liner will be required (for reasons of structural stability), but it will have a lesser effect because the host rock is likely to be less permeable than the liner.

The EDZ
For the case of a higher strength rock, the EDZ will have little effect on migration of gas out of the GDF [62]. This is because the host rock is taken to be fractured without a gas entry pressure, and therefore the gas can migrate readily upwards under gravity.

This is very different from the case of a lower strength sedimentary rock, where the rock will have a significant gas entry pressure, and therefore the EDZ could be an important part of the gas pathway.

In situ gas sorption
A concept that was proposed several years ago was to fill the crown space of a vault with anthracite. This could reduce the flux of carbon-14 bearing methane out of the vaults, because some of the methane would sorb to the anthracite.

However, the amount sorbed depends on the partial pressure of the methane, and because the carbon-14 bearing methane is a small fraction of the gas, the amount that sorbs will be a small fraction of the amount that would sorb were all the gas to be carbon-14 bearing methane [62].

6.2 Work for Phase 2
In Phase 2, the work programme will include interaction with the following relevant tasks:
• An ongoing task to determine how effectively CO$_2$(g) released from waste packages will react with the NRVB to form carbonates. (NNL task);
- Ongoing work within the EC FORGE project to investigate the reaction of carbon dioxide as gas, and in solution with the NRVB, and the impact of the reaction on the evolution of permeability (BGS task);
- A PhD project at the University of Manchester to investigate the microbiological metabolism of hydrogen within a GDF. Evidence will be gathered as part of this PhD project, which may give some insights during Phase 2 of this project;
- A task to investigate the interaction of gas and cement during backfilling.

The evolving understanding from these tasks will be integrated into the modelling basis spreadsheet and be used to inform scoping calculations and the development of the total system model.

More detailed process-level modelling of gas and groundwater interactions at the package scale may also be developed within the IPT, following on from the work carried out within FORGE [73], where gas generation and resaturation issues were explored for the three geological environments (see Section 7).
7 Migration of gas through the geosphere

For carbon-14 bearing gases to lead to significant doses and risks, they have to migrate through the rocks around the GDF to the biosphere. They could migrate as a gas, or they could migrate part of the way as a gas, and part of the way in solution.

Gas migration is a highly site specific issue. In Phase 1 we have examined how site specific features affect gas migration. Gas is most likely to migrate from the GDF to the biosphere if the host rock is a higher strength rock. Lower strength sedimentary rocks and evaporites would pose very significant barriers to gas migration, and therefore the risk from carbon-14 bearing gases would be assessed to be low in these geological environments.

We have also considered the approach for the site characterisation programme to answer the key questions relating to gas migration in the three example geological environments (higher strength rock, lower strength sedimentary rock and evaporite). Ultimately the question on whether gases migrate through the geological environment can only be answered once sites have been identified, and the features of the site understood.

In Phase 2, we will not undertake detailed development of gas migration models. We will keep work elsewhere under review and input into other work streams. We will aim to understand the envelope of geological environments in which carbon-14 bearing wastes can safely managed. If required, we will develop an understanding to inform the requirements for the site characterisation programme.

In Phase 1 of the work we have summarised the impact of site-specific geological features on gas migration – this is discussed in Section 7.1. We have summarised the key questions that will inform our understanding of the envelope of geological environments in which carbon-14 bearing wastes can be safely managed (Section 7.2). We also outline work for Phase 2 (Section 7.3).

7.1 Impact of site-specific geological features on gas migration

Once carbon-14 bearing gases enter the host rock around the GDF, their migration will be controlled by the properties of the rock that they encounter. Gas migration modelling can be employed to assess gas transport through the geology towards the ground surface, and to estimate potential gas breakthrough times and fluxes at the surface. All gas migration models require site-specific information. The factors that could affect the gas migration through the geosphere include:

- Physical properties:
  - Presence of groundwater;
  - Presence of geological features such as cap rocks and faults;
  - Properties of the rocks such as permeability and pore structure, and their variability;
  - Two-phase flow properties of the rocks.
- Chemical properties:
  - Chemistry of the groundwater;
  - Mineralogy of the rocks;
  - Presence of microbes.
• Mechanical effects:
  o Micro-fracturing (pathway “dilation”);
  o Macro-scale fracturing.

In many geological environments there is likely to be coupling between the groundwater flow, gas generation reactions and the subsequent migration of gas into the geosphere [14] and this coupling may need to be represented in any modelling. The impacts of the above factors on gas migration are discussed briefly below.

**Physical properties**

*Presence of groundwater*

Gas can be generated only in the presence of adequate quantities of water. In very low permeability environments, water inflow rates may be too slow to sustain a continuous gas generation process. This may have a significant effect on the timescales for the gas generation processes, and the rates at which gas is transported away from the repository and through the host rock. In practice this would not be expected in hard, fractured rocks, where the rock is able to supply plenty of groundwater. However, this could be an important phenomenon in a lower strength sedimentary rock, and is almost certainly so in an evaporite.

The presence of high-permeability units, and thus the availability of groundwater in the overlying geology, will affect the dissolution rate of gases. The presence of a large flow of groundwater offers the possibility of the gas dissolving in the groundwater. As the groundwater approaches the surface, the pressure would drop, and there would be “outgassing”. However, groundwater flow may be slower than the direct gas migration pathway.

*Geological features*

The presence of low-permeability features, which act as barriers to flow, and transmissive zones such as joints and faults, will have a significant impact on gas migration. A homogeneous, low-permeability cap rock would be expected to trap gas below it, thus delaying the gas breakthrough time at the surface. The breakthrough time will be affected by the location, thickness and permeability of the cap rock in relation to the GDF. In a modelling study of gas migration at Sellafield [18], for example, it was found that for all but one of the variants studied, there was no breakthrough of gas at the surface. On the other hand, transmissive features with higher permeabilities may allow quick progression of the gas front through the geosphere.

*Rock properties*

Rock properties, such as permeability, and pore structure and connectivity, play a major role in gas migration modelling. These have an effect on the ease with which fluids migrate through the rock. This in turn affects:

- the availability of groundwater for gas generation;
- the rate at which both gas and groundwater migrate away from the GDF; and
- the amount of water the gas comes into contact with, resulting in dissolution of all, or some, of the gas.

*Two-phase flow properties*

The two-phase flow properties required for gas migration modelling (i.e. relative permeability and capillary pressure functions) also will have a significant effect on the
results of the modelling. The coefficients required for these functions are specific to a
geological formation, and would need to be investigated during site characterisation. If the
relative permeability and capillary pressure functions have not been measured for similar
geologies in the past, measurement of these would be needed, using rock samples
obtained from the site.

**Chemical properties of the groundwater, mineralogy and microbes**
The chemical constituents of the groundwater could affect both gas generation within the
GDF and gas migration in the geosphere. For example, the presence of dissolved chloride
in the groundwater will affect the corrosion rates of some metals.

Some chemical processes could cause retardation of carbon-14 bearing gases (particularly
carbon dioxide). Reactions such as carbonation on rocks that contain calcium carbonate
(e.g. limestone and chalk) could lead to a reduction of porosity and permeability, and thus a
reduced fluid flow rate.

Microbial processes also could occur in the geosphere [71]. Methanogenesis:

\[
\text{CO}_2(g) + 4\text{H}_2(g) \rightarrow \text{CH}_4(g) + 2\text{H}_2\text{O}
\]

which would compete with the carbonation reaction, is one such process. Another
microbial process, which could consume some of the hydrogen that will be released from a
GDF, is the reduction of sulphate in the groundwater:

\[
4\text{H}_2(g) + \text{H}_2\text{SO}_4 \rightarrow \text{H}_2\text{S}(g) + 4\text{H}_2\text{O}
\]

**Mechanical effects**
The pore structure of the host rock will affect the ease with which gas can migrate away
from the GDF. Fractures, which could have apertures of 10 microns or even more, will
pose little resistance to gas, whereas sedimentary and evaporite rocks have much smaller
pores.

If initially gas is unable to enter a rock formation and it collects in a certain location, the
pressure in this location may increase. If the gas pressure exceeds the strength of the host
rock, both microscopic and macroscopic fracturing may occur. Pathway “dilation” is
potentially an important aspect of gas flow in weak, low-permeability environments such as
lower strength sedimentary rocks. Clay-rich rocks (indeed, any rock) cannot withstand
long-term gas pressures greater than the minimum principal stress. If the pressure is
increased above this level, micro-fracturing of the rock may occur, leading to an increase in
the porosity and permeability of the rock. Gas migration would then occur through the
fractures rather than the rock matrix, fundamentally affecting the nature of fluid flow. While
new gas pathways are formed, existing fractures may re-seal as the pressure in them
drops.

Large-scale fracturing may also occur if the gas pressure increases rapidly. The
permeability of the newly formed fracture could be several orders of magnitude higher than
that of the host rock.

**7.2 Approach to addressing key questions for different geological environments**
As far as the migration of carbon-14 bearing gases is concerned, some key questions are:

- Will there be a gas phase present in the GDF?
- How will the host rock affect migration of the gas?
- How quickly will the gas migrate through the host rock?
- How will any geological features overlying the host rock affect the gas pathway?
• Over what area and what geometry will gas be released to the biosphere?

For the three illustrative geological environments (i.e. higher strength rocks, lower strength sedimentary rocks, and evaporites), we address each of these questions in turn below.

7.2.1 Higher strength rock

**Will a gas phase be present in the GDF?**
For the case of a higher strength host rock, scoping calculations [74], which assumed that

- the host rock had a rather high permeability ($2 \times 10^{-16} \text{ m}^2$),
- the vaults included a crown space, and
- the regional hydraulic gradient was aligned with the axes of the vaults,

predicted that the groundwater flow through the UILW vaults would be about 200 m$^3$yr$^{-1}$. This is not quite enough to transport all of the bulk gas in solution (see Section 6.1.2). In a higher strength rock, gas generation may not be limited by water availability [14]

If, however, the crown space were backfilled, or the vaults were lined with low-permeability (i.e. less permeable than the host rock) concrete, then the groundwater flow would be reduced. This could result in lower gas generation rates, but there would also be less groundwater available to dissolve any gas being generated.

In this illustrative geological environment, scoping calculations are appropriate for estimating groundwater flows both during resaturation and in the long term, and can be used to determine the timescale for resaturation.

**How will the host rock affect migration of gas?**
The host rock could affect both gas generation and its subsequent migration.

In the case of a higher strength host rock, groundwater (possibly containing chloride) is predicted to resaturate the GDF within a few years [18].

As the GDF resaturates, the pressure of the gas will start to build up. Once the pressure has risen sufficiently (i.e. to the point where it equals the groundwater pressure plus the gas entry pressure$^{25}$ of the fractures), a free gas phase will migrate out of the repository. Because the host rock has a relatively high permeability and low gas entry pressure, it will not pose a significant barrier to gas migration [14].

**How quickly will the gas migrate through the host rock?**
Theoretical [75, 76] and experimental [77] work suggests that gas could rise up through the fractures as a stream of Hele-Shaw bubbles (i.e. bubbles whose diameters are larger than the fracture aperture; see Figure 14).

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$^{25}$ The gas entry pressure (which is a parameter that characterises by how much the gas pressure, $p_g$, has to exceed the water pressure, $p_w$, before gas can move into a saturated material) may be loosely related to the pore size in the porous medium. In particular, the Young-Laplace equation states that $p_g - p_w = \frac{2\gamma}{r}$ where $\gamma$ is the surface tension and $r$ is the pore radius.
The speed $u$ with which a Hele-Shaw bubble rises through a fracture is given by

$$u = \frac{e^2}{12 \mu_w (\rho_w - \rho_g)} g$$

where

- $e$ is the fracture aperture;
- $\mu_w$ is the viscosity of the water, about $10^{-3}$ Pa s;
- $\rho_w$ is the density of the water, about $10^3$ kg m$^{-3}$;
- $\rho_g$ is the density of the gas, which will be much less than that of the water; and
- $g$ is the acceleration due to gravity, about 9.81 m s$^{-2}$.

Hence, for a fracture with a representative aperture of 10 microns, the speed of the bubble is about $2.6 \times 10^3$ m a$^{-1}$. Although this is an overestimate of the speed with which the gas will rise upwards (because, for example, it does not account for trapping of gas at fracture intersections), it does suggest that the time for the gas phase to migrate across a fractured host rock will be negligible compared with the half-life of carbon-14.

**How will any geological features overlying the host rock affect the gas pathway?**

If the gas phase encounters a low-permeability formation (a cap rock) with a high gas entry pressure, then the buoyant rise of the gas will be impeded. The gas will migrate through
the fractures beneath the low permeability formation to a high point, and a gas pocket will form there (see Figure 15).  

**Figure 15  Illustrative calculation (for a representative geology in west Cumbria) showing a gas pocket in fractured rock beneath the North Head Member [18]**

Gas will continue to accumulate in the gas pocket, and eventually the pressure will increase sufficiently that it overcomes the gas entry pressure of the overlying rocks. Then the gas will migrate from the pocket into the overlying rocks and upwards.

The cap rock either could trap gas, and so limit release, or could focus the gas release. The former would be beneficial for reducing the risk from carbon-14 bearing gases, while the latter could be unhelpful.

A feature which could prevent a free gas phase from breaking through at the surface is the groundwater flowing through high-permeability, near-surface units. Some of the gas will dissolve in this groundwater. The volume of gas, $V_g$, can be estimated from

$$V_g = W b q H p$$

where:

- $W$ is the width (normal to the groundwater flow) of the gas pathway through which the gas is migrating upwards. If the gas phase is localised to a few plumes, then $W$ is the sum of the widths of the individual plumes;
- $b$ is the thickness of the high-permeability unit. This is likely to be some tens of metres;
- $q$ is the specific discharge in the high-permeability unit. This will be site specific, but a representative value could be about 1 m a$^{-1}$;
- $H$ is the Henry’s constant for the gas. From Section 6.1.2, Henry’s constant (at 20°C and zero salinity) for hydrogen is $1.78 \times 10^{-7}$ m$^3$ at STP m$^{-3}$ Pa$^{-1}$;
- $p$ is the pressure of the gas, which will be similar to hydrostatic pressure (i.e. about $10^5$ Pa at a depth of 100m, and $10^5$ Pa at the surface).

The width of the gas pathway, $W$, is a very uncertain parameter in the analysis. However, we can use the data listed above to calculate the width that would be required to dissolve the gas at its long-term generation rate (i.e. about $10^3$ m$^3$ at STP a$^{-1}$). Using cautious

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26 The figure is a contour plot of gas saturation (i.e. it shows the fraction of the pore volume that is occupied by gas). The black lines demarcate the different rock units. The shaded region shows the contours of gas saturation. The gas plume rises upwards from the GDF, and then is impeded by a particular low-permeability formation.
numbers suggests that the width has to be larger than about 1,000 m, which is comparable to the width of the vault footprint from which the gas will be released. A tentative conclusion therefore is that there is the potential for gas to dissolve in the groundwater, but any focusing of the gas pathway would lead to the release of a free gas phase to the surface. Earlier site-specific modelling of gas migration at Sellafield [18] showed that for many of the variants studied, there was no gas breakthrough to the surface, but for one there was. This remains a site-specific issue.

Another potential sink for hydrogen is microbial processes that could occur in the geosphere [71]. In particular, sulphate reducing microbes could facilitate the oxidation of hydrogen.

Gas injection tests performed at Reskajeage Farm in Cornwall [78] demonstrate how problematic it can be to predict gas migration. Helium was injected from a borehole into fractured rock at a depth of about 54m. Then repeated soil-gas surveys were used to determine the helium soil-gas concentrations in fields surrounding the borehole. The experiments showed interesting features:

- The first appearance of helium was some distance laterally (80m) from the source, and was of a transient nature.
- A larger helium concentration than in the first release appeared at a different location (40m from the source) after helium injection had ceased.
- The main helium anomaly persisted for an extended period (more than two years) after helium injection had ceased, although with a varying helium concentration.

A plausible, though not necessarily unique, explanation of the observed behaviour is shown schematically in Figure 16.

**Figure 16  Schematic view showing a possible route for migration of injected gas at Reskajeage Farm**

While it is clear that it will be difficult to predict the extent of localisation of gas release at the surface, both modelling [62, 74] and experimental [78] work suggest that the rate of gas migration through the rocks overlying the fractured host rock could be quick (i.e. the travel
time could be insignificant compared to the half-life of carbon-14). The gas phase would be trapped for a significant period of time only if the cap rock is homogenous and laterally extensive.

**Over what area and what geometry will gas be released to the biosphere?**

A key parameter which is used in the model to assess the risks from carbon-14 bearing gases is the area over which the gases will be released to the biosphere (this is discussed further in Section 8). The discussion above has shown that it is difficult to predict this area. For that reason, previous assessment calculations have assumed either:

- The area of release is $10^4$ m$^2$. This is considered to be the minimum area that could support the potentially exposed group, and therefore is cautious.
- The area of release is about $4 \times 10^5$ m$^2$. This is the area of the GDF footprint above the UILW and SILW/LLW vaults. This would be a realistic area, particularly if the fractured host rock extends all the way to the surface and therefore there is no focusing of the gas pathway.

Release areas are discussed in more detail in Section 8.1.

### 7.2.2 Lower strength sedimentary rock

**Will a gas phase be present in the GDF?**

The groundwater flow through the GDF scales approximately with the permeability of the host rock. In the case of a mudstone, which will have a permeability of about $10^{-20}$ m$^2$ (i.e. several orders of magnitude less than for a higher strength rock), the groundwater flow will be much reduced compared with a higher strength rock, making it probable that a gas phase will be present.

**How will the host rock affect migration of the gas?**

In the case of a lower strength sedimentary rock, both the permeability and the pore size (which is inversely related to the gas entry pressure) are much smaller than for a higher strength rock. As a consequence it is harder for gas to enter, and then to flow through the host rock. Another important difference from a higher strength rock is that there is not much variability in the physical properties [79]. A recent modelling study concluded that coupling between water availability and gas generation reactions is particularly important in lower strength sedimentary rocks [14].

Gas that is generated will accumulate in the GDF, and its pressure will increase above the hydrostatic pressure. As a result, some porewater will be flushed out of the vaults. This could affect the rate of gas generation (i.e. limited availability of water). Eventually, the gas pressure may exceed the threshold (i.e. the water pressure plus the gas entry pressure) for gas to flow into the host rock.

The gas would migrate slowly across the lower strength sedimentary rock. Andra, who have modelled this scenario, state that, “The impact of radionuclide transfer in gaseous form can be considered to be negligible all the more because the transfer times to the outlets of several tens of thousands of years would significantly contribute to their radioactive decay.” [80] Coupled modelling of gas generation and migration in a lower strength sedimentary rock showed that release of free radioactive gas from the host rock was calculated to be zero or negligible [14].

However, it is probable that the GDF will include engineering measures to release gas from the pressurising vaults before there would be any risk of damage to the structural
components of the vault. The flow of gas through both the GDF tunnels and the excavation disturbed zone around the tunnels could be a significant pathway. Nagra has accounted for this pathway, and their simulations show that, “desaturation of the host rock is limited to a few metres in the immediate near-field of the caverns. The gas saturation in this zone is a few percent … The gas flux in the repository system indicates two flow regimes: (1) one part flowing axially along the underground structures (engineered gas transport system), and (2) another part flowing radially into the host rock.” [81]. This is illustrated in Figure 17.

**Figure 17**  Gas saturation and specific gas flux in the vicinity of the repository: contours of gas saturation at 10% are plotted on a vertical cross-section through a vault. The vertical scale is 80m [81] – reproduced with permission from Nagra. **Red** indicates high gas saturation, **Blue** low gas saturation. The black arrows show the gas velocity vectors.

*How quickly will the gas migrate through the host rock?*

These results suggest that the host rock will be a significant barrier to carbon-14 bearing gases, and could delay them sufficiently so that the carbon-14 decays to an insignificant activity.

*How will any geological features overlying the host rock affect the gas pathway?*

The lower strength sedimentary rock could be overlain by high-permeability, near-surface units. Some of the gas that might migrate across the host rock will dissolve in the groundwater flowing through these units.

**7.2.3 Evaporite**

*Will a gas phase be present in the GDF?*

An evaporite host rock will be essentially impermeable. However, rock salt is expected to creep, and will compress any gas that is trapped within the void spaces in the GDF [82].

*How will the host rock affect migration of the gas?*

The waste environment will be so dry that gas generation could be very limited (although water may be available in some waste packages, e.g. in the form of grout porewater).

The pressure required for the gas to enter the host rock will be higher than for other potential host rocks.

Although modelling [82] for a German disposal facility shows that the gas pressure could increase up to the minimum principal stress in the rock, even if this were to happen no
significant over-pressurisation would occur (assuming that gas generation is limited). The results of laboratory and field tests demonstrate that if the gas pressure equals the minimum principal stress, a rapid increase in permeability will take place (i.e. secondary permeability will be created). There will be limited flow of gas into the host rock.

**How quickly will the gas migrate through the host rock?**

The risk of radioactive gas migrating from a GDF through the host rock is assessed to be low [82] or zero [14].

### 7.2.4 A summary of the behaviour of a gas phase in the geological environments

A gas phase, containing carbon-14 bearing gases, is expected to be present in the GDF (even in the long-term).

Gas is most likely to migrate from the GDF to the biosphere if the host rock is a higher strength rock. Clay and rock salt would pose very significant barriers to gas migration, and therefore the risk from carbon-14 bearing gases would be assessed to be low in these geological environments. Therefore, modelling of gas migration in the total system model should focus on higher strength rocks.

In the case of a higher strength rock, a feature which could mitigate against a free gas phase from breaking through at the surface is groundwater flowing through high-permeability, near-surface units. Some of the gas will dissolve in this groundwater. Otherwise gas will migrate to the biosphere on a timescale that is short compared to the half-life of carbon-14. A significant uncertainty in assessing the risk from carbon-14 is associated with the area of release of the gas. At present, a cautious assumption is made that the area of release is $10^4$ m$^2$ (see discussion in Section 8.1). This is considered to be the minimum area that could support the potentially exposed group, but it does imply significant focusing of the gas pathway. (The area of the GDF footprint above the UILW and SILW/LLW vaults is about $4 \times 10^5$ m$^2$.) Site characterisation and scoping modelling studies may help justify a larger area of release.

### 7.2.5 Site characterisation

A GDF is a multi-barrier system and it may be possible to take credit for the role of the geosphere in preventing or delaying the breakthrough of gas at the surface. In this case, it would be necessary to appropriately characterise the geosphere in order to demonstrate its performance.

Geological features are site specific and it may be possible to investigate them during desk-based studies if there is relevant existing information. The results of these investigations can then be confirmed using borehole investigations, remote investigations such as geophysics, laboratory measurements and natural analogues. The data obtained from these studies can be interpreted to develop the conceptual understanding of the geological processes and properties, which can subsequently be used to develop gas migration models to assess the behaviour of gases in the geosphere.

Gas migration studies are, however, complicated by the heterogeneous nature of rocks. Large-scale fluid flow observations, either in borehole investigations or in laboratory experiments, will not give information about the micro-scale behaviour that takes place in the rock pores. Describing this behaviour accurately for a large volume is complex, due to the varying pore sizes and their connectivity, the wetting behaviour of the rock, the miscibility of the fluids, etc. A gas migration model at GDF scale is an approximation, which aims to represent adequately the large-scale behaviour of the gas as it migrates from the GDF through the geosphere.
Table 18 below lists some of the parameters required for gas modelling studies and how these could be obtained during site characterisation.

**Table 18   Data requirements for gas modelling studies**

<table>
<thead>
<tr>
<th>Data requirement</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Groundwater flow</td>
<td>Groundwater level measurement and logging across a network of monitoring boreholes, borehole flow logging, packer testing, borehole geophysics</td>
</tr>
<tr>
<td>Geological features</td>
<td>Desk study complemented with borehole tests and surface geophysics</td>
</tr>
<tr>
<td>Rock properties</td>
<td>Cored boreholes to provide samples for laboratory testing of rock properties. In situ testing including packer testing for determination of local permeability and borehole geophysics</td>
</tr>
<tr>
<td>Two-phase flow properties</td>
<td>Laboratory tests using rock samples</td>
</tr>
<tr>
<td>Groundwater chemistry</td>
<td>Sampling and laboratory analysis</td>
</tr>
<tr>
<td>Mineralogy</td>
<td>Rock sample thin section observation, laboratory testing, learning from analogues</td>
</tr>
</tbody>
</table>

**7.2.6 Modelling approaches**

Modelling approaches are well established and do not require further development within this project. The approach that is widely used to describe gas migration (by other radioactive waste organisations [78, 80, 81], and also used in the oil and gas industry) is based on the use of continuum models, parameterised using capillary and relative permeability functions. These functions would have to be determined as part of a site characterisation programme.

**7.3 Work for Phase 2**

It is not proposed to undertake detailed development of gas migration models in Phase 2. Based on the understanding described above, the total system model (described later in Section 9.5) will be developed initially for a higher strength rock. The radiological consequence from carbon-14 is unlikely to be an issue in other geologies; tools and approaches exist that have been used to model gas generation and migration in lower strength sedimentary rock and evaporite and no further models will be developed within this programme. Understanding of the impact of geological features on gas migration may be drawn upon in the later stages of the project if it is found necessary to develop requirements on the geosphere to delay or prevent the migration of gas to the biosphere.

Work for Phase 2 of the project will involve:

- Ongoing involvement in the EC project FORGE to ensure we remain at the forefront of developments in this area;
- Development of an understanding of the envelope of geological environments in which carbon-14 bearing wastes can be safely managed, and explore whether there are analogues relevant to gas release and release area;
- If required, we will develop an understanding to inform the requirements for the site characterisation programme;
- Input to development of a total system model for higher strength rock.
8 Carbon-14 in the biosphere

The final step in the process of evaluating the consequences of the release of carbon-14 bearing gases is to consider how they might lead to doses to future generations. In particular we consider how they are taken up by plants, which in turn might enter the food chain.

In the Phase 1 work, we have reviewed previous work undertaken for Nirex, current work being undertaken for NDA RWMD, and work undertaken recently for LLWR in support of their Environmental Safety Case, and have derived a factor that converts a flux of carbon-14 bearing methane ($^{14}CH_4$) (in Bq yr$^{-1}$) after closure of the GDF into an annual dose (mSv) or an annual risk, taking into account the important processes in the soil zone and plant canopy.

In Phase 2 we will:

- Complete the current experimental programme on carbon-14 in the biosphere;
- Carry out a focused literature review on methane oxidation in soils;
- Participate in the BIOPROTA review of biosphere models for carbon-14.

In Phase 1 of the project we have agreed the approach to biosphere assessment within the IPT (Section 8.1), taking into account the laboratory and field experiments being undertaken for NDA RWMD [83], work being undertaken for LLWR in support of their Environmental Safety Case [84, 85], and work being undertaken as part of the international BIOPROTA project [86, 87, 88] (Section 8.2). We also looked to see if there were any requirements for further work in support of quantitative assessments (Section 8.3).

The adopted approach is different in the operational phase (before final closure of the GDF) and the post-closure phase (after final closure). The approach for the post-closure phase is discussed in the next subsection below. The approach for the operational phase is discussed in Section 9.4.

8.1 Dose conversion factor for carbon-14 bearing methane

The adopted approach calculates the consequences arising from $^{14}CH_4$ and $^{14}CO_2$ entering the biosphere. The main aim of the work in Phase 1 is to derive a well-founded factor that can be used to convert a flux of carbon-14 bearing methane ($^{14}CH_4$) entering the biosphere (in Bq yr$^{-1}$) into an annual dose (mSv) or an annual risk.

A detailed description of the analysis is provided in this section. The conceptual model is first described (Section 8.1.1), followed by a description of the model implementation (Section 8.1.2). The derived flux to dose conversion factor is described in Section 8.1.3. A comparison with values in previous assessments is given in Section 8.1.4. The release area is an important input into the assessment calculations, and this is discussed in Section 8.1.5. The possible implications of a release of carbon monoxide is discussed in Section 8.1.6.

8.1.1 The conceptual model

A conceptual model of $^{14}CH_4$ and $^{14}CO_2$ behaviour following injection into the subsoil is shown in Figure 18 and summarises the processes within the biosphere that should be accounted for in understanding and quantifying the fate of carbon-14 as $^{14}CH_4$ emerging in the gas phase into the subsoil. This conceptual understanding underpins the NDA RWMD experimental and modelling programme currently being conducted jointly by AMEC and the University of Nottingham [89]. The same processes are now also represented in the
assessment model for carbon-14 recently developed for the LLWR. An account of the model used by the LLWR in its 2011 Environmental Safety Case is given in [90], and documentation of the updated model used in more recent assessment studies is currently being developed by LLWR Ltd [91].

Some of the key pathways for carbon-14 entering the food chain are:

- Migration of $^{14}$CH$_4$ into the soil zone from the sub-surface;
- Oxidation of a portion of that methane to carbon dioxide through microbial action;
- Take up of $^{14}$CO$_2$ into the plant, either directly through the root system or through photosynthetic fixation of $^{14}$CO$_2$ within the above-ground plant canopy;
- Entry of $^{14}$C-contaminated plant material into the human food chain, either directly (for example through human consumption of crops grown on a small-holding) or indirectly through the consumption of milk or meat from animals grazing, or otherwise fed on, $^{14}$C-contaminated plant material.

**Figure 18  Conceptual model for the transport of carbon-14 released to soil as either methane or carbon dioxide,**

1. Microbially mediated oxidation of methane to carbon dioxide.
2. Diffusion and atmospheric pumping.
3. Turbulence, diffusion and atmospheric pumping.
4. Uptake via stomata and incorporation into carbohydrates via photosynthesis.
5. Above-ground respiration.
6. Direct root uptake and translocation to the sites of photosynthesis.
7. Translocation to the roots.
8. Root respiration.
9. Direct and indirect incorporation of dead plant material into the soil organic matter.
10. Decomposition.
In the LLWR model, it is assumed that $^{14}$CH$_4$ entering the soil zone is completely converted to $^{14}$CO$_2$. In addition, the rate of production of stable carbon dioxide in the soil is entered into the model as an input parameter. The upper boundary of the model is a layer of air some metres thick overlying the plant canopy. Both the $^{14}$CO$_2$ and stable carbon dioxide concentrations in this atmospheric layer are input to the model as boundary conditions. The stable carbon dioxide concentration is that in the global atmosphere (around 385 ppmv), whereas the $^{14}$CO$_2$ concentration is calculated using a simple dilution model applied to the overall release area. Within the model, a resistance analogue approach is used to model both stable carbon dioxide and $^{14}$CO$_2$ concentrations in the soil atmosphere and in the sub-canopy atmosphere, which is treated as two layers, so that the stem region can be distinguished from the foliar region, where this is appropriate to a particular crop type. The resistances are effectively the inverse of vertical transport rates in the system and the resistance analogue approach has been extensively used in studies of the transport of momentum, heat and moisture through plant canopies.

Because the concentration and transport of both stable carbon dioxide and $^{14}$CO$_2$ are modelled, the specific activity of the soil atmosphere and two layers of the sub-canopy atmosphere can be calculated on a self-consistent basis. These specific activity values are used to estimate the specific activities of plant tissues. The specific activity of carbon-14 used in photosynthesis is a weighted average of the specific activity values from the soil atmosphere (used to represent direct root uptake of carbon) and from the two layers of the sub-canopy atmosphere (with partitioning based on the relative proportions of photosynthesis arising in the two layers, taking account of the attenuation of incident light with depth in the canopy). The products of photosynthesis are partitioned to respiration and biomass production in above- and below-ground plant tissues according to empirical observations of plant growth. Documentation of this model, including a full account of sensitivity studies undertaken using it, is currently being completed for LLWR Ltd. When finalised, this documentation will be available in the public domain.

An important result from the model sensitivity studies was the finding that the plant specific activity at harvest (or during the growing season for pasture) is not very sensitive to most of the model input parameters. The main sensitivity is to the fraction of plant carbon that derives from root uptake. This arises because the specific activity of the soil atmosphere is much higher than the specific activity of the sub-canopy atmosphere (due to mixing of gas released from soil with gas entrained below the canopy from the above-canopy atmosphere). Experimental observations from the literature (or acquired directly from the originators) have been analysed by LLWR Ltd to demonstrate that no more than 5% of plant carbon is derived from direct root uptake and that a cautious upper bound in most circumstances is around 2%.

### 8.1.2 Model implementation

A flow chart is provided in Figure 19 showing the approach to assessment used in the LLWR model and adopted in the calculations reported here.

The release rate of $^{14}$CH$_4$ to soil is specified by the user. A release rate of $^{14}$CO$_2$ can also be specified, which is added to the fraction of the $^{14}$CH$_4$ release rate that is converted to $^{14}$CO$_2$. The release rates are expressed in units of Bq m$^{-2}$ y$^{-1}$.

The degree of conversion of $^{14}$CH$_4$ to $^{14}$CO$_2$ is cautiously taken as 1.0 in the assessment calculations undertaken for the LLWR. This cautious assumption is also adopted here, but it is noted that there is experimental evidence to show that the degree of conversion may be substantially lower than this in agricultural soils.
It has been demonstrated that uptake of $^{14}$CO$_2$ by plants does not significantly reduce the flux of $^{14}$CO$_2$ through the plant canopy. Thus, the total area-integrated flux of $^{14}$CO$_2$ from the soil is used to calculate the $^{14}$CO$_2$ concentration in the above-canopy atmosphere. The concentration is calculated by diluting the area-integrated flux into the flow of air over the canopy. In general, the resultant concentration is small compared with the concentrations in soil gas and the below-canopy atmosphere, so the parameter values characterising the air flow (wind speed, extent of release area and height of mixing) are of limited importance in determining the results of the calculations. The concentration of stable carbon dioxide in the above-canopy atmosphere is specified by the user. Typically, a present-day value of 385 ppmv is used. Based on these quantities, the specific activity of carbon-14 in carbon dioxide in air can be calculated. This is only used for comparative purposes and is not required elsewhere in the calculations. The $^{14}$CO$_2$ and stable carbon dioxide concentrations constitute the upper boundary conditions of the model.

The lower boundary conditions of the model comprise the $^{14}$CO$_2$ flux to the soil zone and the stable carbon dioxide flux to the soil zone. The latter arises from the degradation of organic matter in soil and is well constrained by field observations in different agricultural conditions. With both the lower and upper boundary conditions well defined, a resistance
analogue model is used to calculate both $^{14}$CO$_2$ and stable carbon dioxide concentrations in the soil atmosphere and two layers of the below-canopy atmosphere. This model is based on observations of heat, momentum and moisture fluxes through plant canopies, and on observed carbon dioxide concentrations in soils. From these results, the specific activity of carbon-14 in carbon dioxide can be calculated for the soil atmosphere and two below-canopy layers. In these calculations, the time evolution of the plant canopy is represented for different types of crop plants. For pasture, time-independent canopy characteristics are adopted. Different types of crop plants and different types of pasture can be simulated.

The specific activity in the biomass of plants being produced at any time is computed as a weighted combination of the specific activities in the carbon dioxide in the soil atmosphere and two layers of below-canopy atmosphere. The fraction of plant carbon derived from the soil atmosphere via soil solution and root uptake is a user-defined quantity. Based on empirical observations, it would generally be legitimate to adopt a value of 0.0. However, values of up to 0.02 cannot be excluded in the better data sets that are available and values of up to 0.05 have been reported in the literature. A reasonably cautious value of 0.02 is adopted in the assessment calculations undertaken by LLWR. This value is a primary determinant of the assessment results, because the specific activity of the soil gas (and hence soil solution) is much larger than the specific activity of the below-canopy atmosphere. The partitioning of carbon dioxide uptake between the two sub-canopy layers is generally determined by the relative degree of photosynthetic activity in each of these layers. This is determined by the vertical distribution of foliage in the canopy and the associated degree of light attenuation. Thus, this partitioning is time-dependent for crop plants, but is well constrained by available growth curves, which also determine rates of biomass production.

The specific activity of pasture is determined in a time-independent equilibrium calculation. In contrast, the specific activity of crop plants at harvest is determined from the time-integrals of the activity taken up by above- and below-ground parts of the plant throughout the growing season. The rate of incorporation of activity at any time is the above- or below-ground biomass production rate (obtained from the growth curve) multiplied by the weighted specific activity computed as described above.

As pasture is included in the model, the specific activity of animal tissues is computed as the specific activity of pasture multiplied by the fraction of the animal's dietary carbon that is obtained from the contaminated area. For the assessment calculations reported here, that fraction is cautiously taken as 1.0. All animal tissues, including milk, are taken to exhibit the same specific activity. This is appropriate to conditions of chronic exposure.

Similarly, for humans, the specific activity of tissues is computed as the average specific activity of the dietary intake (including both plant and animal products and taking into account the fraction of dietary carbon that is contaminated). In the assessment calculations reported here, the fraction of carbon in the diet obtained from locally sourced foodstuffs (all taken to be from the contaminated area) is cautiously taken as 0.3 (major contributors to carbon in the diet, such as cereals, would not generally be produced locally to any great extent).

Once the specific activity of human tissues is calculated, the absorbed dose rate can be calculated without significant uncertainty, since it depends only on the fractional carbon content of human tissues and the energy emitted per transformation by carbon-14. As carbon-14 emits only low LET (linear energy transfer) radiation and is relatively uniformly distributed throughout all human organs and tissues, the absorbed dose rate is numerically identical to the effective dose rate.
8.1.3 Flux to risk conversion factor

A key output for the biosphere component of Phase 1 of the IPT was an agreed approach to assessing the biosphere in the post-closure phase. The model developed for the LLWR, and described above, provides this capability. Specifically, as part of the IPT Biosphere activities, the model has been used to calculate a factor to convert flux of carbon-14 (Bq yr\(^{-1}\)) into annual doses and risks.

Summarising this calculation, we require a factor that relates unit flux of carbon-14 into the soil zone (1 Bq m\(^{-2}\) s\(^{-1}\)) to the effective dose rate (Sv y\(^{-1}\)) to a representative member of a Potential Exposed Group (PEG). A major cautious assumption is made that all \(^{14}\)CH\(_4\) is converted to \(^{14}\)CO\(_2\) when it enters the soil zone (the oxidation step in Figure 18). Two calculations have been undertaken based on alternative assumptions, namely that:

- no plant carbon is obtained by direct root uptake; or
- 0.02 of plant carbon is obtained by direct root uptake (pathway 6 in Figure 18).

The difference in the overall calculated uptake of carbon-14 by vegetation is small, 2 × 10\(^5\) Bq kg[C]\(^{-1}\) and 5 × 10\(^5\) Bq kg[C]\(^{-1}\), respectively, both calculated for a flux of 1 Bq m\(^{-2}\) s\(^{-1}\). If it is assumed that grazing animals obtain all their dietary intake from the contaminated vegetation then the activity concentration of carbon-14 in animal tissues will also be 5 × 10\(^5\) Bq kg[C]\(^{-1}\) for a gas flux of 1 Bq m\(^{-2}\) s\(^{-1}\).

For humans, it is assumed that not all the dietary requirements are obtained from the contaminated area - \(f\) is the fraction of the carbon in a person's diet obtained from the contaminated area (\(f\) is assigned value of 0.2 to 0.3). The expected specific activity of carbon-14 in human tissues is the same as that in animals (5 × 10\(^5\) Bq kg[C]\(^{-1}\)) multiplied by \(f\).

This specific activity is converted to a rate of energy deposition in human tissues from which an effective dose rate in Sv y\(^{-1}\) is calculated. Using the cautious assumption that \(f\) is 0.3, the required dose conversion factor is 0.009 Sv y\(^{-1}\) for a flux 1 Bq carbon-14 m\(^{-2}\) s\(^{-1}\) to the soil.

8.1.4 Comparison with previous assessments

It is relevant to compare this value with values that have been previously used or implied in post-closure assessment studies of a GDF. The earlier calculations used the Enhanced RIMERS model (“Enhanced” refers to a correction to the original RIMERS model developed for Nirex, the correction relating to the way in which specific activity values were calculated in the various atmospheric compartments). Using the enhanced RIMERS model [92], it was reported that, for an input of 1 Bq m\(^{-2}\) d\(^{-1}\), the carbon-14 activity in standing biomass is 130 Bq kg[C]\(^{-1}\) (range 18 to 1500 Bq kg[C]\(^{-1}\)). Calculations using a simplified version of the model [93], give a best estimate of 130 Bq kg[C]\(^{-1}\), with a range of 25 to 130 Bq kg[C]\(^{-1}\).

Based on these studies, the Enhanced RIMERS model, as previously used by Nirex, gives a plant concentration of between 18 and 1500 Bq kg[C]\(^{-1}\) for a flux of 1 Bq m\(^{-2}\) d\(^{-1}\). The new LLWR model gives 2 × 10\(^5\) Bq kg[C]\(^{-1}\) to 5 × 10\(^5\) Bq kg[C]\(^{-1}\) for a flux of 1 Bq m\(^{-2}\) s\(^{-1}\). This corresponds to 2.3 to 5.8 Bq kg[C]\(^{-1}\) for a flux of 1 Bq m\(^{-2}\) d\(^{-1}\). Thus, the new model gives specific activity values in plants (and hence in animals and humans) a factor of 3 to 650 lower than the Enhanced RIMERS model. The best estimate of the reduction in specific activity is around 30.

The reason for this reduction is that the Enhanced RIMERS model and the model used in the 2011 Environmental Safety Case for the LLWR [90] adopted a diffusion-only approach to modelling C-14 transport in the lower part of the plant canopy. However, empirical observations demonstrate that the wind velocity never drops to zero within the plant canopy, though it does exhibit a distinct minimum. Thus, turbulent mixing occurs
throughout the depth of the canopy and this enhances the upward movement of carbon-14 through the canopy and its release to the overlying air.

8.1.5 Release area

There remains the question of what release area to take. We cautiously take an area of $10^4$ m$^2$ (1 hectare). If the area is smaller than this then concentrations of carbon-14 in plant material will be larger, but any food derived would need to be supplemented by food from elsewhere. Thus, the risk will not depend on release area. If the release area is larger, then the risks will be smaller (in inverse proportion to the release area).

In the 2011 Environmental Safety Case for the LLWR, consideration was given to the minimum area that would support a family group [94]. Four potential alternatives were considered:

A. The smallholder with 4 to 12 hectares of land who keeps several head of cattle and uses them to provide meat and milk products;
B. The smallholder with 1 to 3 hectares of land who keeps a single cow for milk production only;
C. The smallholder with 0.5 to 1 hectare of land who keeps two goats for milk production only;
D. The kitchen gardener who grows his own vegetables and fruit on 0.05 hectare.

Only in case D would the area of land be less than $10^4$ m$^2$ and, in this case, the contaminated component of the diet would be limited to vegetables and fruit grown for domestic consumption. Other fruit and vegetables, grain and other plant products, and all animal products, would be imported from uncontaminated areas. For this case, $f$, would be $<0.06$ rather than the value of 0.3 adopted above.

8.1.6 Other gases generated in the repository

The possibility has been raised (see Section 4) that carbon monoxide might be one of the gases released from the GDF. No photosynthetic fixation of CO would occur in the plant canopy, and as a consequence there are no food-chain implications to the release of CO. The inhalation dose from $^{14}$CO would be less than the inhalation dose from a corresponding release of $^{14}$CO$_2$, because the value of the effective dose per unit intake is smaller [95].

8.2 Links to other programmes

Earlier Nirex, NDA RWMD and LLWR work

A comparison of the current model with recent assessments has been presented above. Here we provide some wider context for the developments in this area.

The original RIMERS model characterising the behaviour of gaseous forms of carbon-14 released to the soil zone, was developed for Nirex [96] and used in both the Nirex 97 assessment [97] and the Nirex Generic Safety Assessment [98]. However, in 2005, Thorne and MacKenzie [99] identified substantial discrepancies between the RIMERS model and a carbon-14 model developed for the Food Standards Agency (FSA). These discrepancies were investigated in Thorne [100], where it was reported that by re-implementation of the original RIMERS model and by implementation of the FSA model for carbon-14, the reasons for the differences between the results obtained with the two models were identified. In the first stage of the analysis, deficiencies in the stable carbon balance of the original RIMERS model were corrected and the model was re-parameterised. Exploratory studies with this re-parameterised model and the FSA model showed that differences between the models largely arose from the different approaches that were adopted to representing exchanges between soil solution, soil atmosphere,
below-canopy atmosphere and above-canopy atmosphere. The original RIMERS model treated these exchanges as being very rapid and assumed that the four components could be considered to be in equilibrium at any time. Although the model included provision for different specific activities in these compartments, this provision was not used, so the four compartments collapsed to a single well-mixed compartment.

The FSA model did not treat these compartments as being in equilibrium and calculations using it showed clearly that for a source of carbon-14 entering soil biota, the specific activities of carbon-14 in the four compartments differed from each other and with time. Therefore, in order to explore the issues further an enhanced version of RIMERS was implemented that represented the various exchanges between these compartments explicitly. Using this enhanced version, it was demonstrated that similar results to those from the FSA model could be achieved, providing care was taken to ensure that the key parameter values used in the two models were appropriately cross-calibrated.

On the basis of this analysis, it was concluded that the enhanced version of RIMERS [101] was suitable for use in assessment studies, both for releases of carbon-14 to the soil zone and releases to the above-canopy atmosphere. Therefore, illustrative calculations were undertaken for both a constant unit input rate of carbon-14 to the above-canopy atmosphere and a unit spike input to the above-canopy atmosphere at time zero. These calculations showed that the enhanced RIMERS model closely approximates to a specific activity model for this mode of input, providing that the chronic release period is in excess of about a year. For the acute input case, it was found that standing biomass reaches its maximum concentration on a timescale of considerably less than one day and that a value close to that maximum is maintained for about 100 days, before it begins to decrease as a result of growth dilution (production of additional biomass uncontaminated by carbon-14), with the originally contaminated biomass entering various carbon pools in soil.

The Enhanced RIMERS model and simplified versions of it were subsequently used in the international BIOPROTA project. These studies identified the importance of understanding gas exchange rates between the soil, below-canopy atmosphere and above-canopy atmosphere. However, no significant advances were made in the modelling approach and a similar approach was used in the studies of the radiological impacts of disposal of graphite wastes in 2010 [102], which is based on the Enhanced RIMERS model and refers back to the analyses conducted by Thorne in 2005.

The next major change in modelling approach was that adopted for the 2011 ESC for the LLWR. This involved computation of transport velocities in the below-canopy atmosphere based on the wind velocity within the canopy. However, vertical transport in the lower part of the canopy was cautiously estimated on the basis of diffusion only (a still air approximation) [90]. It was recognised that this was a very cautious approach and, in the update to the 2011 ESC [91], a resistance analogue model is used to compute gas exchanges between the soil atmosphere, below-canopy atmosphere and above-canopy atmosphere. This gives non-zero advective velocities throughout the system and results in more effective mixing (and hence greater dilution of the $^{14}$CO$_2$ flux from the ground) than in a diffusion-only model.

The current NDA RWMD experimental programme

The current NDA RWMD Experimental and Modelling Programme is examining the distribution of both ambient (naturally occurring) and isotopically labelled CH$_4$ and CO$_2$ in the soil zone. The data from this study are being used to quantify diffusion rates in soil for CH$_4$ and CO$_2$ as well as oxidation rates for conversion of CH$_4$ to CO$_2$, as represented in the LLWR conceptual model (Figure 18). The LLWR assessment model is written in a general way to be able to incorporate further understanding and the current experimental programme can therefore support the calibration of the model.
A discrepancy exists between current modelling assumptions for LLWR and experimental observations of the rate of oxidation of CH$_4$ to CO$_2$. As previously mentioned, the assessment model cautiously assumes complete oxidation of CH$_4$ to CO$_2$ in the soil, whereas experimental measurements of both ambient and injected CH$_4$ indicate the rate of oxidation is variable and generally <<100%. The current assumption is that oxidation of CH$_4$ to CO$_2$ can be quantified as a first-order process. Controls on the oxidation rate are not fully understood, but there is evidence that the rate varies from top soil to subsoil, hence a single first-order rate coefficient may be insufficient to describe the process quantitatively.

**BIOPROTA**

The international BIOPROTA group has proposed further international review of carbon-14 modelling in the soil-plant system (and in a freshwater system) for 2012-13. This will involve peer review of recent experimental work and modelling developments, e.g. the use of resistance analogue models in representation of gas transport through the plant canopy. We plan to continue our involvement in BIOPROTA activities in the coming year as part of Phase 2 of the carbon-14 IPT.

8.3 **Work for Phase 2**

In Phase 2 of the project we will:

- Complete the current experimental work at the University of Nottingham to measure the rate of conversion of CH$_4$ to CO$_2$ (i.e. low oxidation rates), as described above [83].
- Carry out a focused literature review to quantify methane oxidation in a wider variety of soils under different conditions. It is also noted that the rate of oxidation of methane to carbon dioxide may depend on the flux of stable methane. With a high flux of stable methane, the capacity of the microbial community to oxidise that methane may be exceeded. Thus, with high fluxes of stable methane the degree of conversion of $^{14}$CH$_4$ to $^{14}$CO$_2$ may decline [99].
- Review of biosphere models and inter-comparison with other approaches adopted internationally through BIOPROTA.
9 Assessments

We use an assessment approach to quantify the potential impacts of carbon-14 bearing gases. In Phase 1 we have:

- Documented the modelling basis for the assessments;
- Used SMOGG to calculate gas generation rates (as described in Section 5.2);
- Taken the OESA methodology from the generic DSSC and the post-closure methodology developed in Section 8 to calculate potential consequences in the operational, the early post-closure and longer-term post-closure periods. These calculations have ignored the potential benefits from the geosphere in retarding or preventing gas from reaching the surface. The consequences have been broken down by waste type to identify the dominant contributors.

In Phase 2 we will:

- Keep the modelling basis up to date, in the light of improved models and data;
- Develop the OESA methodology, so that it better represents the envisaged discharges;
- Develop a total system model for the post-closure phase in higher strength rocks, to provide a structured understanding of the implications of uncertainty;
- Update the calculations at key points of the programme.

In Phase 1 we held a workshop to discuss the current position regarding the assessment of carbon-14 in the generic DSSC [3] and the way forward. The discussion focused on:

- The modelling basis for the calculations currently being undertaken – this is described in Section 9.1 below;
- Whether a scoping modelling tool should be developed – this is described in Section 9.3 below;
- The way forward for the OESA – this is described in Section 9.4 below;
- Whether a total system model should be developed for carbon-14 – this is described in Section 9.5 below.

The way forward on the biosphere element of post-closure safety assessments has already been described in Section 8 – this complements the discussion on the OESA. The overall assessments results, based on the gas generation calculations described in Section 5.1 are described in Section 9.2.

9.1 Modelling basis

As one of the tasks under Phase 1 of this IPT, the modelling basis of the calculations undertaken has been documented. This summarises the understanding described in the early sections of this report, and provides the basis of the calculations reported in Sections 5.1, 5.2 and 9.2.

This basis is documented in the following tables:

- Table 19 focuses on the model for the release of carbon-14 from graphite;
- Table 20 focuses on the model for the release of carbon-14 from Magnox wastes;
- Table 21 focuses on the model for the release of carbon-14 from Al wastes;
• Table 22 focuses on the model for the release of carbon-14 from wastes containing uranium;
• Table 23 focuses on the model for the release of carbon-14 from steel wastes, waste containing other ferrous metals and Zircaloy;
• Table 24 focuses on the model for the release of carbon-14 from other wastes;
• Table 25 focuses on other processes contributing to the generation of bulk gases;
• Table 26 focuses on other factors that affect gas generation (such as water availability and temperature dependence);
• Table 27 focuses on the engineering aspects that affect gas generation (such as the emplacement strategy);
• Table 28 focuses on the migration of gases through engineered materials;
• Table 29 focuses on the migration of gases through the geosphere;
• Table 30 focuses on biosphere aspects relevant to the Operational Environmental Safety Assessment (OESA) and the Post-Closure Safety Assessment (PCSA).

The columns in the tables describe:
• The model component (e.g. generation or migration);
• The aspect (e.g. gas generation from graphite wastes);
• The conceptual understanding of the relevant processes;
• The model implementation, for example in SMOGG used in the calculations described in Section 5.1;
• The source of the data currently used;
• Any relevant comments in the implementation or application.

These tables are not stand-alone; for example Table 20 should be read alongside Table 26, as water availability is crucially important in the generation of gas from Magnox wastes.

The aim of these tables is to provide a transparency to the approach adopted. The aim is to regard this modelling basis as a live document that will be kept up-to-date. To enable these tables to be treated as a stand-alone component of this report, they are given separate references at the end of Table 30 (in the form [M1] etc.); cross-references to the main list of references are provided at the end of those references.

The tables provide the source of the data. NDA RWMD uses a formal elicitation methodology to build confidence in the most significant parameter values used in the assessment modelling. This is based on a formal protocol developed by Nirex [103]. At this stage of the programme, it has not been considered necessary to elicit formally parameter values in the modelling reported here; this is consistent with the approach adopted in the calculations reported for the groundwater pathway in the PCSA [104].
Table 19  Modelling basis – gas generation from graphite wastes

<table>
<thead>
<tr>
<th>Model component</th>
<th>Aspect</th>
<th>Conceptual understanding</th>
<th>Model implementation (Assessment 2012)</th>
<th>Data (including references)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generation</td>
<td>Graphite</td>
<td>Release of C-14</td>
<td>Simple release rate proportional to the activity of C-14 in the graphite (so remaining quantity is exponentially reducing). All C-14 available. 1% released as methane (representing anything that is not CO₂), 99% as CO₂, which carbonates.</td>
<td>Total release rate constant for C-14 bearing gas is taken from a review [M1] giving $5 \times 10^{-4}$ yr⁻¹ 1% taken from [M2] Inventory from 2007 Derived Inventory [M3]</td>
<td>Possible release as CO is flagged in Issue 1 of the Roadmap? Will all C-14 all be released – some may be immobilised in the graphite matrix? Does the rate decrease? Readily separable group of waste streams Note the shape and size of the graphite “blocks” could be factored into the rate constant The current model is very simple</td>
</tr>
<tr>
<td>Model component</td>
<td>Aspect</td>
<td>Conceptual understanding</td>
<td>Model implementation (Assessment 2012)</td>
<td>Data (including references)</td>
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<tr>
<td>Generation</td>
<td>Reactive metals – Magnox</td>
<td>Release of C-14</td>
<td>100% release as CH₄ (might be something else that is not CO₂) C-14 uniformly distributed throughout metal 2007 DI [M3] divides between spheres and plates Acute and chronic corrosion rates Temperature and chloride dependence</td>
<td>Quantities of magnesium/Magnox metal, shape data and C-14 data from 2007 DI [M3] Corrosion rates from [M5]</td>
<td>Separated in 2012 assessment, because of water availability Assumes high pH Assume no additional corrosion until emplacement</td>
</tr>
<tr>
<td>Generation</td>
<td>Reactive metals – Magnox</td>
<td>Bulk gas from Magnox</td>
<td>Derived Inventory divides between spheres and plates Acute and chronic corrosion rates Temperature and chloride dependence</td>
<td>Quantities of Mg/Magnox metal and shape data from 2007 DI [M3] Corrosion rates from [M5] 1 mole of metallic Mg generates 1 mole of H₂</td>
<td></td>
</tr>
<tr>
<td>Generation</td>
<td>Reactive metals – Magnox</td>
<td>Gas generation – water availability</td>
<td>Some water is available initially Further water enters subsequently as a result of resaturation</td>
<td>Initial water availability comes from assumed conditioning factor of 4 and standard wasteform porosity (see Table 26) and initial saturation</td>
<td>For water entering subsequently – see Table 26. Note if water enters slowly corrosion may be limited, and extended in time</td>
</tr>
<tr>
<td>Generation</td>
<td>Reactive metals – Magnox</td>
<td>Gas generation – chloride availability</td>
<td>Assume zero during operations CI is assumed to enter as a result of resaturation This is then diluted with fraction of initial water remaining in the containers</td>
<td>Post-closure CI enters with groundwater, and it is assumed there is a threshold concentration for corrosion enhancement [M5]</td>
<td>If CI entry is slow or delayed – then the peak will be delayed If the CI does not reach the threshold value, the peak will be significantly lower</td>
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<tr>
<td>Model component</td>
<td>Aspect</td>
<td>Conceptual understanding</td>
<td>Model implementation (Assessment 2012)</td>
<td>Data (including references)</td>
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<tr>
<td>Generation</td>
<td>Reactive metals – Al</td>
<td>Gas generation</td>
<td>Water availability</td>
<td>Initial water availability comes from assumed conditioning factor of 4 (based on discussions with NDA RWMD) and standard wasteform porosity (see Table 26) and initial saturation</td>
<td>For water entering subsequently – see Table 26. Note if water enters slowly corrosion may be limited, and extended in time.</td>
</tr>
<tr>
<td>Model component</td>
<td>Aspect</td>
<td>Conceptual understanding</td>
<td>Model implementation (Assessment 2012)</td>
<td>Data (including references)</td>
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<tr>
<td>Generation</td>
<td>Reactive metals – U</td>
<td>Release of C-14</td>
<td>Assume 100% release as CH₄ (might be something else that is not CO₂) Uniformly distributed throughout metal 2007 DI [M3] divides (evenly) between spheres and plates Chronic corrosion rates: anaerobic, aerobic Temperature but no chloride dependence</td>
<td>Quantities of U metal, shape data and C-14 data from 2007 DI [M3] Corrosion rates from [M5]</td>
<td>Reasonably readily separable group of waste streams? Assumes high pH U corrodes throughout operational period (only needs humidity) - little U left post-closure (assuming there is either air or water available) Assume no additional corrosion until emplacement</td>
</tr>
<tr>
<td>Model component</td>
<td>Aspect</td>
<td>Conceptual understanding</td>
<td>Model implementation (Assessment 2012)</td>
<td>Data (including references)</td>
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<tr>
<td>Generation</td>
<td>Stainless steel, other ferrous metals and Zircaloy</td>
<td>Release of C-14</td>
<td>Assume 100% release as CH₄ (might be something else that is not CO₂) Uniformly distributed throughout metal 2007 DI [M3] divides mild steel between spheres and plates, stainless steel &amp; Zircaloy plates Various corrosion rates: anaerobic, aerobic Assume Zircaloy does not corrode aerobically Some temperature but no chloride dependence</td>
<td>Waste metals, shape data and C-14 data from 2007 DI [M3] Corrosion rates from [M4]</td>
<td>There is evidence that significant proportion of the release is to the solution phase, as a range of organic species and carbonate Surface layer on Zircaloy may be important</td>
</tr>
<tr>
<td>Generation</td>
<td>Stainless steel, other ferrous metals and Zircaloy</td>
<td>Bulk gas from wastes</td>
<td>2007 DI [M3] divides mild steel between spheres and plates, stainless steel &amp; Zircaloy are given as plates Various corrosion rates, anaerobic (gives H₂), aerobic gives Metal oxide (no bulk gas) Assume Zircaloy does not corrode aerobically Some temperature but no chloride dependence</td>
<td>Quantities of waste metals and shape data from 2007 DI [M3] Corrosion rates from [M4] 1 mole of metallic waste generates various moles of H₂</td>
<td>Hydrogen may be taken up by Zircaloy</td>
</tr>
<tr>
<td>Model component</td>
<td>Aspect</td>
<td>Conceptual understanding</td>
<td>Model implementation (Assessment 2012)</td>
<td>Data (including references)</td>
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<tr>
<td>Generation</td>
<td>Spent fuel</td>
<td>Depends on containment period, and rate of water ingress</td>
<td>Simple arguments if the container is long-lived&lt;br&gt;Much more complex with a shorter-lived container&lt;br&gt;Not included in the calculations published in this report</td>
<td>Corrosion data in [M6]&lt;br&gt;Note higher temperature and lower pH than ILW</td>
<td>Considered in [M6], but less well-developed than ILW approach because high integrity container would be used.&lt;br&gt;C-14 is primarily in cladding</td>
</tr>
<tr>
<td>Generation</td>
<td>HLW</td>
<td>Does not contain C-14</td>
<td>Not included in the calculations published in this report</td>
<td></td>
<td>Not in most recent inventory</td>
</tr>
<tr>
<td>Generation</td>
<td>GE Healthcare organic waste streams</td>
<td>Release of C-14 by microbial degradation</td>
<td>Included as small organic molecules&lt;br&gt;Simplified model of microbial degradation (the second half of the chemical/microbial model - see below)</td>
<td>Inventory - quantity of material and C-14 – from 2007 DI [M3]&lt;br&gt;Rate data not well defined [M7]</td>
<td>Nature of material less clear&lt;br&gt;One waste stream in 2007 assessment [M8], variant includes both streams&lt;br&gt;2012 gas assessment base case includes one stream&lt;br&gt;Indications that will be incinerated – so will not be an issue</td>
</tr>
<tr>
<td>Generation</td>
<td>Carbonate wastes</td>
<td>Assumed not to generate gas</td>
<td>Not included in the calculations published in this report</td>
<td></td>
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<tr>
<td>Model component</td>
<td>Aspect</td>
<td>Conceptual understanding</td>
<td>Model implementation (Assessment 2012)</td>
<td>Data (including references)</td>
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<tr>
<td>Generation</td>
<td>Bulk gas from mild steel in packaging (such as stillages)</td>
<td>Bulk gas from corrosion</td>
<td>Aerobic chronic and acute corrosion rate (not gas generating) Anaerobic chronic and acute corrosion rate Some temperature but no chloride dependence</td>
<td>2007 DI [M3] gives amount of packaging and shape data Corrosion rates from [M4]</td>
<td>Dependence on temperature, chemical conditions, type of radiation, mix of materials, and total dose are not taken into account G values for water reasonably well characterised, other materials less so Organic ion-exchange resins are included in those wastes that generate bulk gas from radiolysis</td>
</tr>
<tr>
<td>Generation</td>
<td>Radiolysis</td>
<td>Bulk gas from radiolysis</td>
<td>Decay and ingrowth of radionuclide inventory determines energy emission G values give gas generation per unit energy absorbed</td>
<td>Radionuclide inventory from 2007 DI [M3] G values from [M9] and [M10]</td>
<td></td>
</tr>
<tr>
<td>Generation</td>
<td>Cellulose degradation</td>
<td>Bulk gas from cellulose degradation</td>
<td>Chemical degradation followed by microbial degradation Simplified as first-order reactions</td>
<td>Quantities and types from 2007 DI [M3] Model data from [M7] Proportion of CO₂:CH₄ input by user (cautious values used)</td>
<td>Chemical step is rate limiting Microbial rate depends on conditions Rate data at high pH uncertain Spatial and temporal evolution of microbial populations are uncertain Only get CH₄ when no O₂, NO₃ or SO₄</td>
</tr>
<tr>
<td>Model component</td>
<td>Aspect</td>
<td>Conceptual understanding</td>
<td>Model implementation (Assessment 2012)</td>
<td>Data (including references)</td>
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</tr>
<tr>
<td>Generation</td>
<td>Water availability</td>
<td>Initial water in packages is determined by the saturation of grout. Following closure, there will be inflow of groundwater – the inflow rate will depend on the geological environment</td>
<td>Initial water available for gas generation processes in general Option of resaturation over a period Option to apply a rate directly Inflow divided proportionately between unsaturated voidage inside and outside packages</td>
<td>Assume 100% saturation of wasteform pore space initially Assume porosity of wasteform of 20% Tend currently to use resaturation over a period for higher strength rock Assume 75% saturation of backfill pore space initially Assume porosity of backfill of 55% Values – originally from Nirex 97 [M8], and have been re-used in GPA (03) update [M11] and are consistent with near-field status report [M12]</td>
<td>What is cautious for post-closure may not be cautious for operations, and vice versa</td>
</tr>
<tr>
<td>Generation</td>
<td>Oxygen availability</td>
<td>O₂ available during operational period, and is then consumed post-closure</td>
<td>Aerobic conditions in operational period. Oxygen consumption is modelled post-closure to determine switch to anaerobic</td>
<td>See water availability (above)</td>
<td>Possibility of anaerobic niches in operational period not currently considered For HSR, assume O₂ is flushed out by incoming water (rather than pressurising)</td>
</tr>
<tr>
<td>Generation</td>
<td>Temperature dependence</td>
<td>Increase in T on backfilling. Otherwise ambient temperature determined by depth for ILW SF hotter</td>
<td>T profile imposed - determines corrosion rates</td>
<td>Temperature profile based on [M13, M14]</td>
<td>Likely to be updated after the 2012 assessment</td>
</tr>
<tr>
<td>Model component</td>
<td>Aspect</td>
<td>Conceptual understanding</td>
<td>Model implementation (Assessment 2012)</td>
<td>Data (including references)</td>
<td>Comments</td>
</tr>
<tr>
<td>-----------------</td>
<td>--------</td>
<td>--------------------------</td>
<td>---------------------------------------</td>
<td>-----------------------------</td>
<td>----------</td>
</tr>
<tr>
<td>Generation</td>
<td>Emplacement strategy</td>
<td>Gradual emplacement</td>
<td>Currently emplace gradually but in discrete fractions</td>
<td>ILW split into 50 fractions over 50 years (between assumed opening of GDF and latest arisings)</td>
<td>Evenly split – we do not take account of when waste arises</td>
</tr>
<tr>
<td>Generation</td>
<td>Treatment of future arisings</td>
<td>Waste arises at different times, but this is not easy to represent in SMOGG</td>
<td>Take radionuclide inventory at 2090 and back decay to 2040</td>
<td>2007 DI [M3]</td>
<td>SMOGG requires an inventory at a single date</td>
</tr>
<tr>
<td>Generation</td>
<td>Heterogeneity</td>
<td>Occurs at different levels (within a package, within a waste stream but between packages, and between vaults)</td>
<td>SMOGG is a one box model, which can be split into a number of discrete one box models representing e.g. groups of waste streams or individual vaults, etc.</td>
<td></td>
<td>Mg and Al have been treated separately to date, otherwise homogeneous treatment Some variants can be considered without re-running SMOGG</td>
</tr>
</tbody>
</table>
### Table 28  Modelling basis – migration through engineered materials

<table>
<thead>
<tr>
<th>Model component</th>
<th>Aspect</th>
<th>Conceptual understanding</th>
<th>Model implementation</th>
<th>Data (including references)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Near-field migration &amp; reaction with cementitious materials</td>
<td>Carbonation</td>
<td>CO₂ mopped up by cementitious materials</td>
<td>In theory can lose a fraction, in practice it is assumed that all $^{14}$CO₂ is lost to carbonation It is also assumed that CO₂ is lost to carbonation in preference to reaction with H₂ leading to CH₄</td>
<td>Experimental measurements of carbonation capacity AEAT/Serco work on carbonation [M15, M16, M17] UCL work [M18]</td>
<td>Potentially affects the bulk gas Note may get CO₂ from graphite etc. – however, recent experiments do not see significant $^{14}$CO₂ in the gas phase in alkaline environments Note assumption that CO₂ is lost to carbonation in preference to reaction with H₂ leading to CH₄</td>
</tr>
<tr>
<td>Near-field migration &amp; reaction with cementitious materials</td>
<td>Amount of backfill</td>
<td>Sufficient backfill to mop up CO₂</td>
<td>Carbon dioxide is assumed to dissolve in the near-field porewater and react with calcium hydroxide or CSH phases in the backfill to form calcium carbonate</td>
<td></td>
<td>Also future NNL work</td>
</tr>
<tr>
<td>Model component</td>
<td>Aspect</td>
<td>Conceptual understanding</td>
<td>Model implementation</td>
<td>Data (including references)</td>
<td>Comments</td>
</tr>
<tr>
<td>-----------------</td>
<td>--------</td>
<td>-------------------------</td>
<td>---------------------</td>
<td>-----------------------------</td>
<td>----------</td>
</tr>
<tr>
<td>Geosphere</td>
<td>Geological environment</td>
<td>Different for different environments</td>
<td>2012 assessment focuses on HSR</td>
<td>5 yr resaturation (historical) Oxygen flushed out (modelling basis)</td>
<td>Affects the movement of fluids (water in, and gas out) Other environments discussed in Hoch and Swift [M19]</td>
</tr>
<tr>
<td>Geosphere</td>
<td>HSR</td>
<td>ILW resaturation</td>
<td>Range of models confirm resaturation is rapid – the time is a function of host rock permeability</td>
<td></td>
<td>If a low permeability liner is used, resaturation will occur over an extended period</td>
</tr>
<tr>
<td>Geosphere</td>
<td>HSR</td>
<td>HLW/SF resaturation</td>
<td>Long-lived containers will be used, but bentonite (if used) will delay resaturation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Geosphere</td>
<td>HSR</td>
<td>Travel time biosphere</td>
<td>Once the geology of the site has been identified, two-phase flow modelling can be undertaken</td>
<td></td>
<td>The relative permeabilities will depend on the site</td>
</tr>
<tr>
<td>Geosphere</td>
<td>HSR</td>
<td>Release area in the biosphere</td>
<td>Once the geology of the site has been identified, two-phase flow modelling can be undertaken</td>
<td>Biosphere models currently use a cautious area of $10^4 m^2$ [M20]</td>
<td>Evidence from the Nirex work at Reskajeage suggests it may be difficult to calculate the release area (and its geometry)</td>
</tr>
<tr>
<td>Geosphere</td>
<td>LSSR</td>
<td>Resaturation of the GDF</td>
<td>Once the geology of the site has been identified, coupled multi-phase flow modelling will be required, including coupling gas generation to water ingress</td>
<td></td>
<td>Site dependent</td>
</tr>
<tr>
<td>Geosphere</td>
<td>LSSR</td>
<td>Travel time</td>
<td>Once the geology of the site has been identified, multi-phase flow modelling will be undertaken; longer travel times are expected</td>
<td></td>
<td>GDF structures could provide a preferential pathway</td>
</tr>
<tr>
<td>Geosphere</td>
<td>Evaporite</td>
<td></td>
<td>Dry conditions are expected, which will limit gas production</td>
<td></td>
<td>If gas is produced, a limited amount may migrate into the host rock, which would then be a significant barrier to gas. Mechanical process, e.g. rock creep, comes into play</td>
</tr>
<tr>
<td>Model component</td>
<td>Aspect</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----------------</td>
<td>--------</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biosphere - OESA model</td>
<td>EA methodology</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biosphere - PCSA model</td>
<td>Update of GPA (03) – CH4 released to sub-surface zone and taken up by plants</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model component</td>
<td>Conceptual understanding</td>
<td>Model implementation</td>
<td>Data (including references)</td>
<td>Comments</td>
<td></td>
</tr>
<tr>
<td>-----------------</td>
<td>------------------------</td>
<td>---------------------</td>
<td>-----------------------------</td>
<td>----------</td>
<td></td>
</tr>
<tr>
<td>Biosphere - OESA model</td>
<td>EA methodology</td>
<td>EA methodology</td>
<td>15m stack height</td>
<td>Uses cautious EA methodology – scope for making less cautious</td>
<td></td>
</tr>
<tr>
<td>Biosphere - PCSA model</td>
<td>Recent developments building on experimental programme and LLWR work, building on the earlier RIMERS work [M22]</td>
<td>Recent LLWR work [M20]</td>
<td>For further details see Section 8 [M20]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
References for the modelling basis tables:


M2 B.J. Handy, *Experimental Study of C 14 and H 3 Release from Irradiated Graphite Spigot Samples in Alkaline Solutions*, NNC Report 11996/TR/001, Issue 1, 2006. [26]


9.2 Potential consequences of carbon-14 containing gas generation

Assessments of the potential environmental consequences of carbon-14 bearing gas generation from a GDF are discussed in the Operational Environmental Safety Assessment (OESA) [105] and the Post-closure Safety Assessment (PCSA) [104].

The OESA evaluates the environmental consequences of discharges (liquid effluents, gaseous and solid discharges) during the operational period. This complements the Operational Safety Case, which considers the radiological safety consequences during the operational period. The operational period covers waste emplacement, storage in open vaults, and the period of backfilling currently taken to be with a cementitious grout. In the published OESA [105], tritium, radon and carbon-14 are the most significant in terms of gaseous discharges.

The PCSA considers environmental safety following closure. These assessments are based on previous gas generation assessment results, so it is appropriate to update these based on the current gas generation assessment summarised in Section 5.1. In addition, a breakdown by waste group of the current assessment results for carbon-14 containing gas generation is presented in Section 5.2. To aid understanding of the importance of each waste group in terms of carbon-14 release, it is useful to consider the contributions to the consequences for each waste group. This analysis of the potential consequences of carbon-14 containing gas generation is considered in turn for the operational and post-closure periods of a GDF below.

Operational period

A methodology for determining off-site doses from radioactive gas generation during the operational period of a GDF is described in the OESA [105]. It uses an Environment Agency methodology, with the release assumed to be from a discharge stack of height 15 m. It is recognised that this methodology includes several simplifications or cautious assumptions, and improvements to these are considered in Section 9.4. However, for simplicity, the methodology previously used is used here to determine doses based on the current gas generation assessment results.

Doses are calculated by multiplying carbon-14 containing gas generation rates by a factor of 0.018 mSv a⁻¹ per (TBq a⁻¹). This is calculated from effective dose per unit release factors combined with scaling factors for food, external and inhalation exposure pathways [105]. Doses, broken down by source waste group, based on the maximum carbon-14 containing gas generation rates for the main operational period and for the backfilling period (during which the total rate is higher) are presented in Table 31. These are based on the calculations reported in Section 5.1.
### Table 31 Calculated effective dose rates from off-site discharge of carbon-14 to the local resident family receptor group

<table>
<thead>
<tr>
<th>Waste group</th>
<th>Operational period (2040-2140)</th>
<th></th>
<th>Backfilling period (2140-2150)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum discharge (TBq a(^{-1}))</td>
<td>Dose rate (mSv a(^{-1}))</td>
<td>Maximum discharge (TBq a(^{-1}))</td>
<td>Dose rate (mSv a(^{-1}))</td>
</tr>
<tr>
<td>UILW core graphite</td>
<td>7.53×10(^{-5})</td>
<td>1.35×10(^{-8})</td>
<td>7.29×10(^{-5})</td>
<td>1.31×10(^{-6})</td>
</tr>
<tr>
<td>Magnox fuel element graphite</td>
<td>2.92×10(^{-5})</td>
<td>5.25×10(^{-7})</td>
<td>2.83×10(^{-5})</td>
<td>5.09×10(^{-7})</td>
</tr>
<tr>
<td>AGR fuel element graphite</td>
<td>2.35×10(^{-4})</td>
<td>4.23×10(^{-6})</td>
<td>2.28×10(^{-4})</td>
<td>4.10×10(^{-6})</td>
</tr>
<tr>
<td>AGR SS fuel cladding</td>
<td>5.14×10(^{-3})</td>
<td>9.26×10(^{-5})</td>
<td>9.44×10(^{-3})</td>
<td>1.70×10(^{-4})</td>
</tr>
<tr>
<td>AGR SS assembly components</td>
<td>1.05×10(^{-2})</td>
<td>1.90×10(^{-4})</td>
<td>1.93×10(^{-2})</td>
<td>3.48×10(^{-4})</td>
</tr>
<tr>
<td>UILW steel decommissioning waste</td>
<td>1.15×10(^{-2})</td>
<td>2.06×10(^{-4})</td>
<td>1.77×10(^{-2})</td>
<td>3.19×10(^{-4})</td>
</tr>
<tr>
<td>UILW reactive metals</td>
<td>2.74×10(^{-1})</td>
<td>4.93×10(^{-3})</td>
<td>5.98×10(^{-1})</td>
<td>1.08×10(^{-2})</td>
</tr>
<tr>
<td>GE Healthcare organic waste(^{27})</td>
<td>9.30×10(^{-4})</td>
<td>1.67×10(^{-5})</td>
<td>4.33×10(^{-4})</td>
<td>7.79×10(^{-6})</td>
</tr>
<tr>
<td>Other UILW</td>
<td>3.01×10(^{-4})</td>
<td>5.42×10(^{-6})</td>
<td>5.52×10(^{-4})</td>
<td>9.94×10(^{-6})</td>
</tr>
<tr>
<td>SILW core graphite</td>
<td>2.98×10(^{-2})</td>
<td>5.36×10(^{-4})</td>
<td>2.89×10(^{-2})</td>
<td>5.20×10(^{-4})</td>
</tr>
<tr>
<td>SILW steel decommissioning waste</td>
<td>2.59×10(^{-3})</td>
<td>4.66×10(^{-5})</td>
<td>3.37×10(^{-3})</td>
<td>6.06×10(^{-5})</td>
</tr>
<tr>
<td>Other SILW</td>
<td>2.06×10(^{-6})</td>
<td>3.71×10(^{-8})</td>
<td>4.99×10(^{-6})</td>
<td>8.98×10(^{-8})</td>
</tr>
<tr>
<td>Total Carbon-14</td>
<td>3.35×10(^{-1})</td>
<td>6.03×10(^{-3})</td>
<td>6.78×10(^{-1})</td>
<td>1.22×10(^{-2})</td>
</tr>
</tbody>
</table>

The total contribution to effective dose rate to members of the public from carbon-14 containing gas generation for the operational period is calculated to be 0.006 mSv a\(^{-1}\). This is predominantly due to corrosion of reactive metals, but also to release from SILW core graphite and corrosion of UILW steels. The contribution to effective dose rate from carbon-14 during the operational period is below the effective dose limit for members of the public of 1 mSv a\(^{-1}\). It is also below the maximum effective dose rate to individuals which may result from the discharges from any single site, stated in the Environmental Permitting Regulations 2010, of 0.5 mSv a\(^{-1}\), and below the maximum effective dose rate constraint to members of the public from a new facility of 0.15 mSv a\(^{-1}\) adopted by NDA RWMD. Lastly, it is below the design target of 0.01 mSv a\(^{-1}\). However, it is a substantial fraction of the design target, so, allowing for doses from other radionuclides, the total dose is likely to exceed the design target. In particular, it is noted that the previously calculated dose from radon-222 during this period was significant.

The total contribution to effective dose rate to members of the public from carbon-14 bearing gas generation for the backfilling period is calculated to be 0.012 mSv a\(^{-1}\). This is again predominantly due to corrosion of reactive metals. The contribution from carbon-14 during the backfilling period is below the effective dose limit for members of the public of 1 mSv a\(^{-1}\). It is also below the maximum effective dose rate to individuals which may result from the discharges from any single site, stated in the Environmental Permitting Regulations 2010, of 0.5 mSv a\(^{-1}\), and below the maximum value of effective dose rate constraint.

\(^{27}\) GE Healthcare organic waste is not expected to be disposed in its current form, so would not be expected to generate C-14. However, generation of C-14 from this waste is included in the most recent gas assessment, so is also included here for consistency.
constraint to members of the public from a new facility of 0.15 mSv a⁻¹ adopted by
NDA RWMD. However, this assessment presents an effective dose rate to members of the
public from carbon-14 during the backfilling period that exceeds the design target of
0.01 mSv a⁻¹.

There is scope for reducing the calculated impact of carbon-14 during the operational
period, by consideration of the inventory, the amounts of gas generated and by revising
aspects of the assessment methodology. These aspects will be taken forward in Phase 2
(see Section 9.4).

Post-closure period
To calculate dose (and associated risk) from radioactive gas release during the post-
closure period of a GDF, both the rate of radioactive gas generation in the GDF and its
migration through the geosphere need to be taken into account. If a rate of release at the
surface is calculated, factors that represent the interactions of the gas in the biosphere can
be applied to calculate potential dose and risk. In Section 8, a value for this factor for
carbon-14 of 0.009 Sv a⁻¹ per (Bq m⁻² s⁻¹) has been determined based on the most up-to-
date information available.

To consider dose generically, in the absence of specific data for the geosphere, a simplified
approach can be taken in which the gas generated in the GDF is assumed to be
immediately released at the surface. The conversion to dose requires a flux at the surface.
The minimum area to which the calculation of dose can be applied is taken to be 10⁴ m² (as
described in Section 8). Applying these assumptions to the current gas generation
assessment results, (ignoring any potential contribution from the geosphere) annual
effective doses from carbon-14 have been calculated.

Table 32 presents doses and associated risks, broken down by source waste group, based
on the maximum carbon-14 containing gas generation rates for the early post-closure
period (during which the total rate is higher than at other times).

Table 33 presents doses and associated risks, broken down by source waste group, based
on the maximum carbon-14 bearing gas generation rates in the longer term post-closure
period. Again, these are based on the calculations reported in Section 5.1.

Table 32 and Table 33 show that, using the cautious assumptions described above, the
potential doses from carbon-14 containing gas during the post-closure period, and
particularly during the early post-closure period, are potentially substantial. The calculated
total annual effective doses correspond to annual risks of 3×10⁻² during the early post-
closure period and 9×10⁻⁵ at longer times, compared with the regulatory risk guidance level
of 10⁻⁶ [106].

During the early post-closure period, the dominant contribution to the dose and risk arises
from the corrosion of reactive metals, but the contributions from a number of other waste
groups are also individually calculated to be above the risk guidance level. In the longer
term, over half the contribution to the dose and risk is due to release of carbon-14 from
core graphite, and the contributions from GE Healthcare organic waste and UILW steels
are also individually calculated to be above the risk guidance level. The GE Healthcare
organic waste is included in the assessment, but is not expected to be disposed of in its
current form. Therefore it is reasonable to discount this contribution.
Table 32  Calculated annual effective doses and risks from direct release of carbon-14 containing gas to the biosphere\(^{28}\) for the GDF early post-closure period

<table>
<thead>
<tr>
<th>Waste group</th>
<th>Maximum generation rate (TBq a(^{-1}))</th>
<th>Annual Effective Dose (Sv)</th>
<th>Annual Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>UILW core graphite</td>
<td>7.25×10(^{-5})</td>
<td>2.07×10(^{-6})</td>
<td>1.24×10(^{-7})</td>
</tr>
<tr>
<td>Magnox fuel element graphite</td>
<td>2.81×10(^{-5})</td>
<td>8.01×10(^{-7})</td>
<td>4.81×10(^{-8})</td>
</tr>
<tr>
<td>AGR fuel element graphite</td>
<td>2.27×10(^{-4})</td>
<td>6.46×10(^{-6})</td>
<td>3.88×10(^{-7})</td>
</tr>
<tr>
<td>AGR SS fuel cladding</td>
<td>9.43×10(^{-3})</td>
<td>2.69×10(^{-4})</td>
<td>1.61×10(^{-5})</td>
</tr>
<tr>
<td>AGR SS assembly components</td>
<td>1.93×10(^{-2})</td>
<td>5.51×10(^{-4})</td>
<td>3.30×10(^{-5})</td>
</tr>
<tr>
<td>UILW steel decommissioning waste</td>
<td>2.74×10(^{-2})</td>
<td>7.82×10(^{-4})</td>
<td>4.69×10(^{-5})</td>
</tr>
<tr>
<td>UILW reactive metals</td>
<td>1.57×10(^{1})</td>
<td>4.47×10(^{-1})</td>
<td>2.68×10(^{-2})</td>
</tr>
<tr>
<td>\textit{GE Healthcare organic waste}(^{29})</td>
<td>2.14×10(^{-2})</td>
<td>6.11×10(^{-4})</td>
<td>3.67×10(^{-5})</td>
</tr>
<tr>
<td>Other UILW</td>
<td>1.46×10(^{-3})</td>
<td>4.16×10(^{-5})</td>
<td>2.50×10(^{-6})</td>
</tr>
<tr>
<td>SILW core graphite</td>
<td>2.87×10(^{-2})</td>
<td>8.19×10(^{-4})</td>
<td>4.91×10(^{-5})</td>
</tr>
<tr>
<td>SILW steel decommissioning waste</td>
<td>9.66×10(^{-3})</td>
<td>2.75×10(^{-4})</td>
<td>1.65×10(^{-5})</td>
</tr>
<tr>
<td>Other SILW</td>
<td>1.02×10(^{-4})</td>
<td>2.91×10(^{-6})</td>
<td>1.75×10(^{-7})</td>
</tr>
<tr>
<td>Total Carbon-14</td>
<td>1.58×10(^{1})</td>
<td>4.50×10(^{-1})</td>
<td>2.70×10(^{-2})</td>
</tr>
</tbody>
</table>

Overall, these results show that, given the current modelling basis, the risk target is exceeded. However, there is considerable scope for reducing the calculated risk, by improving the inventory, by developing improved models of gas generation, or by taking into account the effect of the geosphere in controlling the release of carbon-14 bearing gas to the biosphere. Work in Phase 2 of the project will address the basis of the models and the data used therein.

\(^{28}\) Note that these calculations ignore any contribution from the geosphere in retarding or preventing gas from reaching the surface.

\(^{29}\) GE Healthcare organic waste is not expected to be disposed in its current form, so would not be expected to generate carbon-14. However, generation of C-14 from this waste is currently included in the gas assessment, so is also included here for consistency.
### Table 33 Calculated annual effective doses and risks from release of carbon-14 containing gas to the biosphere in the longer term post-closure

<table>
<thead>
<tr>
<th>Waste group</th>
<th>Maximum generation rate (TBq a⁻¹)</th>
<th>Annual Effective Dose (Sv)</th>
<th>Annual Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>UILW core graphite</td>
<td>7.12×10⁻⁵</td>
<td>2.03×10⁻⁶</td>
<td>1.22×10⁻⁷</td>
</tr>
<tr>
<td>Magnox fuel element graphite</td>
<td>2.76×10⁻⁵</td>
<td>7.87×10⁻⁷</td>
<td>4.72×10⁻⁸</td>
</tr>
<tr>
<td>AGR fuel element graphite</td>
<td>2.22×10⁻⁴</td>
<td>6.34×10⁻⁶</td>
<td>3.81×10⁻⁷</td>
</tr>
<tr>
<td>AGR SS fuel cladding</td>
<td>9.37×10⁻⁴</td>
<td>2.67×10⁻⁵</td>
<td>1.60×10⁻⁶</td>
</tr>
<tr>
<td>AGR SS assembly components</td>
<td>1.92×10⁻³</td>
<td>5.47×10⁻⁵</td>
<td>3.28×10⁻⁶</td>
</tr>
<tr>
<td>UILW steel decommissioning waste</td>
<td>1.25×10⁻³</td>
<td>3.56×10⁻⁵</td>
<td>2.14×10⁻⁶</td>
</tr>
<tr>
<td>UILW reactive metals</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>GE Healthcare organic waste³⁰</td>
<td>1.98×10⁻²</td>
<td>5.63×10⁻⁴</td>
<td>3.38×10⁻⁵</td>
</tr>
<tr>
<td>Other UILW</td>
<td>1.53×10⁻⁴</td>
<td>4.38×10⁻⁶</td>
<td>2.63×10⁻⁷</td>
</tr>
<tr>
<td>SILW core graphite</td>
<td>2.82×10⁻²</td>
<td>8.03×10⁻⁴</td>
<td>4.82×10⁻⁵</td>
</tr>
<tr>
<td>SILW steel decommissioning waste</td>
<td>1.19×10⁻⁴</td>
<td>3.40×10⁻⁶</td>
<td>2.04×10⁻⁷</td>
</tr>
<tr>
<td>Other SILW</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Total Carbon-14</td>
<td>5.26×10⁻²</td>
<td>1.50×10⁻³</td>
<td>9.00×10⁻⁵</td>
</tr>
</tbody>
</table>

### 9.3 Scoping model

As part of the Phase 1 of the IPT, consideration was given to whether it would be beneficial to have a simple scoping modelling tool. It was agreed that it would be helpful to have a scoping tool to carry out quantitative assessments to determine the effect of alternative options, to implement changes to the modelling basis (including the inventory) and to carry out simple assessments of the impact of uncertainty in data values on the calculated risk. (A fuller understanding of the impact of uncertainty would be developed using a total system model, which is discussed below.)

Five possibilities were identified:

- A simple spreadsheet tool;
- SMOGG, with simple biosphere models included for the operational and post-closure phases;
- SMOGG with a “wrapper” specifically designed to make changes to input data easier to implement;
- MAGGAS – a code similar to SMOGG developed specifically by Magnox and other site licence companies [107];

³⁰ GE Healthcare organic waste is not expected to be disposed in its current form, so would not be expected to generate carbon-14. However, generation of carbon-14 from this waste is currently included in the gas assessment, so is also included here for consistency.
A GoldSim model, including simple geosphere & biosphere models; GoldSim is currently used for post-closure assessments of the groundwater pathway [104].

It was agreed that a solution based on SMOGG was preferable, as this is already tailored to NDA RWMD’s requirements (but noting that other models with similar capability exist and could also be used for this task). It was considered that the simple spreadsheet would be over-simplified, and would evolve into SMOGG as the required functionality was added. It was felt that the option of using GoldSim was complementary, and should form the basis of a total system model, as discussed in Section 9.5 below. The use of a wrapper to make inputs easier is considered desirable, but it is recognised that this might not be practicable because of the complexities of the data required to be input.

9.4 OESA

The approach adopted in the OESA [105] was to use gas generation rates during the operational phase taken from the Update of the GPA (03) [10] through the Gas Status Report [5], and the consequent doses were calculated using the Environment Agency’s methodology as detailed in [108, 109].

The main path for release from aerial discharges from the underground facilities would be through the GDF ventilation system, out through a discharge stack. The discharge stack height and location would be designed to meet with the requirements specified in [110]. Doses were calculated using the average and peak gas release rates for discharges from a 15m stack height for the operational period to the local resident family receptor group [105], which is assumed:

- to be located 100 metres from a discharge point of a GDF; and
- to consume food grown at 500 metres from a GDF.

The results described in Section 9.2 show the calculated values are slightly above the design target of 0.01 mSv a⁻¹. The EA’s approach is based on a general application of PC-CREAM that is not tailored to the particular nature of the release being considered. The data on which this is based and the adopted methodology could be revised so that it is a better representation of the discharge pathway considered for the GDF. The EA’s methodology is intended to be applied to the release of ¹⁴CO₂. It is expected that discharges of ¹⁴CH₄ would give lower doses, as there would be substantially less uptake of carbon-14 by plants.

It is proposed that a task would be undertaken as part of Phase 2 to develop a more appropriate methodology. This work would take into account previous (Nirex-funded) work on the release of carbon-14 into the environment [111].

9.5 Total system model

The approach adopted in the current assessments has been described above in Sections 9.1 and 9.2. This approach is different from the one used by NDA RWMD for assessments of the groundwater pathway, where probabilistic methods are used to provide a structured view of the significance of data uncertainty [104]. In that approach, it is recognised that parameter values are not known definitively, and so are represented by probability distribution functions.

There are two implications of this: first different approaches have been adopted for the two pathways, and secondly it is difficult to develop an overall view of the performance of the system as far as carbon-14 is concerned.
As part of Phase 1 of the carbon-14 IPT, consideration has been given to the function, and implementation, of a total system model for the gas pathway analogous to the total system model for the groundwater pathway.

Essentially the objectives of the total system modelling approach for the gas pathway are:

- to aid, and communicate, system understanding for the assessment of GDF-derived gases in the post-closure phase, with a focus on understanding the key controls on performance measures of the system;
- to provide an appropriate consideration of uncertainty; and
- to provide focus and guidance for a needs-driven Research Programme which, in turn, can be used to update the safety case iteratively.

The total system model will be of greater use if it is developed to allow the implications of different concept design and waste emplacement options to be explored. However, modelling gas generation and its interactions with the environment in a geological disposal system is highly dependent on the nature of the host rock and its overlying formations (and features) and is potentially very complex and non-linear. NDA RWMD’s Gas Status report [5] states: “This use of illustrative calculations is consistent with the advice of the regulator that ‘we should focus on identifying key gas transport questions that need to be addressed to support a site selection and characterisation process’ rather than ‘detailed modelling for any particular geologic formation’” – quoting [19].

The behaviour and generation of GDF-derived gas in different host rock formations is potentially quite variable and may require different modelling approaches (and tools) in order to assess the potential for gas generation and migration; the appropriate approach for higher strength rock might be expected to be rather different from that for lower strength sedimentary rock.

In the absence of site-specific information, a simple representation of the system may be justifiable, particularly for higher strength rock. For instance, a simple, but cautious treatment of the geosphere can be taken by assuming instant release of a free gas phase into the biosphere, or by using a given delay time before any gas is released. Therefore, emphasis, at this stage in NDA RWMD’s programme, is being placed on developing system understanding of the gas source term. Understanding of the important processes for gas generation in a higher strength host rock, where water can be assumed to be readily available (for gas generation purposes), is well developed. As discussed already in this report, NDA RWMD has developed a simple component-level model of gas generation in a higher strength host rock, called SMOGG. Although SMOGG has been used to assess the potential gas generation rates from ILW wastes, NDA RWMD would like to understand better the key processes viewed in the light of the associated parameter uncertainty. This, in turn, will allow NDA RWMD to focus on those processes that are found to be key controls on gas generation and, in particular, on carbon-14 containing gases. As a first step in developing this approach, and in parallel with other tasks in Phase 2, a focused review of the uncertainty in SMOGG input parameters could be undertaken. This could then be followed by associated probabilistic assessment studies, including sensitivity calculations and the interpretation of the results. The uncertainties in the generation model could be set in the context of other uncertainties in our understanding of the system. The total system model approach could also be used to develop an integrated view of the groundwater and gas pathways. It is expected that the speciation of carbon-14 may be important [112] in determining the relationship between carbon-14 in the gas, dissolved phases and solid phases. Careful consideration should be given as to how this should be incorporated.

The first step would be to develop an approach to the total system model for carbon-14, which may include groundwater as well as gas, in higher strength rocks, based on
consideration of uncertainty and the modelling basis spreadsheet (see Section 9.1 above). It is expected that this would be incorporated into a GoldSim model, as is currently used for post-closure assessments of the groundwater pathway [104].

For other host rock settings, the approach outlined above may need to be adapted substantially. For example, to simulate gas production in a clay host rock setting a two-phase model that couples together waste evolution and heat / gas production, water inflow to a GDF, gas pressurisation within the facility and gas migration away from the facility may be required to represent the coupled processes, building on understanding being developed as part of the research programme. The approach to modelling gas generation and migration from a GDF in evaporite is similar to the approach in lower strength sedimentary rock, except that creep is a more important process that needs to be taken into account; in addition, the lack of water availability is expected to be important for an evaporite setting. The Gas Status report [5] references more detailed studies to illustrate the behaviour of gas in such systems. However, again it may be practicable to develop some simple representations of these systems [81, 82, 113].

This process- and component-level understanding should be evaluated by the assessments team to determine if abstraction of the information to a total system model is informative and in order to develop further NDA RWMD’s understanding of such systems in collaboration with other members of the IPT. It is suggested that “stylised case studies” to investigate specific aspects of coupled systems are considered purely for the purposes of internal development and to enhance NDA RWMD’s existing capability. For example, for lower strength rock types NDA RWMD could investigate setting up simple cases based on the more detailed modelling already undertaken, looking to represent: a limited-water-availability case; the sensitivity of various gas generation rates to gas entry pressures; pressure increases where permeability is low; and so on. This may help to show how system behaviour (in particular situations) is sensitive to certain aspects of the system and how to best represent these sensitivities. This knowledge may then be useful when considering how to represent more complicated systems with uncertain processes and data.

The approach of developing a total system model would complement other approaches in terms of quantifying the implications of uncertainty, such as the use of SMOGG. It would also support the work in determining the role played by different barriers in the system, and inform the requirements to develop alternative options. It is proposed that the development of a total system model be explored in Phase 2 of the work of the IPT, with initial developments considering higher strength rocks.

9.6 Work for Phase 2

In Phase 2 we will:

- Keep the modelling basis up to date, in the light of improved models and data;
- Develop the OESA methodology so that it better represents the envisaged discharges;
- Develop total system model for the post-closure phase in higher strength rocks, to provide a structured understanding of the implications of uncertainty;
- Update the calculations at key points of the programme.
10 Alternative treatment, packaging, design and disposal options

In order to develop a holistic approach to carbon-14 management, we have considered whether there are alternative options for the treatment, packaging, design and disposal of the key waste types.

In Phase 1 we have identified a number of potential options, and considered whether the benefits merit further consideration in the light of the results of the calculations described in Sections 5.2 and 9.2.

In Phase 2, there will be a small number of tasks to consider alternative packaging, design and disposal options. The focus of this work will be to consider segregation of ILW core graphite and to give further consideration to alternative options for irradiated reactive metals.

The objectives of this area are:

- To inform strategic decisions on disposal options for specific problematic waste types and inform packaging decisions for specific waste streams;
- To develop options for an integrated waste management approach to disposal of these wastes; and
- To establish whether mitigation measures or design solutions are required.

This work complements that in other areas of the project, which focus on the current “Baseline” for the management of the wastes. In those areas we are seeking to refine our understanding of important processes and data, and to reflect this improved understanding in the models. The focus of this Section is to identify alternative approaches that could be adopted, that could result in a reduction in the calculated radiological consequence from carbon-14 in a GDF. The work reported in this section is a simple desk study and does not give full consideration of alternative management approaches.

The work in Phase 1 of the project has been concerned with:

- Developing a list of viable alternative treatment, packaging, design and disposal options worthy of qualitative evaluation;
- To frame a number of questions to feed in to other work packages;
- To identify suitable tools and quantitative approaches for the evaluation of the viable alternative treatment, packaging, design and disposal options; and
- To develop the specification for a bid task in Phase 2 of the work of this IPT.

The structure of this section is as follows. To help frame the questions, the waste streams with similar characteristics are grouped together; this is described in Section 10.1. The alternative options for these groups of waste streams are described in Section 10.2. The implications of the various options are considered in Section 10.3, in the light of the gas generation modelling described in Section 5.

10.1 Grouping of waste streams

The first step was to separate the inventory into a number of separate groups of waste streams that could be considered separately. This focused on those wastes with a
significant inventory of carbon-14 that could potentially be managed in a distinct manner. It also took into account their physical and chemical characteristics.

The groups identified were as follows:

- **Graphite:**
  - ILW core graphite;
  - ILW Magnox fuel element graphite;
  - ILW AGR fuel element graphite;

- **Steels, etc.:**
  - ILW AGR stainless steel fuel cladding;
  - ILW AGR stainless steel assembly components;
  - ILW stainless steel and other ferrous metals, reactor decommissioning wastes;

- **ILW reactive metals;**

- **Other wastes that may be significant:**
  - ILW organics, ILW carbonates, spent fuel, ion-exchange resins, HLW, Al nitride cartridges, DNLEU, separated Pu. Sellafield miscellaneous wastes.

10.2 Alternative options

Having identified a number of groups, the focus was on examining whether there are any alternative treatment, packaging, design and disposal options that could be considered. These include:

- Segregation of wastes by emplacing them in separate vaults; such vaults could potentially utilise different geological horizons;
- Long-lived containers or containers that limit water flow;
- Surface treatments to remove surface contamination;
- Thermal treatment to change waste or wasteform properties, including melting;
- Treatments to oxidise or dissolve wastes;
- Long-lived or alternative wasteforms that limit water flow (e.g. polymeric wasteforms);
- Hydraulic cages that divert the flowing groundwater away from the emplaced wastes.

The “AND” approach was used to develop a number of questions, to support consideration of the various options. These questions focused on the areas of:

- Inventory;
- Carbon-14 gas generation;
- Bulk gas generation;
- Migration through engineered materials; and
- Migration through the geosphere.

The biosphere was considered to be outside the scope of alternative options.

With regard to the **inventory**, the questions included:
• Do we have confidence in the inventory?
• Could the inventory of carbon-14 be reduced by surface treatment or other processes, and if it were reduced, where would it go? (Recognising that it is important to consider the impact of such treatments in the round and some treatment processes could result in atmospheric release of carbon-14.)

With regard to **carbon-14 gas generation**, the questions included:

• Would excluding water reduce the generation rate?
• Does the release depend on the groundwater chemistry? What role does chloride in groundwater play, and could it be excluded?
• What are the conditions required to minimise the release? Can such conditions be achieved through design or mitigation measures?
• Are we getting an accurate picture from the modelling, are the important processes represented appropriately?

With regard to **bulk gas generation**, the questions included:

• How much bulk gas is associated with conventional packaging if segregated vaults were to be adopted?
• Does the segregated waste need packaging?
• If segregation of, for example, graphite were adopted, how far would the vaults need to be separated?

With regard to **migration through engineered materials**, the questions included:

• Does cement yield any benefit for particular waste streams?
• Would bentonite serve a beneficial purpose?

With regard to the **migration through the geosphere**, the questions included:

• Is there a gas pathway if the wastes are segregated?
• Would a hydraulic cage help?
• Are there issues for either the gas or groundwater pathways if the wastes are emplaced in shallower vaults?

In the tables presented, one of “Yes”, “No” or “Maybe” is given to indicate whether this option is a possible design measure that would reduce the impact of carbon-14. This is not intended to be a definitive judgment, rather an initial indication. Further work would be required were such design measures to be taken forward. The tables were constructed in a workshop, with relevant staff from NDA RWMD and other members of the IPT.

**Graphite**

The current baseline for graphite wastes is to manage them through geological disposal [114]. Reference [114] lists other credible options as including near-surface disposal, either at LLWR or using a separate disposal facility (or facilities), and treatment to remove part of the radionuclide inventory, prior to reuse or release of the graphite. Reference [114] also reports the results of a review to determine whether there are opportunities to optimise the baseline option for the management of core graphite. The main features of the more optimal baseline recommended include:

• Most core graphite waste streams are likely to be acceptable for disposal without encapsulation; and
A range of packaging options are potentially suitable. Some degree of shielding is likely to be required for operational and transport safety, but provision of such shielding is not considered to be challenging.

Work on the geological disposal of graphite has been undertaken as part of the European Commission CARBOWASTE project. NDA RWMD has participated in this project. To support this work, modelling studies have been undertaken [115, 116]. The first of these studies [115] concludes that it is desirable to segregate graphite wastes from:

- Organic wastes, to minimise the potential for the development of methanogenic conditions and the incorporation of carbon-14 into methane; and
- Reactive metal wastes in lower strength sedimentary rock environments, to prevent relatively rapidly rising vault pressures and high peak gas pressures, pushing radionuclides in water out of the GDF.

The second report [116] concludes that, although it may not be necessary in all cases, there are advantages in disposing graphite wastes in isolation, compared with co-disposal in the same vaults with other ILW. These advantages include:

- Simpler more predictable behaviour;
- Improved performance, e.g. transport in gas is not likely to be an issue; and
- Simplified safety arguments and safety case.

The analysis of the alternative treatment, packaging, design and disposal options for graphite undertaken as part of Phase 1 of this project is presented in Table 34, and a discussion of the potential benefits of these options is given in Section 10.3.

**Steels**

As seen from Table 9, activated steels come from a number of sources. Many of them have not yet been packaged, and so there are a number of options moving forward. However, AGR fuel cladding, which contains a significant proportion of the inventory, has already been packaged.

The analysis of the alternative treatment, packaging, design and disposal options for steels is presented in Table 35 and a discussion of the potential benefits of these options is given in Section 10.3.

**Reactive metals**

Much of the waste containing reactive metals originates from Sellafield. As shown in Table 10, many of the streams have either already been packaged or are currently being packaged in a cementitious wasteform in 500 litre drums. They arise from high hazard facilities at Sellafield, and are being packaged to accelerate the clean-up of the Sellafield site [117]. There are a number of potential options. Treatment of certain wastes is already the baseline for many stations. Gas capture during the operational phase of the GDF could be considered, as could alternative backfilling strategies. Wasteforms or containers that limit the ingress of water and possibly chloride may also be worth considering, as could be the use of lower pH cements.

The analysis of the alternative treatment, packaging, design and disposal options for reactive metals is presented in Table 36 and a discussion of the potential benefits of these options is given in Section 10.3.

**Other wastes**

There are a number of other waste streams that may be worthy of further consideration. These are:
• **GE Healthcare organic wastes.** It is now proposed that these wastes are incinerated, and not disposed to the GDF.

• **ILW carbonates.** Currently these do not constitute a large volume group of waste streams. However, were thermal treatment adopted more widely, the volume could increase. Segregation may be a practicable option.

• **Spent fuel.** In a higher strength rock environment, it is expected that a very long-lived container would be used. Such a container might not be necessary in other geological environments, but it is still expected that a high integrity package would be used. To contain the carbon-14 for ten half-lives would require a container life of around 50,000 years.

• **Ion exchange resins.** Segregation may be practicable, but there are a number of streams from a number of sources. Such wastes may be considered as part of the upcoming international CAST project.

• **HLW.** This probably does not require further consideration, as the carbon-14 inventory is believed to be negligible, and this will be confirmed through the proposed work on the inventory (see Section 3.3).

• **Aluminium nitride cartridges.** These may require a tailored engineering solution.

• **DNLEU and separated Pu.** Possible carbon-14 contamination of these materials may require consideration.

• **Sellafield miscellaneous wastes.** Possible carbon-14 contamination of these wastes may require consideration.
Table 34  Possible Alternative Treatment, Packaging, Design and Disposal Options for Graphite Wastes

<table>
<thead>
<tr>
<th>Waste Stream Group</th>
<th>Design mitigation</th>
<th>Include (Yes, Maybe or No)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILW core graphite¹</td>
<td>Segregation</td>
<td>Yes</td>
<td>Distinct groups of waste streams could be segregated into separate vaults</td>
</tr>
<tr>
<td></td>
<td>Shallow vaults</td>
<td>Maybe</td>
<td>Not a mitigation - but an opportunity (N.B. $^{36}$Cl present in graphite may be significant for the groundwater pathway)</td>
</tr>
<tr>
<td></td>
<td>No cement</td>
<td>Yes</td>
<td>Cement may not be needed</td>
</tr>
<tr>
<td></td>
<td>Minimal packaging</td>
<td>Yes</td>
<td>With the aim of eliminating the bulk gas phase</td>
</tr>
<tr>
<td></td>
<td>Surface treatments</td>
<td>No</td>
<td>Probably not practicable</td>
</tr>
<tr>
<td></td>
<td>Combustion</td>
<td>No</td>
<td>Not practicable</td>
</tr>
<tr>
<td></td>
<td>Long-lived container</td>
<td>No</td>
<td>Not necessary</td>
</tr>
<tr>
<td></td>
<td>Long-lived wasteform (e.g. glass)</td>
<td>No</td>
<td>Not practicable</td>
</tr>
<tr>
<td>ILW Magnox fuel element graphite²</td>
<td>Segregation</td>
<td>No</td>
<td>Not a complete solution – does not work for all such streams</td>
</tr>
<tr>
<td></td>
<td>Shallow vaults</td>
<td>No</td>
<td>As segregation</td>
</tr>
<tr>
<td></td>
<td>No cement</td>
<td>Maybe</td>
<td>May be practicable</td>
</tr>
<tr>
<td></td>
<td>Minimal packaging</td>
<td>No</td>
<td>Not practicable because of the contamination</td>
</tr>
<tr>
<td></td>
<td>Surface treatments</td>
<td>No</td>
<td>Not practicable because it is broken up</td>
</tr>
<tr>
<td></td>
<td>Combustion</td>
<td>No</td>
<td>Not practicable because of the contamination</td>
</tr>
<tr>
<td></td>
<td>Long-lived container</td>
<td>No</td>
<td>Not necessary</td>
</tr>
<tr>
<td></td>
<td>Long-lived wasteform (e.g. glass)</td>
<td>No</td>
<td>Not practicable</td>
</tr>
<tr>
<td>ILW AGR fuel element graphite³</td>
<td>Segregation</td>
<td>Maybe</td>
<td>Potentially practicable</td>
</tr>
<tr>
<td></td>
<td>Shallow vaults</td>
<td>Maybe</td>
<td>As segregation</td>
</tr>
<tr>
<td></td>
<td>No cement</td>
<td>Yes</td>
<td>Cement may not be needed</td>
</tr>
<tr>
<td></td>
<td>Minimal packaging</td>
<td>Yes</td>
<td>Potentially practicable</td>
</tr>
<tr>
<td></td>
<td>Surface treatments</td>
<td>Maybe</td>
<td>Grouting process or polymer treatment - not remove surface</td>
</tr>
<tr>
<td></td>
<td>Combustion</td>
<td>Yes</td>
<td>Could be suitable for a thermal treatment plant</td>
</tr>
<tr>
<td></td>
<td>Long-lived container</td>
<td>Maybe</td>
<td>Small volume, so may be practicable</td>
</tr>
<tr>
<td></td>
<td>Long-lived wasteform (e.g. glass)</td>
<td>Maybe</td>
<td>Thermal treatment or vitrification is possible, but will they work for graphite?</td>
</tr>
</tbody>
</table>

Notes

1. This applies to commercial reactors, and not experimental reactors.
2. These wastes come from a number of sources, and have different characteristics. Hunterston A wastes are held in a dry store and have minor contamination with Magnox, etc., whereas those from the Berkeley vaults are heavily contaminated with reactive metals.
3. This is a small quantity of waste. Is it worth considering separately? It is in steel containers, and so there may be a bulk gas phase.
### Table 35 Possible Alternative Treatment, Packaging, Design and Disposal Options for Steel and Other Ferrous Wastes

<table>
<thead>
<tr>
<th>Waste Stream Group</th>
<th>Design mitigation</th>
<th>Include (Yes, Maybe or No)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ILW AGR</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>stainless steel fuel cladding</td>
<td>Segregation</td>
<td>No</td>
<td>Not seen as beneficial</td>
</tr>
<tr>
<td></td>
<td>Spread out over many vaults</td>
<td>Maybe</td>
<td>May be practicable, investigate benefits</td>
</tr>
<tr>
<td></td>
<td>Surface treatments</td>
<td>No</td>
<td>Already packaged</td>
</tr>
<tr>
<td></td>
<td>Melting or thermal treatment</td>
<td>Maybe</td>
<td>Could be put through thermal treatment plant, but already packaged</td>
</tr>
<tr>
<td></td>
<td>Long-lived container</td>
<td>Maybe</td>
<td>Would be an overpack – think about overpressurisation (waste already in cement)</td>
</tr>
<tr>
<td><strong>ILW AGR</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>stainless steel assembly components</td>
<td>Segregation</td>
<td>Yes</td>
<td>Practicable, but there would still be a bulk gas phase</td>
</tr>
<tr>
<td></td>
<td>Spread out over many vaults</td>
<td>Maybe</td>
<td>May be practicable, investigate benefits</td>
</tr>
<tr>
<td></td>
<td>Surface treatments</td>
<td>No</td>
<td>No benefit</td>
</tr>
<tr>
<td></td>
<td>Melting or thermal treatment</td>
<td>Yes</td>
<td>Thermal treatment plant</td>
</tr>
<tr>
<td></td>
<td>Long-lived container</td>
<td>Maybe</td>
<td>Not very attractive</td>
</tr>
<tr>
<td><strong>ILW stainless steel and other ferrous metals reactor decommissioning wastes</strong></td>
<td>Segregation</td>
<td>Yes</td>
<td>Large boxes - therefore naturally separable (~80% late, ~20% early &amp; variable)</td>
</tr>
<tr>
<td></td>
<td>Spread out over many vaults</td>
<td>No</td>
<td>Hard for a large stream</td>
</tr>
<tr>
<td></td>
<td>Surface treatments</td>
<td>No</td>
<td>Hard for a large stream</td>
</tr>
<tr>
<td></td>
<td>Melting or thermal treatment</td>
<td>Maybe</td>
<td>Could be a challenge to implement</td>
</tr>
<tr>
<td></td>
<td>Long-lived container</td>
<td>Maybe</td>
<td>If you really had to - hard for a large stream</td>
</tr>
</tbody>
</table>

**Notes**

1. These are taken to be WEP packages (containing cladding hulls, etc.). These are already packaged or committed to packaging in 500 l drums.
2. These are taken to be struts and braces – these are not encapsulated and are stored.
3. These wastes are not just steel; there is some Al, which could be separable. The quantity may increase if LLWR limits the receipt of wastes containing carbon-14. Carbon-14 from new build reactor pressure vessels should be considered.
<table>
<thead>
<tr>
<th>Waste Stream Group</th>
<th>Design mitigation</th>
<th>Include (Yes, Maybe or No)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILW reactive metals</td>
<td>Segregation</td>
<td>No</td>
<td>Could for Magnox cladding, but probably would not help</td>
</tr>
<tr>
<td></td>
<td>Container that limits water inflow</td>
<td>Maybe</td>
<td>For fuel ends - but a small stream</td>
</tr>
<tr>
<td></td>
<td>Wasteform that limits water availability e.g. polymer</td>
<td>Maybe</td>
<td>For fuel ends. Some streams already packaged. May help operations, transport and backfilling</td>
</tr>
<tr>
<td></td>
<td>Lower pH cement</td>
<td>Maybe</td>
<td>For U. Major streams already packaged</td>
</tr>
<tr>
<td></td>
<td>Treatment e.g. oxidise/dissolve FED</td>
<td>Yes</td>
<td>Is baseline for most stations</td>
</tr>
<tr>
<td></td>
<td>Gas capture during backfilling</td>
<td>Yes</td>
<td>If required</td>
</tr>
<tr>
<td></td>
<td>Alternative backfilling strategy</td>
<td>Yes</td>
<td>May just be about gradual backfilling. If crushed rock, think about wider implications (e.g. solubility limits)</td>
</tr>
</tbody>
</table>

Notes

1. Corrosion is sensitive to the level of Cl. Al wastes probably do not have a large carbon-14 inventory
10.3 Effects of alternative options for each waste group

As discussed above, there are a range of alternative options that could be applied to different groups of ILW, which may change the volume or the rate of generation of carbon-14 containing gas and/or bulk gas from those wastes. To estimate the effect of such alternative options on the overall potential for carbon-14 containing gas to be an issue, these alternatives can be considered in the context of the breakdown of gas generation rates from ILW presented in Section 5.2. The alternative options identified above are examined in this way for each of the waste groups in turn below.

ILW core graphite

The majority of the core graphite is currently classified as shielded ILW (SILW), and only a small fraction (and a very small fraction of the carbon-14 contained in it) is unshielded ILW (UILW) (see Table 15 and Table 14). The significance of core graphite in the UILW vaults is also small. Given this, any alternative options applied to the UILW core graphite will have a minimal impact on the potential carbon-14 generation or release. In contrast, core graphite is the main source of carbon-14 in the SILW/LLW vaults. Therefore alternative options are examined for SILW core graphite, which is potentially a significant contributor to the post-closure annual risk (Table 32 and Table 33).

Potential alternative options that may be relevant for this waste are segregation, packaging without cement and minimal steel packaging. Based on the assumptions made in the assessment calculations, none of these alternative options would affect the carbon-14 containing gas generation rate from the core graphite. However, emplacing the graphite into the vaults without any containers would reduce the bulk gas generation post-closure. In fact, since the main contribution to bulk gas generation in the long term is from the stainless steel containers, and the graphite comprises 70% of the volume of the waste in the SILW/LLW vaults (see Table 15), removing the containers for the graphite waste will reduce the long term bulk gas generation rate by around a factor of 3. Segregation or the absence of cement may not have a significant impact on the bulk gas generation, if the waste is still packaged in steel containers.

Although removing the containers will reduce the bulk gas generation rate, bulk gas will still be generated at a significant rate from the other SILW/LLW, so there may be little effect on the containment of the carbon-14 containing gas. However, if minimal steel packaging and segregation of the graphite are considered in combination, this would remove virtually all the bulk gas generation from the segregated waste vaults, and it would then be likely that the carbon-14 containing gas would remain within those vaults, and probably dissolve in the groundwater. Thus this combination of alternative options could substantially reduce (or remove) the issue of carbon-14 for the SILW/LLW vaults in the gas phase.

ILW Magnox fuel element graphite

The Magnox fuel element graphite is UILW. The significance of Magnox fuel element graphite in the UILW vaults is small. Given this, any alternative options applied to the Magnox fuel element graphite will have a minimal impact on the potential carbon-14 generation or release. Therefore, alternative options for this waste need not be considered further.

ILW AGR fuel element graphite

The AGR fuel element graphite is UILW. Although it makes up nearly 5% of the UILW volume and contains a similar fraction of the inventory of carbon-14 in UILW (Table 14), the significance of AGR fuel element graphite in terms of gas generation is small. Given this, any alternative options applied to the AGR fuel element graphite will have a minimal impact on the potential carbon-14 generation or release. Therefore, alternative options for this waste need not be considered further.
ILW AGR stainless steel fuel cladding

The AGR stainless steel fuel cladding is UILW. Although it makes up only a small fraction of the UILW volume, it contains over 15% of the inventory of carbon-14 (see Table 14), and is a significant source of carbon-14 bearing gas generation long term post-closure. This waste has already been packaged.

Potential alternative options that may be relevant for this waste are spreading it throughout the UILW, thermal treatment before disposal and over-packing in a long-lived container. Spreading the waste out would redistribute the carbon-14 containing gas generated, but is unlikely to significantly change the overall impact. Treatment of the waste to convert it to a form from which the carbon-14 could not easily be released, or from which the carbon-14 is released during the treatment process, would effectively remove the corresponding fraction of the carbon-14 from the gas generated, so would reduce the long term carbon-14 containing gas generation rate by ~20%. Use of a long-lived overpack would prevent release of gaseous carbon-14 from these wastes until the container was breached (which would likely be after the carbon-14 had decayed sufficiently that it would no longer be an issue). The benefits of thermal treatment or over-packing of AGR steel fuel cladding are not considered sufficient to make these options viable and therefore these options will not be considered further in Phase 2.

ILW AGR stainless steel assembly components

The AGR stainless steel assembly components are UILW. Although this makes up only a small fraction of the UILW volume, it contains over 30% of the inventory of carbon-14, and is a significant source of carbon-14 containing gas generation long term post-closure.

Potential alternative options that may be relevant for this waste are segregation, spreading it throughout the UILW, thermal treatment before disposal and use of a long-lived container. As this waste generates almost half of the carbon-14 containing gas in the long term, but only ~1% of the bulk gas, segregation could potentially prevent this fraction of the carbon-14 from being released from the vaults. However, the volume of this waste is also only ~2% of the UILW volume (see Table 14), so the bulk gas generation rate per unit volume remains similar. Further, this waste will only occupy a small fraction of a vault, so overall it is not clear that segregation would have a significant impact. The last two options (thermal treatment or a long-lived container) would reduce the long-term carbon-14 containing gas generation rate by around a factor of 2 for the UILW wastes. This is not considered sufficient to make these options viable and therefore these options will not be considered further in Phase 2.

ILW stainless steel and other ferrous metals reactor decommissioning wastes

Some of the steel reactor decommissioning waste is UILW and some is SILW. However, the carbon-14 content of the waste is only a small fraction of that in all the SILW, and the significance of this waste in the SILW/LLW vaults is also small. Given this, any alternative options applied to the SILW steel reactor decommissioning waste will have a minimal impact on the potential carbon-14 generation or release. In contrast, steel reactor decommissioning waste contains almost 30% of the carbon-14 in the UILW, and provides a significant contribution to the carbon-14 containing gas generation in the UILW vaults in the long term. Therefore alternative options could be considered for UILW steel reactor decommissioning waste.

Potential alternative options that may be relevant for this waste are segregation, thermal treatment before disposal and use of a long-lived container. This waste generates nearly 30% of the carbon-14 containing gas in the long term, and ~10% of the bulk gas, but makes up only ~6% of the UILW volume (see Table 14). As discussed above, this means that segregation is unlikely to have a significant impact. The other options are thermal treatment before disposal and use of a long-lived container. For this waste, these options would reduce the long term carbon-14 containing gas generation rate by nearly 30%. This
is not considered sufficient to make these options viable and therefore these options will not be considered further in Phase 2.

**ILW reactive metals**

All of the reactive metals containing a significant inventory of carbon-14 are UILW. This waste makes up nearly 20% of the UILW volume, and contains ~10% of the inventory of carbon-14 (Table 14). It is the main source of both carbon-14 containing and bulk gas generation in the UILW vaults during the operational and early post-closure periods.

Potential alternative options that may be relevant for this waste are use of containers that limit water inflow, conditioning to generate a wasteform that limits access of water to the waste, treatment or dissolution before disposal, gas capture during backfilling and use of an alternative backfilling strategy. Gas capture during backfilling would affect the release of the gas rather than the gas generation, so the affect of this cannot be assessed in the context of the gas generation results, so is not considered here.

The second option (conditioning to limit water access) would be expected to reduce the corrosion rates of the reactive metals over the modelled period, which would reduce both the carbon-14 containing and bulk gas generation rates, but would result in a longer period over which corrosion of these metals occurred. The first option (container to limit water access) would be similar, but would only apply during post-closure, once the water initially in the waste packages had been consumed. There is a sufficient rate of bulk gas generation from other sources that controlling bulk gas generation from the reactive metals is not likely to be important in terms of the effect on carbon-14 release. However, effectively spreading the early, more rapid carbon-14 containing gas release over a longer period could reduce the impact of carbon-14. A reduction of one order of magnitude during the operational period and two orders of magnitude during the early post-closure period may be possible.

Treatment of the waste before disposal to convert it to a form from which the carbon-14 could not easily be released, or from which the carbon-14 is released during the treatment process, would effectively remove the corresponding fraction of the carbon-14 (as well as the bulk gas) from the gas generated. It is judged that this would reduce the carbon-14 containing gas generation rate by one order of magnitude during the operational period and two orders of magnitude during the early post-closure period (although it should be recognised that carbon-14 could be released to atmosphere during such a treatment and this would have associated radiological consequences, so it would be important to consider all aspects of this option if it were to be considered further). Use of an alternative backfilling strategy could cause the peak carbon-14 containing gas generation rate associated with backfilling to be distributed over more of the operational period, so would reduce the peak operational release rate, provided the reactive metal waste was distributed between all the vaults. More detailed calculations would be required to quantify this effect. This would build on work already undertaken on the transition from the operational to the post-closure phase [14].

The source term from these wastes is important and is the focus of an ongoing research project with NNL.

### 10.4 Work for Phase 2

In Phase 2, there will be a small number of tasks to consider alternative packaging, design and disposal options.

The focus of this work will be to consider segregation of ILW core graphite and to give further consideration to alternative options for irradiated reactive metals. The most appropriate option for the reactive metals depends on understanding whether the
carbon-14 from these materials is likely to be released in the operational and early post-closure period, or whether it is more likely to be spread over a longer period and so consideration of options will be linked to a related task that aims to develop this understanding.
11 Roadmap for Phase 2 (Issue 2)

One of the key outputs from Phase 1 is the Roadmap for Phase 2; this is presented as a stand-alone Section here. Work for Phase 2 has been identified at the end of the previous Sections. These are integrated here using the “AND” approach to present a prioritised work programme. It is envisaged that Phase 2 will start at the end of 2012 and will run for two years until the end of 2014.

A Roadmap is a document that sets out the future direction of a project, including how it will be implemented. We have written this Roadmap so that this Section could be read separately. For this reason there is some overlap of material in the preceding Sections.

This updates the Roadmap Issue 1 [8], which was completed at the end of May 2012.

In the first part of this Section (Section 11.1), we describe the objectives for the integrated project on carbon-14. In Section 11.2, we describe the broad approach of our integrated project team.

In Phase 1, work programmes have been undertaken to examine the current understanding and identify key knowledge gaps (Section 11.3). We have also developed a “modelling basis spreadsheet” to record and communicate our current understanding of the various aspects of the carbon-14 issue and to record how we represent this understanding in the scoping model. The scoping model has been used to assess alternative options and to develop our understanding of the impact of different components of the overall system. This work is summarised in Section 11.4.

The Phase 2 programme is described in Section 11.5 and the project deliverables in Section 11.6. It is envisaged that Phase 2 will start at the end of 2012, and run until the end of 2014.

11.1 Objectives

Carbon-14 is a key radionuclide in the assessment of the safety of a geological disposal facility (GDF) for radioactive waste. In particular, the radiological consequences of gaseous carbon-14 bearing species is a potential issue and has been recognised as such in Nirex report N/122 [2], in the generic DSSC [3], and in the issues register [4].

NDA RWMD has been carrying out a range of research and assessment tasks on carbon-14 to improve the understanding of the expected evolution of the disposal system and the consequences for the calculated annual risk. Much of this work is summarised in the gas status report [5], the radionuclide behaviour status report [6], and in the R&D Programme Overview document [7]. However, following publication of the DSSC, it has been decided to adopt a collaborative approach to tackling issues related to carbon-14 by establishing an Integrated Project Team, in which the partners work together to develop a holistic approach to carbon-14 management in a geological disposal facility.

The overall aim of the integrated project is:

“To support geological disposal of UK wastes containing carbon-14, by integrating our evolving understanding from current and pre-existing projects, in order to develop a holistic approach to carbon-14 management in the disposal system. This includes the following sub-objectives:

- To inform strategic decisions on disposal options for specific waste types and inform packaging decisions for specific waste streams;
• To provide data and understanding and, if necessary, develop conceptual and component-level models to support the transport, operational and environmental safety cases;
• To develop options for an integrated waste management approach to disposal of these wastes;
• To establish whether mitigation measures or design solutions are required;
• To develop data and understanding required to inform the siting process that will be undertaken during MRWS stage 5;
• To inform the requirements for site characterisation;
• To deliver value for money.

A successful outcome from this project would be that we understand the envelope of conditions within which disposal of the UK’s wastes containing carbon-14 can be managed.”

11.2 The integrated project approach

The integrated project team has developed an integrated technical approach based on understanding of the key gas generation and migration processes. We call this integrated technical approach the “AND” approach; it was described in Section 2, and is summarised again in Box 2 below. We have used the “AND” approach as a way of considering the problem comprehensively and to break the problem down in a manageable way. We have used it to underpin the prioritisation of the technical work and we have also used it to underpin other activities, in particular the approach to alternative treatment packaging and design options (Section 10 above), and the justification for further experiments on the release of carbon-14 from stainless steel.

In Phase 2 of the work, the AND approach will be taken forward, broken down by waste type and the programme for Phase 2 (Section 11.5) is presented in this way.

The project will continue to be managed using our integrated project team approach, where a team of people work in partnership to develop a holistic approach to carbon-14 management in the disposal system.

The lead contractor will assemble a team to deliver the proposed programme and meet the project objectives and will provide a costed proposal, which will include more detail on the scope of each task and the deliverables. The project team incorporates a wide range of expertise following a “best athlete” approach and includes members from a number of our contracting organisations and members from the different technical functions within NDA RWMD.

Some of the tasks are already ongoing outside of, but co-ordinated with the integrated project team. For the planned tasks it is proposed to develop and enhance the “best athlete” team, which may be expanded to include additional experts as appropriate.

Progress review meetings will be held at approximately sixth monthly intervals and if required the project scope and programme will be revised. The project team will report to the project and programme boards on a monthly basis.
Box 2  The integrated technical approach (the AND approach)

For a waste stream containing carbon-14 to be an issue:

- There must be a significant inventory of carbon-14 in the waste stream; **AND**
- That waste stream has to generate carbon-14 bearing gas; **AND**
- A bulk gas phase has to entrain the carbon-14 bearing gas; **AND**
- These gases must migrate through the engineered barriers in significant quantities; **AND**
- These gases must migrate through the overlying geological environment (either as a distinct gas phase or as dissolved gas); **AND**
- These gases must interact with materials in the biosphere (i.e. plants) in a manner that leads to significant doses and risks to exposed groups or potentially exposed groups.

11.3 Phase 1 of the IPT

At the start of Phase 1, Issue 1 of the Project Roadmap was prepared [8]; in that document we set out the work that the Integrated Project Team would carry out in order to meet the project objective. The Roadmap divided the work into 2 Phases. In Phase 1, we had a six month programme of work with three elements:

- Initially the project team updated Issue 0 of the Roadmap (which was a key component of the successful tender) to Issue 1 to ensure that NDA RWMD’s requirements were fully incorporated. This was achieved over a two month period, concluding at the end of May 2012;
- We then undertook a series of tasks, to examine individual aspects of the programme in more detail. The aims of this work were:
  - to summarise the current understanding, identify knowledge gaps and clarify key uncertainties, so the subsequent work in Phase 2 is appropriately focused;
  - to capture the understanding in a live “modelling basis” spreadsheet;
  - to identify the approaches, models and tools required to support assessments;
  - to develop fully costed work packages for Phase 2 of the IPT.
- The Roadmap is now updated to Issue 2, to define more fully the work for Phase 2. This Section forms Issue 2 of the Roadmap.

At the end of Phase 1, the project team considers that adopting an integrated approach to managing wastes containing carbon-14 has had a number of benefits:


• Working in an integrated project team to address an integrated problem in a holistic way has resulted in a change of culture, with a wider group of people working together collaboratively to solve a problem. This has been rewarding for all involved and has meant that the project has a real-world focus.

• Adopting an integrated approach has provided a framework in which the team can pull together existing and current work and identify where there are gaps and how these could best be filled.

• The integrated project team is a forum that encourages exchange between different technical areas and across different funding mechanisms. For example, the project is co-ordinating with the GEOWASTE project (funded jointly by NDA RWMD and EPSRC) and the proposed CAST project that will be funded by the IGD-TP (Implementing Geological Disposal Technology Platform).

• Timely consideration of our understanding of the carbon-14 source term has informed our contribution to the CAST project.

• Participation in the project team will provide training to some individuals and increase capability within NDA RWMD as well as in the supply chain. In particular, there will be a good opportunity to build the NDA RWMD capability in total system modelling for gas.

• The integrated project has provided good value for money, by drawing on a wide range of existing data, expertise and process understanding.

11.4 Summary of the position at the end of Phase 1

As part of Phase 1, work programmes have been undertaken to examine the current understanding, data and implications of different waste types, and in particular graphite, irradiated steels, and irradiated reactive metals. The work has examined: the inventory, the experimental data for the source term, modelling approaches (particularly for gas generation), interactions with engineered materials, migration through the geosphere, transport and uptake in the biosphere, assessment approaches, and possible alternative treatment, packaging, design and disposal options.

We have captured this understanding in a “modelling basis” spreadsheet and carried out scoping assessments that help us to understand better the potential significance of carbon-14. Using the current modelling basis, but ignoring any potential benefits from the geosphere in retarding or preventing gas from reaching the surface, the calculated release of carbon-14 exceeds the risk guidance level and is dominated by: corrosion of reactive metals (in the operational and early post-closure time frame); corrosion of irradiated stainless steel and leaching of irradiated graphite. The Phase 1 work has shown, however, that there is considerable scope for improving the calculated radiological consequence for these wastes and this will form the basis of the Phase 2 work as follows:

• The inventory is based on assumed material precursor concentrations, which may be overestimated. Work is proposed in Phase 2 that will improve the inventory.

• Some carbon-14 might be lost from wastes before disposal. Work is proposed in Phase 2 that aims to allow these losses to be taken into account.

• The current graphite release model is simple and could be revised to reflect the data and understanding from arising work, with the aim of reducing the graphite source term. Work is proposed in Phase 2 that will update the modelling basis for release of carbon-14 from graphite, based on data arising from the NDA RWMD programme and from other relevant work. It is possible that a significant proportion of the graphite carbon-14 inventory is associated with the graphite matrix and is
essentially immobilised. The arguments associated with the long-term stability of graphite will be reviewed.

- There are only very limited data on carbon-14 release from irradiated stainless steels. An experimental programme to gather these data will be undertaken through the proposed collaborative international CAST project and will form part of the Phase 2 work.

- The modelling approach could take into account more appropriate surface area data to calculate the gas produced by corrosion of specific metal wastes (e.g. AGR fuel cladding). This will form part of the Phase 2 work.

- There are no available data on carbon-14 release from irradiated reactive metals. An experimental programme to gather these data has just started and will form part of Phase 2.

- Generation of carbon-14 bearing gases is dependent on water availability and this may be overestimated in the modelling approach. Work is proposed in Phase 2 to consider the impact of water availability, particularly on the corrosion of reactive metals, to investigate whether gas generation is more likely to occur in the operational and early post-closure period (in which case the peak generation rate would be high, but could perhaps be mitigated), or whether it is more likely to be spread out over a longer period.

- There may be microbial metabolism of hydrogen in the near field of the ILW system, which would reduce the amount of bulk gas migrating through the disposal system. Evidence for such microbial processes will be gathered as part of an existing PhD project, which may give some insights during the Phase 2 work.

- The geosphere may have features, such as cap rocks that retard or prevent the breakthrough of gas at the surface. In an evaporite or lower strength sedimentary rock, there is unlikely to be a significant release of carbon-14 bearing gas to the biosphere. In regions of higher groundwater flow, gas may be dissolved. Work is proposed in Phase 2 to develop the geosphere modelling approach for the total system model for higher strength rocks. If required in the later phases of the project, information will be developed that could inform site characterisation requirements. This would allow a future site-specific model to be developed.

- There may be scope to reduce the calculated consequences in the generic Operational Environmental Safety Assessment, by revising the approach to reflect the expanded knowledge base generated in this project. This will be addressed in Phase 2.

- There may be scope to reduce the calculated post-closure consequences by revising the current assumption that methane is fully converted to carbon dioxide in the soil zone. This will be considered in Phase 2, based on data and understanding from our experimental programme, together with a literature review and participation in an international review project. If justified, the improved understanding will then be reflected in the modelling basis.

- There is some scope for alternative approaches to management of certain waste streams within the disposal system, and these will be investigated further in Phase 2. For example, ILW core graphite could be segregated so that it is located away from waste packages generating significant quantities of bulk gas, and if appropriate, alternative approaches could be considered for wastes containing reactive metals.
11.5 Phase 2 programme

We have taken the conclusions from the Phase 1 work programme to develop the proposed work programme for Phase 2, and we describe the proposed programme in this Section. The overall programme is tabulated at the end of the Section in Table 37, where the tasks are numbered. These tasks are referenced in the description below.

Some of the proposed work is specific to particular groups of waste streams, such as graphite, irradiated steels and irradiated reactive metals. These are discussed in turn first. This includes consideration of alternative treatment, packaging, design and disposal options.

Other areas of work relate to aspects of the disposal system that are not specific to particular wastes. These include migration through engineered barriers, geosphere migration, and the biosphere. These are discussed afterwards.

Finally there are a number of overarching areas, such as assessments. These are discussed at the end of the Section.

Graphite

In the current modelling approach (and assuming any methane generated is directly released to the biosphere), the graphite in shielded ILW dominates the release from these vaults and the release rate leads to a calculated risk that exceeds the regulatory risk guidance level by a factor of about fifty. However, this is based on a number of simplifications, which need to be better understood.

The proposed way forward is to reduce the current pessimisms in the leach rate based on more recent data and to develop a revised model of release to incorporate within SMOGG (including consideration of uncertainty). It is also proposed to review the arguments associated with the long-term stability of graphite and the potential for taking credit from the immobilisation of a significant fraction of the associated carbon-14 inventory in the graphite matrix (Tasks 4, 5, 6). We will investigate the inventory to see if any of the knowledge gaps for the graphite inventory can be addressed (Tasks 1 and 2). We will also investigate whether there are further graphite samples, should further experiments be necessary (Task 7).

The revised model would be based on data from CARBOWASTE (EC project), BIG (NDA-EPSRC funded task), AMEC experiments (Task 4) and would benefit from participation in the collaborative international CAST project, which will have a work package on carbon-14 in irradiated graphite (Task 5).

The revised model and data will be used to update the modelling basis spreadsheet and scoping calculations (Task 3 and 6). They will also inform development of the total system model (Task 21).

It is possible that the revised model and release rates would result in a calculated release that leads to an assessed risk from these wastes that is below the regulatory risk guidance level. Alternatively we would further consider the benefits of segregation of the larger graphite waste streams, so that they are removed from materials that generate bulk gas. This could mean packaging without steel containers (Task 8).

Irradiated steels

In the current modelling approach, the release from irradiated steels dominates the longer term post-closure release in the unshielded ILW vaults and the release rate leads to a calculated risk that exceeds the regulatory risk guidance level by a factor of about seven. However, this is based on a number of simplifications, which need to be better understood.
The proposed way forward is to:

- Improve the inventory data, including surface area, size and shape (geometry) information (Tasks 1 and 2);
- Gather data on the rate and speciation of carbon-14 release (through the collaborative international CAST project – Task 9). This will include an up-to-date review of all information on rate and speciation of carbon-14 release from steels held by CAST participants at the project outset;
- Develop a revised model of release and associated parameters and uncertainty ranges – Task 10;
- Update the modelling basis spreadsheet and scoping calculations (Task 3 and 10);
- Make inputs to the total system model (Task 21).

**Irradiated reactive metals**

In the current model calculations, the calculated release from Magnox and uranium leads to an assessed risk that is significantly above the regulatory risk guidance level. However, this is based on a number of simplifications, which need to be better understood. The way forward for these wastes depends on understanding whether the carbon-14 from these materials is likely to be released in the operational and early post-closure period (in which case the peak release would be high, but could perhaps be mitigated by some means), or whether it is more likely to be spread out over a longer period. The proposed work for Phase 2 is to:

- Improve inventory data (Tasks 1 and 2);
- Gather data on rate and speciation of the release of carbon-14 from these wastes (from the NNL project – Task 11);
- Consider how much of the carbon-14 may have been released before disposal (Task 12);
- Consider the impact of water availability (or ways to limit access of water to the waste) and the impact of chloride – Task 12;
- Update the modelling basis spreadsheet and scoping calculations (Task 3);
- Make inputs to the total system model (Task 21);
- Consider whether our revised approach can be tested at the system level, by undertaking experiments that integrate wastes with engineered barriers (Task 23);
- Consider the potential benefits from alternative treatment, packaging, design and disposal options, such as gradual backfilling, dissolution, alternative packaging, and mitigations during institutional control (Task 13).

The release from reactive metals leads to doses 20% above the design target during the operational phase. We will examine the cautious assumptions in the assessment model used in the OESA and develop a revised methodology (Task 20).

**Organics, spent fuel and other wastes**

Our scoping assessments show that the most significant impacts will arise from the wastes groups discussed above. However, we update our modelling basis with any new information that becomes available on other wastes groups, such as organic wastes from GE Healthcare, HLW, spent fuel, and ion exchange resins. This will be achieved through participation in the international CAST project, which will provide information on some of
these wastes. Work is proposed on the inventory in Phase 2, which will also aid our understanding for certain of these wastes, in particular HLW and spent fuel (Section 3.3).

Migration through engineered barriers

In Phase 2 of the work programme, we will incorporate the understanding from relevant near field projects in the modelling basis spreadsheet (Task 14), which will be used to inform scoping calculations and the development of the total system model. These projects include:

- An ongoing task to determine how effectively CO$_2$(g) released from waste packages will react with the NRVB to form carbonates. (NNL task).
- Ongoing work within the EC FORGE project to investigate the reaction of carbon dioxide as gas, and in solution with the NRVB, and the impact of the reaction on the evolution of permeability (BGS task).
- A PhD project at the University of Manchester to investigate the microbiological metabolism of hydrogen within a GDF. Evidence will be gathered as part of this PhD project, which may give some insights during Phase 2 of this project.
- A task to investigate the interaction of gas and cement during backfilling.

More detailed process-level modelling of gas and groundwater interactions at the package scale may also be developed within the IPT, following on from the work carried out within FORGE.

Geosphere migration

In the “AND” approach the geological environment could be pivotal in determining whether carbon-14 bearing gases reach the biosphere. In Phase 1, the key questions for geosphere migration have been considered for the three geological environments currently being studied as part of the NDA RWMD programme (HSR, LSSR and evaporite). The geosphere may have features, such as cap rocks that retard or prevent the breakthrough of gas at the surface. In an evaporite or lower strength sedimentary rock, there is unlikely to be a significant release of carbon-14 bearing gas to the biosphere. In regions of higher groundwater flow, gas may be dissolved.

It is not proposed to undertake detailed development of gas migration models in Phase 2. We will continue to be involved in the EC FORGE project to ensure we remain at the forefront of developments in this area.

We will seek to understand the envelope of geological environments in which carbon-14 bearing wastes can be managed safely, by integrating the understanding from relevant geosphere projects with our understanding of the carbon-14 source term. We will explore whether there are analogues relevant to gas release and release area. We will ensure this understanding is included in the modelling basis spreadsheet (Task 15).

If required, we will develop an understanding to inform the requirements for the site characterisation programme (Task 16).

Biosphere

During Phase 2, we will complete the current biosphere laboratory and field experimental programme to measure to measure the rate of conversion of CH$_4$ to CO$_2$, along with the associated model development work (Task 17). These field experiments are concerned
with gaining a detailed understanding in a particular soil type. We will carry out a focused literature review to quantify methane oxidation in a wider variety of soils under different conditions (Task 19).

We will participate in the international BIOPROTA project. This will allow us to draw on wider international developments, and allow us to compare our models to be compared with those in use in other programmes (Task 18).

Taken together, these tasks will allow us to document the basis for the biosphere factor for the post-closure phase in more detail. This will include the dependence of the factor on the release area, the release of inactive methane, and conversion of methane to carbon dioxide in the soil zone. We will investigate the scope for the biosphere factor to be reduced further.

**Modelling and assessments**

We have developed a “modelling basis” spreadsheet, which is used to record and communicate our current understanding of the various aspects of the carbon-14 issue and to record how we represent this understanding in the scoping model. This was described in Section 9.1 above, and is represented in Table 19 to Table 30. As part of Phase 2, this will be developed further, and updated as new approaches are developed and further data become available from other tasks being undertaken as part of the IPT (Task 3).

We have developed plans for a scoping model that will be used to assess alternative options quantitatively and to develop our understanding of the impact of different components of the overall system. This was described in Section 9.3. This approach will be developed as part of Phase 2 (Task 3).

We will develop and justify a revised methodology for the OESA. The doses presented in Table 31 are above the design target (as discussed in Section 9.4). The current approach includes a number of cautious assumptions and approaches; these will be examined as part of Phase 2, with the aim of adopting a revised and less cautious methodology (Task 20).

We plan to develop a total system model for the carbon-14 gas pathway. The post-closure assessment of the groundwater pathway uses a probabilistic approach, whereas for the gas pathway a deterministic approach has been adopted to date (including the calculations reported in Sections 5 and 9.2). We propose to develop a probabilistic approach for the gas pathway, focusing initially on higher strength rocks. This will enable us to adopt a structured approach to parameter uncertainty (Task 21).

We will re-run the calculations, as new models and data become available. In particular, we will re-run the calculations at the end of Phase 2 (Tasks 3 and 22). These will include an investigation of parameter uncertainty, and any alternative approaches that are being considered.

**Integration**

We have set up the project structure to facilitate integration. Core activities are managed by the IPT directly; other relevant existing projects have been transferred into the IPT and are now managed as supporting work packages. This includes projects on gas generation from graphite and irradiated reactive metals, and a project on the behaviour of carbon-14 in the biosphere. We have also established routes for communication with other related activities funded through other sources.

We will continue to use the AND approach to keep Task prioritisation under review in the light of new data that become available, and results from scoping calculations.
The integration activities include project management and attendance at Project Board meetings (Task 24), regular project update and review meetings (Task 25), and the preparation of a report at the end of Phase 2 describing the work undertaken (Task 27). We will also communicate the results of the project to relevant audiences, and in particular we will seek to present the work at an appropriate conference, and in a peer-reviewed journal (Task 28). Around the end of Phase 2, it is expected that the Gas Status Report will be updated, and this project will an important input to that document (Task 26).

**Overview of Phase 2 tasks**

The tasks proposed in Phase 2 of the programme are shown in Table 37, together with the estimated possible assessed risk or dose reduction that might result from the task. The relationships between the tasks are shown in Figure 20. This enables the Tasks to be linked into the “AND” approach.

Colour coding is used to illustrate certain groups of tasks:

- **Tasks shown in green are already ongoing.**
- **Tasks shown in purple will only be carried out if required.**
- Other tasks are shown in Black; these will form much of the work in Phase 2 of the IPT.

Each of the tasks is prioritised as High (H), Medium (M) or Low (L). The criteria used in making these judgments are as follows:

- **High** priority tasks are those associated with the largest contributors to dose and risk (and in particular reactive metals) or have large impacts on dose and risk (typically a factor of 10 to 100) for significant contributors.

- **Medium** priority tasks are those associated with significant contributors (but not the largest contributors) to dose or have moderate impacts on dose or risk (typically a factor of 3 to 10).

- **Low** priority tasks are judged to have lesser importance or potential impact, and may well not be commissioned until other work is undertaken.

The lead contractor will assemble a team to deliver the proposed scope and provide a costed proposal, which will include more detail on the scope of each task and the deliverables. The project will continue to run using an integrated approach with contractors and NDA RWMD working in partnership.

Progress review meetings will be held at approximately sixth monthly intervals and if required the project scope and programme will be revised. For a number of the planned tasks it is proposed to assemble a “best athlete” joint team, which may include experts from organisations not currently represented within the IPT. The tasks are shown in Table 37.
<table>
<thead>
<tr>
<th>Task number</th>
<th>Scope</th>
<th>Feeds into</th>
<th>Timing</th>
<th>Possible risk reduction</th>
<th>H/M/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Improve understanding of current radionuclide inventory data, assumptions and sources (see Section 3 for discussion of scope)</td>
<td>3</td>
<td>Dec 2012 to May 2013</td>
<td>Decrease by factor of ~3?</td>
<td>M</td>
</tr>
<tr>
<td>2</td>
<td>Improve materials data underpinning the inventory (see Section 3 for discussion of scope)</td>
<td>3</td>
<td>Dec 2012 to Aug 2013</td>
<td>Decrease by factor of ~3-5</td>
<td>M</td>
</tr>
<tr>
<td>3</td>
<td>Update modelling basis spreadsheet and scoping model, when revised inventory and experimental data are available</td>
<td>12, 22, 26</td>
<td>Sep 2013 to Dec 2013</td>
<td>(As 1 and 2 above)</td>
<td>H</td>
</tr>
<tr>
<td>4</td>
<td>Measure rate and speciation of carbon-14 release from Oldbury Magnox graphite – ongoing project</td>
<td>6</td>
<td>To Jan 2014</td>
<td>Decrease by factor of 10-100</td>
<td>H</td>
</tr>
<tr>
<td>5</td>
<td>CAST graphite work package (information exchange)</td>
<td>22</td>
<td>Sep 2013 to Feb 2018</td>
<td>Decrease by factor of 10-100 (As 4 above)</td>
<td>M</td>
</tr>
<tr>
<td>6</td>
<td>Develop revised model of graphite leaching, based on information from the AMEC experiments, CARBOWASTE, CAST and C-14 BIG, and drawing on arguments about the long-term stability of graphite. In developing the revised model, consider long-term stability of graphite, and the potential for immobilisation. Update scoping calculations</td>
<td>7, 8, 22, 23, 26</td>
<td>Jan 13 to Jun 13</td>
<td>See above</td>
<td>H</td>
</tr>
<tr>
<td>7</td>
<td>Gather additional graphite samples for possible future experiments</td>
<td>27</td>
<td>n/a</td>
<td></td>
<td>L</td>
</tr>
<tr>
<td>8</td>
<td>Consider further the impact of graphite segregation, drawing on work from CARBOWASTE and CAST</td>
<td>7, 22</td>
<td>Jul 13 to Dec 13</td>
<td>Decrease by factor of 100+</td>
<td>M</td>
</tr>
<tr>
<td>Task number</td>
<td>Scope</td>
<td>Feeds into</td>
<td>Timing</td>
<td>Possible risk reduction</td>
<td>H/M/L</td>
</tr>
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<tr>
<td>9</td>
<td>Gather data on rate and speciation of carbon-14 release from stainless steels through CAST, including an up-to-date review of all information on rate and speciation of carbon-14 release from steels held by CAST participants at the project outset</td>
<td>10</td>
<td>Jul 2013 to Mar 2014</td>
<td>Factor of ~10 on long-term release</td>
<td>M</td>
</tr>
<tr>
<td>10</td>
<td>Update modelling approach for stainless steel, including improved inventory data, shape data and any emerging data from CAST, together with consideration of uncertainty (include cost of participation in CAST stainless steels work package)</td>
<td>3, 22, 23, 26</td>
<td>Sep 2013 to Oct 2013 (combine with inventory update)</td>
<td>Factor of ~10 on long-term release from 8 above (but improved shape data could lead to increase)</td>
<td>M</td>
</tr>
<tr>
<td>11</td>
<td>Gather data on rate and speciation of carbon-14 release from reactive metals – ongoing project</td>
<td>12, 13, 22</td>
<td>To March 2014</td>
<td>Factor of 2 to 10</td>
<td>H</td>
</tr>
<tr>
<td>12</td>
<td>Develop understanding of carbon-14 release from packaged reactive metals in storage environments, during backfilling and following re-saturation, taking into account the likely availability of water and chloride, informed by appropriate experiments, modelling and analogue data</td>
<td>13, 22, 23</td>
<td>Dec 2012 to Mar 2014</td>
<td>Factor of 1 to 1000 (potentially)</td>
<td>H</td>
</tr>
<tr>
<td>13</td>
<td>Based on the above, consider / assess in more detail the impact of alternatives for reactive metals including dissolution, alternative packaging, gradual backfilling, mitigation etc.</td>
<td>22, 27</td>
<td>Jan 2014 to Jun 2014</td>
<td>Decrease by factor of 100+</td>
<td>H</td>
</tr>
<tr>
<td>Task number</td>
<td>Scope</td>
<td>Feeds into</td>
<td>Timing</td>
<td>Possible risk reduction</td>
<td>H/M/L</td>
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<tr>
<td>14</td>
<td>Incorporate understanding from relevant near field projects in the modelling basis spreadsheet, e.g. FORGE, carbonation experiment, interaction of gas and cement porewater during backfilling of vented containers, and PhD on microbial metabolism of hydrogen</td>
<td>22</td>
<td>Jan 2014 to Mar 2014</td>
<td>Possible decreases of 2 to 10</td>
<td>L</td>
</tr>
<tr>
<td>15</td>
<td>Understanding the envelope of geological environments in which carbon-14 bearing wastes can be tolerated, including incorporating the understanding from analogues of gas release and release area and from relevant geosphere projects, and keeping the modelling basis spreadsheet updated</td>
<td>22</td>
<td>Jan 2014 to Mar 2014</td>
<td>Possible decreases of 2 to 100 or more</td>
<td>M</td>
</tr>
<tr>
<td>16</td>
<td>If required, develop understanding to inform the requirements for site characterisation</td>
<td>27</td>
<td>Mar 2014 to Jul 2014</td>
<td>As 15 above</td>
<td>M</td>
</tr>
<tr>
<td>17</td>
<td>Complete biosphere field experiment and reflect revised understanding in model—ongoing project</td>
<td>18, 19</td>
<td>To Dec 2013</td>
<td>Possible decrease of up to 10</td>
<td>H</td>
</tr>
<tr>
<td>18</td>
<td>BIOPROTA. Peer review of biosphere model and inter-comparison with other models used internationally – ongoing project</td>
<td>22</td>
<td>To Dec 2013</td>
<td>n/a</td>
<td>M</td>
</tr>
<tr>
<td>19</td>
<td>Carry our literature review to investigate scope for biosphere factor to be reduced based on available literature and document revised basis</td>
<td>22</td>
<td>Jan 2013 to Jun 2013</td>
<td>Possible decrease by factor of 10</td>
<td>M</td>
</tr>
<tr>
<td>20</td>
<td>Develop and justify a revised methodology for the OESA, addressing pessimistic assumptions in the current approach</td>
<td>3, 22</td>
<td>Dec 2012 – March 2013</td>
<td>Factor of 10 or more, operational period</td>
<td>M</td>
</tr>
<tr>
<td>Task number</td>
<td>Scope</td>
<td>Feeds into</td>
<td>Timing</td>
<td>Possible risk reduction</td>
<td>H/M/L</td>
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<tr>
<td>21</td>
<td>Develop approach to the total system model for carbon-14 (may include groundwater as well as gas) in higher strength rocks, based on consideration of uncertainty and modelling basis spreadsheet</td>
<td>27</td>
<td>Dec 2012 – Dec 2013</td>
<td>n/a</td>
<td>M</td>
</tr>
<tr>
<td>22</td>
<td>Re-run of calculations for Phase 2 report – including a consideration of parameter uncertainties and any alternative approaches under consideration</td>
<td>27</td>
<td>Mar 2014 to Jun 2014</td>
<td>n/a</td>
<td>H</td>
</tr>
<tr>
<td>23</td>
<td>Consider testing the revised approach at a system level – experiments that integrate wastes with the engineered barriers</td>
<td>27</td>
<td>Jan 2014 to June 2014</td>
<td>n/a</td>
<td>M</td>
</tr>
<tr>
<td>24</td>
<td>Project management and attendance at project board meetings</td>
<td>n/a</td>
<td>Dec 2012 to Dec 2014</td>
<td>n/a</td>
<td>M</td>
</tr>
<tr>
<td>25</td>
<td>Project update / review meetings (4-5 in total)</td>
<td>n/a</td>
<td>Dec 2012 to Dec 2014</td>
<td>n/a</td>
<td>M</td>
</tr>
<tr>
<td>26</td>
<td>Input to gas status report</td>
<td>27</td>
<td>Sep 2014 to Dec 2014</td>
<td>n/a</td>
<td>H</td>
</tr>
<tr>
<td>27</td>
<td>Phase 2 report, presenting the work carried out in Phase 2 and describing the current status at the end of the project.</td>
<td>n/a</td>
<td>Jun 2014 to Dec 2014</td>
<td>Realises benefits from above</td>
<td>H</td>
</tr>
<tr>
<td>28</td>
<td>Communicate the results of the project to relevant audiences, in particular to present papers at an appropriate conference, and in a peer-reviewed journal.</td>
<td>n/a</td>
<td>Jun 2014 to Dec 2014</td>
<td>Realises benefits from above</td>
<td>H</td>
</tr>
</tbody>
</table>
Figure 20  **Phase 2 Roadmap tasks – showing the linkage between tasks.**  
The numbers in Bold show the relationship to tasks in Table 37.

- **Graphite**
  - Improve understanding of radioactive and materials inventory for graphite wastes 1, 2
  - Improve data and model for C-14 release from graphite 4, 5, 6, 7
  - Consider segregation of graphite wastes 8
- **Steels**
  - Improve understanding of radioactive and materials inventory for steels 1, 2
  - Gather data on release of C-14 from stainless steel 9
  - Improve model for release of C-14 10
  - Consider alternative options (treatment etc.) for reactive metals 13
- **Reactive metals**
  - Improve understanding of radioactive and materials inventory for reactive metals 1, 2
  - Improve data on release of C-14 from reactive metals 11
  - Understand release of C-14 during storage, backfilling etc. 12
  - Support site characterisation inputs to MRWS 16
- **Organics**
  - No work proposed
- **Spent fuel**
  - Improve understanding of inventory in spent fuel 1
  - No work proposed
  - Long-lived container
- **Overall**
  - Keep modelling basis up-to-date 3
  - Revise OESA methodology 20
  - Develop total system model 21
  - Re-run calculations 3, 22
  - Consider experiments to test at the system level 23
  - Phase 2 report 27
  - Communicate results to relevant audiences 26

  - Incorporate understanding of geosphere migration and understand the envelope of environments in which C-14 bearing wastes are tolerable 15
  - Complete biosphere experiments 17
  - Review biosphere processes and models, including participation in B/PROTA 18, 19
  - Incineration is current baseline
11.6 Deliverables

At the end of Phase 2, the integrated project team will deliver a Phase 2 report, which will deliver the project objectives. The report will include:

- A summary of the updated inventory;
- Data on the generation of carbon-14 bearing gas from irradiated graphite, irradiated reactive metals and irradiated stainless steel;
- Revised models of gas generation from irradiated graphite and irradiated stainless steel;
- An update modelling basis, including updated basis for near field migration and migration and uptake in the biosphere;
- Updated calculations of the consequences of release of gaseous carbon-14;
- Consideration of the envelope of conditions under which wastes containing carbon-14 could be managed in different geological environments;
- A view on whether mitigation measures or design solutions would be beneficial for particular wastes (in particular ILW core graphite and reactive metals); and
- If required, data and understanding to inform the requirements for site characterisation.

At the end of Phase 2, some tasks will still be on-going including:

- The CAST project, which will continue to provide data and understanding of the source term of carbon-14 generation from irradiated materials.
- Relevant near-field work, including for example work to investigate the microbial metabolism of hydrogen.

We will also seek to present the work at an appropriate conference and publish the work in a peer-reviewed journal.

Conclusions at the end of Phase 2 will be generic and thus will need to distinguish between aspects that would apply in all geological environments and aspects that are very dependent on the geological environment. The holistic approach to managing carbon-14 in the disposal system may need to be revised in the light of site-specific information that would arise at future stages of the MRWS process. We will also seek to present the work at an appropriate conference and publish the work in a peer-reviewed journal.
12 **List of acronyms and abbreviations**

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGR</td>
<td>Advanced Gas-cooled Reactor</td>
</tr>
<tr>
<td>BEPO</td>
<td>British Experimental Pile 0</td>
</tr>
<tr>
<td>BGS</td>
<td>British Geological Survey</td>
</tr>
<tr>
<td>BWR</td>
<td>Boiling Water Reactor</td>
</tr>
<tr>
<td>CAST</td>
<td>Carbon-14 Source Term (Proposed international collaborative project as part of the IGD-TP – see below))</td>
</tr>
<tr>
<td>DI</td>
<td>Derived Inventory</td>
</tr>
<tr>
<td>DNLEU</td>
<td>Depleted, Natural and Low Enriched Uranium</td>
</tr>
<tr>
<td>DSSC</td>
<td>Disposal System Safety Case</td>
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<tr>
<td>EARP</td>
<td>Enhanced Actinide Removal Plant</td>
</tr>
<tr>
<td>EBS</td>
<td>Engineered Barrier System</td>
</tr>
<tr>
<td>EDI</td>
<td>Estimated Derived Inventory</td>
</tr>
<tr>
<td>EDZ</td>
<td>Excavation Disturbed Zone</td>
</tr>
<tr>
<td>EPSRC</td>
<td>Engineering and Physical Sciences Research Council</td>
</tr>
<tr>
<td>ESC</td>
<td>Environmental Safety Case</td>
</tr>
<tr>
<td>EU</td>
<td>European Union</td>
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<tr>
<td>FED</td>
<td>Fuel Element Debris</td>
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<tr>
<td>FSC</td>
<td>Final Site Clearance</td>
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<tr>
<td>GDF</td>
<td>Geological Disposal Facility</td>
</tr>
<tr>
<td>GPA (03)</td>
<td>Generic Performance Assessment 2003</td>
</tr>
<tr>
<td>HLW</td>
<td>High Level Waste</td>
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<tr>
<td>HPLC</td>
<td>High Performance Liquid Chromatography</td>
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<tr>
<td>HSR</td>
<td>Higher Strength Rock</td>
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<tr>
<td>IGD-TP</td>
<td>Implementing Geological Disposal - Technology Platform</td>
</tr>
<tr>
<td>ILW</td>
<td>Intermediate Level Waste</td>
</tr>
<tr>
<td>IPT</td>
<td>Integrated Project Team</td>
</tr>
<tr>
<td>IRS</td>
<td>Information Retrieval System</td>
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<tr>
<td>LLW</td>
<td>Low Level Waste</td>
</tr>
<tr>
<td>LLWR</td>
<td>Low Level Waste Repository</td>
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<tr>
<td>MRWS</td>
<td>Managing Radioactive Waste Safely</td>
</tr>
<tr>
<td>NDA</td>
<td>Nuclear Decommissioning Authority</td>
</tr>
<tr>
<td>NRVB</td>
<td>Nirex Reference Vault Backfill</td>
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<tr>
<td>OESA</td>
<td>Operational Environmental Safety Assessment</td>
</tr>
<tr>
<td>PCSA</td>
<td>Post-Closure Safety Assessment</td>
</tr>
<tr>
<td>PDF</td>
<td>Probability Density Function</td>
</tr>
<tr>
<td>Acronym</td>
<td>Full Form</td>
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<tr>
<td>---------</td>
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</tr>
<tr>
<td>PEG</td>
<td>Potential Exposed Group</td>
</tr>
<tr>
<td>PhD</td>
<td>Doctor of Philosophy</td>
</tr>
<tr>
<td>PWR</td>
<td>Pressurised Water Reactor</td>
</tr>
<tr>
<td>R&amp;D</td>
<td>Research and Development</td>
</tr>
<tr>
<td>RWMD</td>
<td>Radioactive Waste Management Directorate</td>
</tr>
<tr>
<td>SGHWR</td>
<td>Steam-Generating Heavy Water Reactor</td>
</tr>
<tr>
<td>SILW</td>
<td>Shielded Intermediate Level Waste</td>
</tr>
<tr>
<td>SMOGG</td>
<td>Simplified Model of Gas Generation</td>
</tr>
<tr>
<td>THORP</td>
<td>Thermal Oxide Reprocessing Plant</td>
</tr>
<tr>
<td>UILW</td>
<td>Unshielded Intermediate Level Waste</td>
</tr>
<tr>
<td>UK</td>
<td>United Kingdom</td>
</tr>
<tr>
<td>UKRWI</td>
<td>UK Radioactive Waste Inventory</td>
</tr>
<tr>
<td>WAGR</td>
<td>Windscale Advanced Gas-cooled Reactor</td>
</tr>
<tr>
<td>WEP</td>
<td>Wastes Encapsulation Plant</td>
</tr>
</tbody>
</table>
13 Glossary of terms

Advanced Gas-cooled Reactor (AGR)
The reactor type used in the UK’s second generation nuclear power plants.

Aerobic
A chemical or biological condition that denotes the presence of free oxygen.

Anaerobic
A chemical or biological condition that denotes the absence or effective absence (i.e. very low partial pressure) of free oxygen.

Aquifer
A layer of rock or drift deposits that has sufficient intergranular and/or fracture permeability that it may support water supply and/or river base flow.

Backfill
A material used to fill voids in a GDF. Three types of backfill are recognised:

- local backfill, which is emplaced to fill the free space between and around waste packages;
- peripheral backfill, which is emplaced in disposal modules between waste and local backfill, and the near-field rock or access ways; and
- mass backfill, which is the bulk material used to backfill the excavated volume apart from the disposal areas.

Backfilling
The refilling of the excavated portions of a disposal facility after emplacement of the waste.

Barrier
A physical or chemical means of preventing or inhibiting the movement of radionuclides.

Baseline Inventory
An estimate of the higher activity radioactive waste and other materials that could, possibly, come to be regarded as wastes that might need to be managed in the future through geological disposal drawn from the UK Radioactive Waste Inventory.

Becquerel (Bq)
The standard international unit of radioactivity equal to one radioactive decay per second. Multiples of becquerels commonly used to define radioactive waste activity are:

- kilobecquerels (kBq) equal to 1 thousand \(10^3\) Bq
- megabecquerels (MBq) equal to 1 million \(10^6\) Bq
- gigabecquerels (GBq) equal to 1 billion \(10^9\) Bq
- terabecquerels (TBq) equal to 1 trillion \(10^{12}\) Bq

Biosphere
Regions of the earth’s surface and atmosphere normally inhabited by living organisms.
**Corrosion**
Progressive surface dissolution of a material. A term generally used for metals. In radioactive waste management, it is also used for glasses and ceramic waste forms. Corrosion can be uniform over the surface of the material or non-uniform through enhanced corrosion in stressed areas at physical discontinuities. Selective localized formation of rounded cavities on the surface is called pitting corrosion.

**Decommissioning**
The process whereby a nuclear facility, at the end of its economic life, is taken permanently out of service and its site made available for other purposes.

**Decommissioning waste**
Radioactive waste produced during operations involved in the decommissioning of a nuclear facility.

**Diffusion**
The movement of atoms or molecules from a region of higher concentration of the diffusing species to regions of lower concentration, due to a concentration gradient.

**Disposal**
In the context of solid waste, disposal is the emplacement of waste in a suitable facility without intent to retrieve it at a later date; retrieval may be possible but, if intended, the appropriate term is storage. (MRWS)

**Emplacement (of waste in a disposal facility)**
The placement of a waste package in a designated location for disposal, with no intent to reposition or retrieve it subsequently.

**Engineered barrier system**
The combination of the man-made engineered components of a disposal facility, including the waste packages/disposal canisters, buffer, backfills and seals.

**Environmental Safety Case (ESC)**
The collection of arguments, provided by the developer or operator of a disposal facility, that seeks to demonstrate that the required standard of environmental safety is achieved.

**Evaporite**
The generic term for a geological environment created by the evaporation of water from a salt bearing solution to form a solid structure.

**G value**
A measure of gas generation by radiolysis, expressed as the amount of gas produced per absorbed radiation energy.

**Geological disposal**
A long term management option involving the emplacement of radioactive waste in an engineered underground geological disposal facility or repository, where the geology (rock structure) provides a barrier against the escape of radioactivity and there is no intention to retrieve the waste once the facility is closed. (MRWS)

**Geological disposal facility (GDF)**
An engineered underground facility for the disposal of solid radioactive wastes.
**Geological Disposal System**

The totality of the physical infrastructure needed to implement geological disposal, including a GDF, an associated transport system and other essential infrastructure.

**Geological unit**

A discrete subdivision of rock mass within which the certain defined characteristics (e.g. hydrogeological properties, age range or rock type) are essentially similar and can be treated as a coherent body for modelling purposes. Each geological unit will have characteristics that distinguish it from adjacent geological units.

**Geosphere**

The rock surrounding a GDF that is located below the depth affected by normal human activities and is therefore not considered to be part of the biosphere.

**Groundwater**

Water located beneath the earth's surface in rock pores and fractures.

**Half-life**

The time taken for the activity of a given amount of a radioactive substance to decay to half of its initial value. Each radionuclide has a unique half-life.

**Higher strength rock**

Typically crystalline igneous and metamorphic rocks or geologically older sedimentary rocks where any fluid movement is predominantly through discontinuities.

**High level waste (HLW)**

Radioactive wastes in which the temperature may rise significantly as a result of their radioactivity, so this factor has to be taken into account in the design of storage or disposal facilities.

**Hydraulic conductivity**

A property of rocks indicating the ease with which water can move through pore spaces or fractures defined as the ratio of flow rate, $q$, to driving force $dh/dl$ (the change of hydraulic head with distance) for viscous flow of a fluid in a porous medium.

**Intermediate level waste (ILW)**

Radioactive wastes exceeding the upper activity boundaries for LLW but which do not need heat to be taken into account in the design of storage or disposal facilities.

**Lower strength sedimentary rock**

Typically geologically “young” sedimentary rocks where any fluid movement is predominantly through the rock matrix.

**Low level waste (LLW)**

Defined as “radioactive waste having a radioactive content not exceeding 4 gigabecquerels per tonne (GBq/te) of alpha or 12 GBq/te of beta/gamma activity”.

**Low Level Waste Repository (LLWR)**

The UK national facility for the near surface disposal of solid LLW, located near to the village of Drigg in Cumbria.

**Magnox**

Reactor type widely used in the UK for the first generation of power stations. Also a magnesium alloy, commonly used as fuel cladding in Magnox nuclear power stations in the UK.
Managing Radioactive Waste Safely (MRWS)
A phrase covering the whole process of public consultation, work by CoRWM, and subsequent actions by Government, to identify and implement the option, or combination of options, for the long term management of the UK’s higher activity radioactive waste.

Methanogenesis
A microbial process leading to the production of methane.

Microbe
A microorganism (small life form).

Modelling basis spreadsheet
A spreadsheet used to record our current understanding and how we represent this in the mathematical model.

Near field
The engineered barrier system (including the wasteform, waste containers, buffer materials, backfill, and seals), as well as the host rock within which the GDF is situated, to whatever distance the properties of the host rock have been affected by the presence of a GDF.

Nirex (United Kingdom Nirex Limited)
An organisation previously owned jointly by Department for the Environment, Food and Rural Affairs and the Department for Trade and Industry. Its objectives were, in support of Government policy, to develop and advise on safe, environmentally sound and publicly acceptable options for the long-term management of radioactive materials in the United Kingdom. The Government’s response to Committee on Radioactive Waste Management in October 2006 initiated the incorporation of Nirex functions into the NDA, a process which was completed in March 2007.

Nuclear Decommissioning Authority (NDA)
The NDA is the implementing organisation, responsible for planning and delivering the GDF. The NDA was set up on 1 April 2005, under the Energy Act 2004. It is a non-departmental public body with designated responsibility for managing the liabilities at specific sites. These sites are operated under contract by site licensee companies (initially British Nuclear Group Sellafield Limited, Magnox Electric Limited, Springfields Fuels Limited and UK Atomic Energy Authority). The NDA has a statutory requirement under the Energy Act 2004, to publish and consult on its Strategy and Annual Plans, which have to be agreed by the Secretary of State (currently the Secretary of State for Trade and Industry) and Scottish Ministers.

Permeability
A measure of the rate at which a gas or a liquid moves under a pressure gradient through a porous material. Often used interchangeably with hydraulic conductivity (see above).

Photosynthesis
A process used by plants and other organisms to convert the light energy captured from the sun into chemical energy that can be used to fuel the organism’s activities

Porewater
Groundwater held within a space or pore in rock.

Porosity
The ratio of the aggregate volume of interstices or porous media to total volume of a body.
**Post-closure period (of a disposal facility)**
The period following sealing and closure of a facility and the removal of active institutional controls.

**Pressurised Water Reactor (PWR)**
Reactor type using ordinary water under high pressure as a coolant and neutron moderator. PWRs are widely used throughout the world for electricity generation. The Sizewell B reactor in Suffolk is of this design.

**Radiological consequence**
The assessed impact to a potentially exposed group as a result of exposure to radiation, for example through inhalation or ingestion.

**Radiolysis**
The degradation of a chemical as a result of exposure to radiation.

**Resaturation**
The process of returning the concentration of water in a system to its maximum holding capacity.

**Risk guidance level**
A level of radiological risk from a disposal facility which provides a numerical standard for assessing the environmental safety of the facility after the period of authorisation.

**Roadmap**
A document that sets out the future direction for a project including how it will be implemented.

**Sedimentary**
A type of rock resulting from the consolidation of loose material that has accumulated in layers. The layers may be built up mechanically or by chemical precipitation. Generally, the material that accumulates has originated from the weathering of other rocks or from secretions of living organisms. Sedimentary rocks constitute one of the three main classes of rocks, the others being igneous and metamorphic.

**Shielded waste package**
A shielded waste package is one that either has in-built shielding or contains low activity materials, and thus may be handled by conventional techniques.

**Site characterisation**
Detailed surface and subsurface investigations and activities at a site to determine the radiological conditions at the site or to evaluate candidate disposal sites to obtain information to determine the suitability of the site for a repository and to evaluate the long term performance of a repository at the site.

**Spent fuel**
Nuclear fuel removed from a reactor following irradiation that is no longer usable in its present form because of depletion of fissile material, poison build-up or radiation damage.

**Total system model**
A simplified model used to calculate overall performance measures of the geological disposal system, such as radiological dose and risk.
UK Radioactive Waste Inventory (UKRWI)

A compilation of data on UK radioactive waste holdings, produced about every three years. The latest version, for a holding date of 1 April 2010, was published in February 2011. It is produced by DECC and the NDA. It is the latest public record of information on the sources, quantities and properties of LLW, ILW and HLW in the UK. It comprises of a number of reports and additional detailed information on the quantities and properties of radioactive wastes in the UK that existed at 1 April 2010 and those that were projected to arise after that date.

Unshielded waste package

A waste package which, owing either to radiation levels or containment requirements, requires remote handling and must be transported in a reusable transport container.

Waste package

The product of conditioning that includes the waste form and any container(s) and internal barriers (e.g. absorbing materials and liner), as prepared in accordance with requirements for handling, transport, storage and/ or disposal.

Zircaloy

A zirconium alloy, commonly used as fuel cladding in PWR nuclear power stations in the UK.
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