NDA Proposed MRWS Research & Development Strategy

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Recommendations

- That Members feedback comments in order to inform the NDA of our position.

- Comments to be made by 30 November 08.

Introduction

Assurance of safety of a geological disposal facility is based on a thorough understanding of the wastes, the engineered materials used in packaging the wastes, the materials used in constructing the geological disposal facility, the geological environment in which the facility is constructed, and the processes that might threaten their integrity as barriers. Such an understanding underpins the safety cases which will be the basis for regulatory submissions and to underpin an application for planning permission to construct and operate a geological disposal facility. Research and development ensures there is an appropriate understanding of the materials and processes, and supports the choices made in waste packaging, concept development and the design of the facility.

This consultation document presents RWMD.s proposals for the research and development (R&D) strategy to underpin the implementation of a geological disposal facility. The consultation deadline is the 30 November 2008.

Waste Management Directorate (NDA RWMD)

The Nuclear Decommissioning Authority (NDA) is the body charged by Government with implementing geological disposal of the UK's higher activity radioactive wastes; the Radioactive Waste Management Directorate (NDA RWMD) is discharging this responsibility. The RWMD will evolve into the organisation responsible for the implementation of a geological disposal facility. In addition, the NDA RWMD is responsible for setting specifications and providing advice for converting raw wastes into safe and stable waste packages, thereby greatly reducing the risk of harm to industry workers and the public.

CoRWM Final Recommendations

CoRWM combined a technical assessment of options with ethical considerations, examination of overseas experience and a wide-ranging programme of engagement both with the public and with interested parties (specific stakeholders). They made

fifteen recommendations. In summary they recommended that geological disposal, preceded by safe and secure storage, was the best available approach for the long-term management of higher activity radioactive wastes, and that a voluntarist and partnership approach be adopted for the selection of a site.

In particular, with reference to R&D, CoRWM.s recommendations number 4 and 5 were pertinent, these are;

4: There should be a commitment to an intensified programme of research and development into the long-term safety of geological disposal aimed at reducing uncertainties at generic and site-specific levels, as well as into improved means for storing wastes in the longer term.

5: The commitment to ensuring flexibility in decision making should leave open the possibility that other long-term management options (for example, borehole disposal) could emerge as practical alternatives. Developments in alternative management options should be actively pursued through monitoring of and/or participation in national or international R&D programmes.

NDA RWMD R&D Priorities
The priorities below are derived from the drivers for the R&D programme discussed in Section 3.2.

In summary these are:
- To prepare for future phases of the implementation programme.
- To build confidence in the concept by addressing residual technical uncertainties.
- To support .upstream optimization and the delivery of cost-effective waste management solutions.
- To provide the required inputs into the Disposal System Safety Cases.
- To pursue research and development on the concept for high-level waste (HLW) and spent fuel, building on work undertaken overseas.
- To support the Letter of Compliance (LoC) process.

These priorities ensure that the safety strategy for the geological disposal facility are underpinned by appropriate R&D, and that the R&D feeds into the programme for the implementation of a geological disposal facility in a timely manner.

The main areas of current research are a follows:

- Corrosion research
- Waste package research
- ILW Wasteform research
- High-level waste and spent fuel
- Criticality research
- Geosphere research
- Biosphere research
- Geosphere characterisation
- Engineering development

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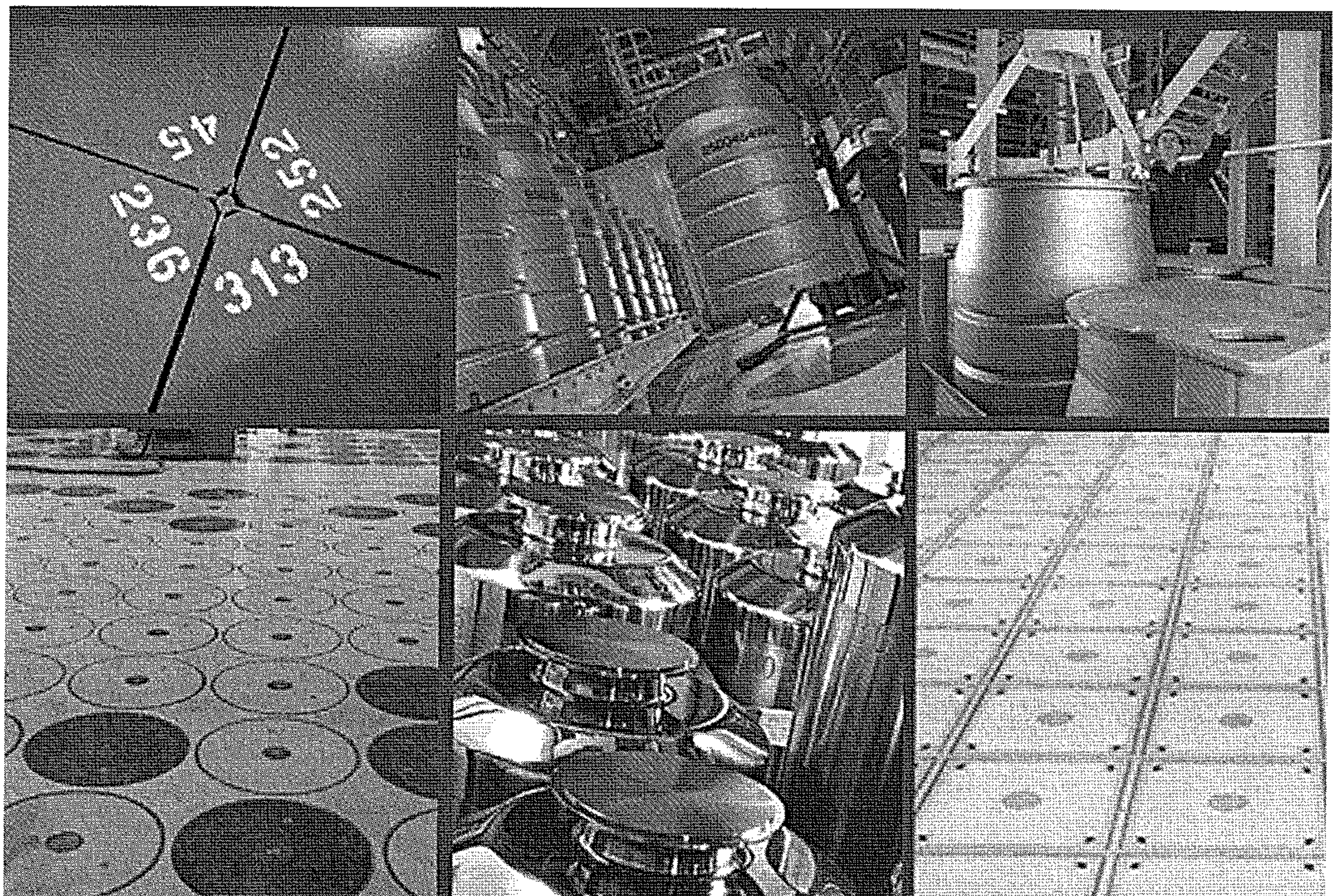
Nuclear
Decommissioning
Authority



NDA Radioactive Waste Management Directorate

Proposed Research and Development Strategy

CONDITIONS OF PUBLICATION

BIBLIOGRAPHY

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FEEDBACK

Readers are invited to provide feedback to the NDA on the contents, clarity and presentation of this report and on the means of improving the range of NDA reports published. Feedback should be addressed to:

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Foreword

The purpose of this publication is to present NDA proposals for a strategy of research and development linked to the implementation of a geological disposal facility for higher activity radioactive wastes. These proposals have been developed largely in-house and it is now appropriate to seek views from a wide range of stakeholders.

It will be sent formally for review by key stakeholders such as the regulators and the Committee on Radioactive Waste Management (CoRWM) (charged with providing ongoing independent scrutiny and advice to UK Government and devolved administrations on the long term management, including interim storage and disposal, of radioactive waste). The NDA proposes also to organise a workshop to facilitate discussion. Equally it welcomes individual comment from all with an interest in the geological disposal facility project. The plan is to publish a revised version of the R&D strategy once input material has been collected and analysed. Please send all such comment to:

rwmd_researchcomments@nda.gov.uk

The revised version of the R&D Strategy is scheduled for publication at the end of March 2009. Hence we would be grateful for comments before the end of November 2008.

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1 INTRODUCTION

The Nuclear Decommissioning Authority (NDA) is the body charged by Government with implementing geological disposal of the UK's higher activity radioactive wastes; the Radioactive Waste Management Directorate (NDA RWMD) is discharging this responsibility. It is envisaged that RWMD will evolve into the organisation responsible for the implementation of a geological disposal facility.

NDA RWMD is responsible for setting specifications and providing advice for converting raw wastes into safe and stable waste packages, thereby greatly reducing the risk of harm to industry workers and, of course, the public at large. The specifications take account of very long time periods (many hundreds of thousands of years) that the wastes will remain hazardous following emplacement in a geological disposal facility. The hazard, however, declines substantially with time as a direct consequence of radioactive decay.

The standards for safety are set by Government, and the regulators ensure they are met. The Nuclear Installations Inspectorate (NII) regulates the nuclear, radiological and industrial safety of nuclear installations, and the environment agencies (The Environment Agency (EA), for England and Wales and the Scottish Environment Protection Agency (SEPA)) authorise and regulate radioactive and non-radioactive discharges and disposals. Transport of radioactive materials is regulated by the Department for Transport (DfT), and security by the Office for Civil Nuclear Security (OCNS).

Assurance of safety of a geological disposal facility is based on a thorough understanding of the wastes themselves, the engineered materials used in packaging the wastes, the materials used in constructing the geological disposal facility, the geological environment in which the facility is constructed, and the processes that might threaten their integrity as barriers. Such an understanding underpins the safety cases which will be the basis for regulatory submissions and to underpin an application for planning permission to construct and operate a geological disposal facility. Research and development ensures there is an appropriate understanding of the materials and processes, and supports the choices made in waste packaging, concept development and the design of the facility. The approach adopted in the UK is very similar to those followed by waste management organisations worldwide. Confidence is derived from the commonality of the adopted approaches.

This document presents RWMD's proposals for the research and development (R&D) strategy to underpin the implementation of a geological disposal facility. The background to the strategy is presented in Section 2. Recent developments in Government policy on long-term waste management are discussed, and in particular the approach to the development of a geological disposal facility in the UK.

The RWMD approach to the development of the R&D strategy is discussed in Section 3. The R&D programme is driven by the needs of the wider programme, primarily the safety cases and the engineering requirements, and the relationship of the R&D programme to other parts of the scientific and technical programme of NDA RWMD is described. The document sets out the drivers for the R&D programme, and describes how the focus of the programme will evolve through the implementation process. It then discusses the way work is prioritised, and the way the programme is implemented and the work is procured. Finally the ways the R&D programme is scrutinised and reviewed, both by scientific peers and by regulators, are described. This is important as it provides assurance on the quality of the science in the programme.

This is followed in Section 4 with a summary discussion of the current status and future programme for research and development in the various technical areas that make up the programme.

2 BACKGROUND TO THE R&D STRATEGY

2.1 The Development of UK Government Policy for the Long-term Management of Radioactive Wastes

In September 2001, Government (UK Government and the devolved administrations) instigated the first stage of its Managing Radioactive Waste Safely Programme (MRWS). The second stage began in July 2002, when Government published its response to the 2001 consultation, followed in 2003 by the appointment of the independent Committee on Radioactive Waste Management (CoRWM). Government commissioned CoRWM to oversee a review of options for the long-term management of the UK's higher activity radioactive wastes, and to recommend the option, or combination of options, that could provide a long-term solution, providing protection for people and the environment. Their objective was to provide recommendations, which inspired public confidence and were practicable in securing the long-term safety of those wastes. CoRWM began its work in November 2003 and delivered its recommendations in its report to Government on 31 July 2006 [1].

2.1.1 The 2006 Recommendations of CoRWM, and the Government's Response

CoRWM combined a technical assessment of options with ethical considerations, examination of overseas experience and a wide-ranging programme of engagement both with the public and with interested parties (specific stakeholders). They made fifteen recommendations, which are set out in full in Appendix 1. In summary they recommended that geological disposal, preceded by safe and secure storage, was the best available approach for the long-term management of higher activity radioactive wastes, and that a voluntarist and partnership approach be adopted for the selection of a site. In particular CoRWM's Recommendation 4 was: 'There should be a commitment to an intensified programme of research and development into the long-term safety of geological disposal aimed at reducing uncertainties at generic and site-specific levels, as well as into improved means for storing wastes in the longer term.'

The CoRWM recommendations became the basis for Government Policy, defining the way forward for long-term management of higher activity wastes. In addition to the extensive quality assurance and peer review mechanisms established by CoRWM, an expert panel set up by the Chief Scientific Advisor to the Department for Environment, Food and Rural Affairs (Defra) provided quality assurance and peer review on behalf of Government. CoRWM's final report [1] has also been considered and reviewed by the cross-Government MRWS Implementation Planning Group.

In its response [2], Government noted that the open and transparent manner in which CoRWM conducted its business had been both effective and original. It welcomed CoRWM's report, commenting that it provided a sound basis for moving forward. It proposed to act on most recommendations immediately but suggested others would require Government to undertake further work. In particular, Government accepted that geological disposal coupled with safe and secure interim storage was the preferred approach for the long term management of the UK's higher activity wastes. It noted that geological disposal was the approach being adopted in the majority of other nuclear nations, including Belgium, Finland, France, Germany, Japan, Sweden, Switzerland and the USA. CoRWM's work had shown that this is also the appropriate way forward for the UK. It observed, however, that securing geological disposal would represent a major challenge requiring commitment over many decades.

The Government's response was supportive of exploring how an approach based on voluntarism (that is, willingness to participate) and partnership could be made to work in practice. Government further noted that this would have to be integrated with the assessment of the geographical and geological suitability of possible sites. Government therefore proposed further work on these issues. It proposed a new consultation about the development of an implementation framework as soon as practicable.

Government accepted CoRWM's recommendation that the implementation process should be staged so as to incorporate a series of appropriate decision points. This would allow the programme and progress to be kept under review, including cost and value for money issues. It also accepted CoRWM's recommendation on the need for independent advice and scrutiny of the implementation process.

In its response, Government announced that the Nuclear Decommissioning Authority, would be given the responsibility for developing and ensuring delivery and implementation of the programmes for interim storage and implementing geological disposal. This was effected early in 2007, when Nirex was integrated into the NDA.

CoRWM, in its deliberations, had access to numerous documents prepared by Nirex describing concepts that had been developed over many years for a UK geological disposal facility. The Nirex position was that the technical basis of the geological disposal was sound, and that it was viable and could be implemented in the United Kingdom. This view had been transmitted in a series of papers for the CoRWM consultation. It was founded both on its own research and development, and that of the substantial number of overseas waste management companies referred to in the Government's response. The Nirex R&D programme, inherited by the NDA, has been developed to add further reassurance to the generic concept and plans in hand. It was based on its own critical and dynamic appraisal and external scrutiny, not least by the regulators. Two important records of this are Nirex Report N/122 "The viability of a phased geological repository concept for the long-term management of the UK's radioactive waste" [3] and the Environment Agency's review of this [4].

A timetable for the first steps to implement CoRWM's recommendations was suggested in Government's response to the CoRWM policy recommendations [2]. A consultation document [5] was issued in June 2007 by Defra, DTI and the Welsh and Northern Irish devolved administrations. It set out a number of proposals for implementation and further provides indicative timescales for a disposal facility covering all stages up to, and including, first waste emplacement[1].

In the consultation document, it is envisaged that some 20 to 30 years would be needed to reach the emplacement stage. Initially the siting process would be agreed, and it would be followed by a number of stages of site selection. The early stages would cover the issuing of invitations for expressions of interest, geological screening and desk-based studies. Thereafter work on potential sites would commence with surface-based investigations.

Once these have been completed, and there is confidence that a site is suitable for a geological disposal facility, underground investigations would be undertaken, to confirm a site's suitability to host a geological disposal facility complying with safety and environmental requirements.

The Government also accepted CoRWM's recommendation on research, and said in the consultation document [5]: 'The implementing organisation – the NDA – has statutory

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[1] The Scottish Executive decided not to sponsor this consultation.

responsibilities under the Energy Act 2004 for carrying out research to support the activities for which it is responsible. The UK Government believes that there is already sufficient research work and international experience available to be confident that geological disposal is technically achievable. However in line with CoRWM's recommendation 4, further research will be carried out during a geological disposal facility development process in order to reduce uncertainties, to support development of site-specific safety cases and to optimise facility design and delivery. In addition, Government and NDA will keep alternative options such as borehole disposal of certain types of waste under review. Research into alternative methods for dealing with wastes is also part of the NDA remit, particularly with regard to the application of the waste management hierarchy. The cost implications of the various options explored will be estimated by the NDA as part of its work programme.'

2.1.2 The Regulatory Process and Regulatory Expectations

The standards for safety are set by Government, and the regulators ensure they are met. The Nuclear Installations Inspectorate (NII) regulates the nuclear, radiological and industrial safety of nuclear installations, and the environment agencies (The Environment Agency (EA), for England and Wales and the Scottish Environment Protection Agency (SEPA)) authorise and regulate radioactive and non-radioactive discharges and disposals. Transport of radioactive materials is regulated by the Department for Transport (DfT), and security by the Office for Civil Nuclear Security (OCNS).

A workshop was held in Manchester in March 2008 which discussed how the environment, health and safety, and transport regulators will review the NDA RWMD's scientific and technical programme to develop a geological disposal facility [6]. Views were sought from stakeholders on the regulatory process and in particular on the most favoured ways to communicate. The regulatory process as then envisaged was set out. The NDA RWMD presented an indicative programme for identifying the scientific and technical work required to support the geological disposal implementation programme including an intensified programme of research and development into the long-term safety of geological disposal. The NDA RWMD noted that the rate of delivery of the programme will be dictated by a number of factors, including available funding.

The regulators expressed the expectation that any application for permission to build a geological disposal facility will be staged, in line with the original CoRWM recommendations. The Environment Agency and the HSE proposed a regulatory process showing potential hold points beyond which the applicant could not proceed without regulatory agreement. The regulators described their role for projects which involve long timescales, such as the geological disposal facility. They said that, prior to any formal application, their role would be to provide advice, which will assist developers in preparing submissions for regulatory approval, and give developers guidance on issues that may arise, while avoiding direct involvement of the Regulators in the design process. The Regulators' approach will be based upon early and continuing interaction. Such interaction is especially important at the strategy development, options assessment and concept stages. The approach of early dialogue is addressed in the draft for public consultation [7] of a revised document on the guidance on the requirements for authorisation of a deep geological disposal facility, recently issued by the Environment Agency and the Environment and Heritage Service of Northern Ireland. That document discusses the benefits from an early dialogue between the implementer of a geological disposal facility and the relevant environment agency. NDA RWMD supports such early dialogue.

This is the framework within which the NDA RWMD will operate to implement the Government's disposal policy.

2.2 The Multi-barrier Concept

Geological disposal facilities for radioactive wastes are in various stages of development in a number of countries. Such facilities utilise a combination of engineered and natural barriers to greatly limit the release of radioactivity to the environment. The engineered barriers typically include container materials, passive wasteforms and barrier materials. A range of geological environments are considered to be appropriate. For most concepts, the main barriers are identified as follows:

- **The Container** – provides the primary mechanical and structural barrier.
- **The Wasteform** – the physical containment afforded by the wasteform itself.
- **The Chemical Barrier or Buffer** – the waste packages are surrounded by a backfill or buffer material, which can act as a chemical or diffusion barrier, significantly retarding the movement of any radionuclides released from the waste packages.
- **The Geological Barrier (the Geosphere)** – the rocks above and around the disposal facility provide a long groundwater travel time to the surface, giving substantial dispersion and dilution and retarding sorbing radionuclides. The long-term stability of the geosphere provides isolation at very long times in the future, even under significant external change. The Geological Barrier also provides physical protection for containers and wasteforms.

Long-term performance of the concept is evaluated using well-established assessment tools:

- The methodology for performance assessment has been developed in line with international best practice as established by the IAEA and the NEA [8].
- The methodology has been subject to international peer review from an OECD-NEA expert group [9].
- Similar assessment tools have been used by other countries to demonstrate the viability of their own geological repository concepts, many of which are at an advanced stage of development with plans for implementation.

The concept is based on storing waste deep underground, where it is less vulnerable to disruption by man-made or natural events. It is designed to prevent, or at worst slow down to a safe level, the release of radio-toxic substances to the environment while the natural process of radioactive decay occurs. The option for monitoring and retrievability means that choices on how, and if to proceed towards closure of the facility are offered to future generations without placing an undue burden on them.

Typically ILW wastes are immobilised in a cement-based grouting material within a standardised, highly engineered stainless steel or concrete container. The resulting packages are an integral part of the disposal concept and have to meet performance standards that are derived from the concept. The packages themselves provide containment times of hundreds of years against release into groundwater under repository conditions. The packaging proposals put forward by waste producers are assessed by NDA RWMD through the Letter of Compliance process [10].

In the UK, a specially formulated cement-based backfill [11, 12] has been designed to maintain alkaline (high pH) conditions in an ILW facility. This alkalinity would suppress the solubility of the most radiotoxic substances in the wastes compared with their solubility in natural groundwaters. The backfill has also been designed to have a very high sorption capacity whereby most radionuclides would be taken up onto the solid surfaces of the backfill material and any movement out of the facility would be slowed considerably as a result. This barrier in the system is not an absolute physical barrier; although it has been designed to remain effective for at least a million years under the hydrogeological conditions that would be expected at a suitable site.

The geological barrier has to provide a long and slow groundwater pathway back to the surface, and ideally, favourable geochemical and mineral properties to prevent or delay the movement of radionuclides along that pathway [13]. This long pathway would allow the natural process of radioactive decay to transform radionuclides into non radioactive species. A very large reduction in activity occurs progressively over time. As a result the possible release of radionuclides from the facility to the surface will be prevented or, in a few cases, limited, and the majority of radionuclides released from the facility will decay away deep underground. Further, the arrival at the surface, and release to the biosphere (the surface environment) would be spread over hundreds of thousands of years.

In long-term safety assessment studies [14] the effect that these long-term, low-level releases might have on the health and safety of people living in the vicinity of the facility is calculated. These assessments show that the rigorous safety and environmental requirements set by the UK regulators can be met [15].

The NDA is also developing plans for geological disposal of High Level Waste (HLW) and spent fuel, in the event that any of spent fuel is deemed to be waste. These plans will be built on the knowledge obtained in the very extensive R&D programmes undertaken by overseas waste management organisations, which, in some cases, are now proceeding to implementation. Technical cooperation agreements with overseas waste management organisations are in place (see Section 3.5.5).

Internationally, a range of geological disposal concepts have been discussed and investigated for HLW and SF over a number of years. The concepts vary according to the nature and quantity of the waste and the different geological settings. One plausible HLW/SF geological disposal facility concept has been selected for in the UK 'viability demonstration' [16], and is based on the KBS-3 concept developed by SKB for spent fuel in Sweden. This concept has been extensively studied by the Swedish and Finnish national programmes for more than 20 years [17]. This selection also reflects the maturity of the Swedish and Finnish programmes, their involvement with stakeholders and their level of regulatory scrutiny and international peer review.

The KBS-3 repository concept can be described by the same barriers as introduced earlier. The Spent Fuel (the wasteform) is sealed inside a copper and cast iron container. Under suitable geochemical conditions, the corrosion of copper is extremely slow, and the copper canister is expected to maintain its integrity for an extremely long time. Within its deposition hole, the canister is surrounded by a bentonite clay buffer that swells when contacted by water. The tunnels and rock caverns would be backfilled with a mixture of bentonite and crushed rock. The HLW/SF reference concept was developed [17] by adapting the KBS-3 concept in terms of canister length, diameter and structure of the insert to handle HLW and spent fuel from the UK's Advanced Gas Cooled Reactors (AGRs) and Pressurised Water Reactor (PWR).

NDA RWMD is using the above concepts, and associated developments of waste packaging standards and specifications, as a starting point for investigating the appropriate concept for geological disposal in the UK. They are also being used to assess the disposability of the other UK radioactive wastes and materials, should they be deemed to be waste. This includes waste and materials such as separated stocks of plutonium and uranium, spent fuel from submarines and research reactors. A review of the disposability issues for a range of packaging and disposal options for UK civil uranium and plutonium, should these materials be declared as wastes, was undertaken recently [18]. This study was also used to provide outline geological disposal facility costs as input into the NDA macro-economic study into the long-term management of uranium and plutonium.

The status of the wider international understanding of R&D on geological disposal of radioactive waste has been reviewed [19]. The aim of the NDA RWMD research programme is to build on the work undertaken to date in the UK and overseas.

3 DEVELOPING THE R&D STRATEGY

In this Section the development of the R&D strategy is described. The R&D programme is driven by the needs of the overall implementation programme, and so R&D is first set in the context of the implementation programme (Section 3.1). In the light of this, the main drivers of the R&D programme are outlined (Section 3.2), and the focus of the R&D in the various phases of the implementation of a geological disposal facility are set out (Section 3.3). This is followed by a description of how the programme is prioritised (Section 3.4), implemented and procured (Section 3.5) and scrutinised and reviewed by scientific peers and by regulators (Section 3.6). This last aspect is important as it provides assurance on the quality of the science in the programme.

3.1 R&D in the Context of the Implementation Programme

The plan for implementation will be driven and informed by a number of influences including Government policy, the NDA strategy, regulatory requirements and compliance with funding requirements. It is not possible to generate a detailed plan for the implementation of a long-term geological disposal facility until a site has been selected following initial geological appraisal as to suitability. In particular there are uncertainties associated with the very long time span for the project and with the political process, particularly insofar as the volunteer process for site identification is concerned.

3.1.1 An Iterative Approach to Safety

The development of a geological disposal facility requires a coherent scientific and technical programme, which requires specification of requirements, development of concepts and designs and the assessment of their performance. In turn, these all support the production of the Safety Cases and the packaging/Letter of Compliance process. In order to support all these, a needs-driven R&D programme is developed. This needs-driven R&D programme addresses the issues identified in other parts of the programme. Figure 3.1 illustrates the relationship between R&D and the wider RWMD programme.

The aim of the **Disposal System Specification** (DSS) is to set out what is required of the disposal system. It includes constraints imposed by regulators, stakeholder's requirements, as well as taking into account the nature, characteristics and quantities of the wastes. The development of the DSS and geological disposal facility design is an iterative process with assessments of safety, environmental effects and cost. The requirements/constraints are continually refined in light of the results from ongoing programmes of work, including design development, assessments and R&D.

The R&D programme also feeds into the **engineering design** and supports the choices made in that part of the programme. The design of the facility should respond to refinements in the quality of the existing inventory and any policy decisions or changes to current nuclear industry operations that will result in future inventory modification. The current responsibilities of the engineering team include:

- Developing the geological disposal facility design and engineering.
- Anchoring advice and designs on principles of sound engineering and best practice.
- Developing the parametric cost model for the geological disposal facility programme.

- Developing the transport system design.
- Developing the engineering design, programme and cost data into a specification that can be taken forward for effective implementation through the supply chain.

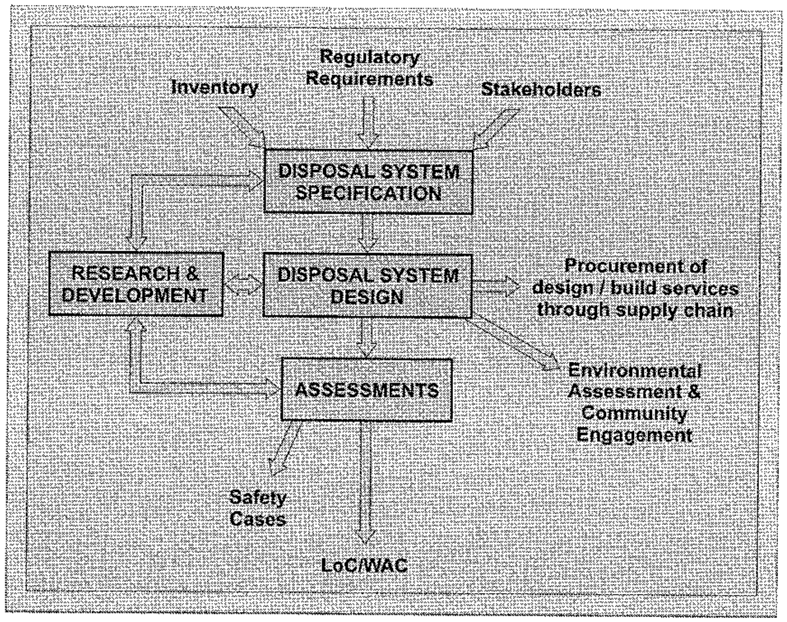

Figure 3.1 Relationship of R&D to the overall long-term waste management programme

The development of engineering solutions is based on sound engineering principles and is, as far as practicable, based upon established and proven technology. Further details on the engineering foundations are provided in [20].

The R&D programme has a major part to play in feeding into the development of the various components of the **Disposal System Safety Case** (DSSC), particularly the post-closure component. The DSSC is the main vehicle for demonstrating the safety of geological disposal. It covers transport, operations and post-closure, and the first "generic" case is planned for delivery in December 2009. It will be the first of a series of Disposal System Safety Cases that will be produced at key stages in the development of the geological disposal facility. As it develops, the DSSC will provide a framework for documenting all the evidence relating to the overall safety and environmental implications of a geological disposal system, including the integrated transportation system needed to move wastes from their current storage locations.

The results of safety assessments are used to highlight those areas where further work is required to improve the understanding of processes and the provision of data. In particular the uncertainties to which the safety case is most sensitive are highlighted and can help focus the research programme in clarifying those uncertainties. This feedback from the safety case to the R&D programme enables research to be focused on those areas where it has the greatest benefit in terms of improving confidence in the safety case.

The R&D programme has to ensure the required information is available in a timely manner at each of the stages in the development of the DSSC.

The results of safety assessments are used to inform the Letter of Compliance (LoC) process. In time, when the geological disposal facility is constructed, Waste Acceptance Criteria (WAC) will be required in preparation for acceptance of waste into the facility.

Geosphere characterisation will also be one of the key providers of information, understanding and data to the safety case and to the engineering design of a facility. It comprises detailed surface and sub-surface investigations and is required to acquire and interpret information on the geological, hydrogeological and environmental conditions at one or more candidate sites throughout all stages of the development of a geological disposal facility. It will be a 'needs-driven programme' providing information for numerical performance assessments, design and construction, and geological understanding. The geosphere characterisation programme will also provide samples and material for use in the R&D programme, and close working will be required in developing an understanding of sites. The current status of work by NDA RWMD in this area is described in two recent reports [21, 22].

3.1.2 Phases in the Implementation of a Geological Disposal Facility

Although it would not be appropriate to undertake detailed planning for the development of a geological disposal facility before candidate sites have been identified, the programme can be divided into a number of phases, and the R&D programme will have a different focus in each of those phases. These phases are shown in Figure 3.2, and are:

- Desk-based siting studies, which are undertaken in support of the government's siting programme, and prepare the project for implementation once sites for investigation are identified. For the purposes of this strategy, this covers the period from the time when Expressions of Interest are sought from communities, under the principles of voluntarism and partnership, through to the time when a decision is taken to undertake surface-based site investigations.
- Surface-based site characterisation, to identify which site should be taken forward for the development of the geological disposal facility.
- Underground investigation and construction, during which work will be undertaken to confirm the suitability of the site.
- Operation, which will focus on the emplacement of wastes underground.
- Closure, which will be concerned with the final backfilling of wastes, and sealing and closure of the facility.

It is envisaged that the construction of the facility will continue as waste is emplaced in already constructed parts. It is anticipated that research in support of backfilling, sealing and closure will have been undertaken during previous phases.

3.2 A Needs-driven R&D Programme

The R&D programme will have a different focus in the different phases of the implementation of the geological disposal facility. This is summarised in Figure 3.2. The main drivers for the R&D programme are:

- To prepare for future phases of the implementation programme, and ensure the R&D is in place to support the delivery of the programme to develop the geological disposal facility.

- To build confidence in the concept, by addressing residual technical uncertainties that have been identified, for example in the Report N122 [3] or regulatory reviews of the project (for example [4]).

PHASE	Desk-based Siting Studies	Site Characterisation	Underground Investigation & Construction	Operation
RESEARCH DRIVER				
Be prepared for future phases	Prepare for site characterisation	Plan underground confirmatory tests		
Build Confidence in the Concept				
Address residual technical uncertainties	Generic	Site specific	Outstanding issues	
Long-term demonstration experiments	Initiate	Ongoing		Retrieval & closure issues
Support 'Upstream Optimisation'	React to proposals, but also be proactive		Additional issues	Retrieval & closure issues
Input into Disposal System Safety Case				
Data and processes – Near field	Main thrust	Outstanding issues		
Data and processes – Geosphere	Generic	Site specific	Confirmation & demonstration	Confirmation & demonstration
Work to support broader strands of DSSC	Support development	Site specific	Confirmation & demonstration	
Develop the concept for HLW & SF				
Recognise work of sister organisations Understand issues for a single facility	Main activity (not as mature as ILW)		Outstanding issues	
Contribute to the wider RWMD programme	Support as required; anticipate requirements			
Programme Review	Regular reviews, with high-profile reviews at key stages of the programme			
Key	Preparatory activities	Main period of work	Outstanding or newly arising issues	Other supporting or underlying activities

Figure 3.2 The focus of research and development in the various phases of the provisional implementation plan

- To support 'upstream optimisation' – the holistic review of waste generation, retrieval, treatment, conditioning and packaging, in order to deliver cost-effective waste management solutions.

- To provide the required inputs into the Disposal System Safety Case, in terms of understanding processes, the provision of data (including an understanding of the uncertainty in the data), and the provision of wider safety arguments in support of performance assessments.

- To pursue research and development on the concept for high-level waste (HLW) and spent fuel. Work on high-level waste and spent fuel, and the associated engineered materials, is currently less mature in the United Kingdom than the work on intermediate-level wastes (ILW). However, concepts for HLW and spent fuel are very advanced on the international stage, and the NDA programme will build on these studies.
- To support current and proposed waste packaging processes, for example those being considered through the Letter of Compliance (LoC) process.

3.3 The Focus of R&D in the Different Phases of the Implementation Programme

In the light of the drivers described in the last Section, the R&D priorities in the different phases of implementation of the geological disposal facility are as follows:

(a) Desk-based Siting Studies

During the desk-based site studies phase, there will be an active research and development programme involving desk-based and modelling studies, laboratory experiments, and international collaborations. The focus will be on the topics described below.

- Long-term demonstration experiments will be initiated to build confidence in the performance of the engineered barrier system.
- Research will be undertaken on the performance of the engineered barrier system, in particular on processes relevant to the containment of radionuclides, including possible release in groundwater or gas. The aim will be to resolve any generic issues on intermediate-level waste. It will include ensuring that the understanding of processes underpin performance assessments, that significant progress is made in resolving outstanding key technical and scientific uncertainties, and that the data required for assessments are obtained. There will be a particular focus on long-term performance assessments, but the research will also address issues arising from accident scenarios during transport and operation. It will include work on the performance of existing waste packages, where this can provide understanding or data relevant to disposal.
- Work on high-level waste and spent fuel, and the associated engineered barrier materials, is currently less mature in the United Kingdom, and work will be undertaken on the long-term performance of the waste forms and barrier materials. This work will build on the wide international experience gained already.
- Research will be undertaken on geosphere processes relevant to radionuclide migration. In the absence of specific sites to be investigated, the focus will be on generic issues. This will include ensuring that the understanding of these processes is fit for purpose in performance assessments, and that, where appropriate, the data required for assessments are obtained. It will also prepare for detailed site-specific work in later phases.
- Research will be undertaken to support the development of broader justification for the long-term performance of the geological disposal facility. Such justification forms an important part of the Disposal System Safety Case, and will focus in particular on developing a more thorough understanding of barrier

performance and the use of multiple lines of arguments in building confidence in the performance of the system.

- Research will be undertaken in support of 'upstream optimisation' studies to ensure that appropriate concepts for waste disposal are adopted. This includes options for container materials for the various waste types (for example alternative steels for ILW and alternative metals for HLW), choice of encapsulant for certain ILW (for example polymer encapsulants) and alternative disposal concepts for certain waste streams (for example graphite wastes).

Regular reviews of the research programme will be undertaken and published.

(b) Surface-based Site Characterisation

During the site characterisation phase, it will be important for the site characterisation programme, the assessments programme and the R&D programmes to be closely integrated, so that the evolving needs of the assessments are understood and met in a timely manner. The Research and Development programme during this phase will focus in particular on the topics described below.

- Long-term demonstration experiments initiated during earlier stages will continue to build confidence in the performance of the engineered barrier system. Further long-term demonstration experiments relevant to site-specific aspects will be planned and initiated.
- Research will be undertaken on site-specific processes relevant to radionuclide migration. This will be based on samples obtained from the surface-based characterisation programme. This will include ensuring that the understanding of these processes is fit for purpose in performance assessments, that outstanding key technical and scientific uncertainties are resolved, and that the data required for assessments are obtained.
- Research will continue on the long-term performance of the engineered barrier system, in particular on processes relevant to the containment of radionuclides. The aim will be to resolve any remaining outstanding issues on intermediate-level waste following work during the desk-based siting studies phase.
- Work on high-level waste and spent fuel, and the associated engineered materials will continue during the site characterisation phase.
- Research will continue to support the development of the broader justification of the long-term performance of the facility. During the surface-based site characterisation phase, this will focus on site-specific aspects, in particular building confidence in barrier performance through the use of multiple lines of arguments, such as how the natural system has evolved over long timescales.
- Towards the end of the site characterisation phase, planning and preparation work will be undertaken for in-situ underground confirmatory tests. These tests will be undertaken during the construction and operation phases. Their purpose will be to confirm that the aspects of site performance are in line with the evaluations made on the basis of results of the surface-based characterisation programme and laboratory tests undertaken as part of the research programme.

It is anticipated that high-profile reviews will be undertaken at key points of the surface-based site characterisation phase.

(c) Construction

The main focus of the Research and Development programme during the construction phase will be to support work confirming the long-term performance of the facility, and in particular:

- Long-term demonstration experiments initiated during earlier phases will continue to build confidence in the performance of the engineered and site-specific aspects of the system.
- In-situ underground confirmatory tests will be undertaken to support the demonstration that site performance is in line with the evaluations made on the basis of results of the surface-based characterisation programme and laboratory tests.
- Research will continue on the long-term performance of the engineered and site-specific aspects of the system, in particular on processes relevant to barrier performance and radionuclide migration. The aim will be to confirm the understanding of any remaining outstanding key technical and scientific uncertainties, and to ensure that the data required for assessments are obtained in a timely manner. It will include work on the performance of existing waste packages, where this can provide understanding or data relevant to disposal.
- Research will be undertaken on issues around possible requirements to retrieve waste packages, and on techniques for closing the facility.
- Research will be undertaken to confirm broader, supporting arguments justifying the long-term performance of the facility.

It is anticipated that high-profile reviews will be undertaken and published at key points of the construction phase.

(d) Operation

The main focus of the Research and Development programme during the operation phase will be to confirm the performance of the system, in particular:

- Long-term demonstration experiments initiated during earlier phases will continue to build confidence in the performance of the engineered and site-specific aspects of the system. These will include in-situ underground tests, and work on monitoring wastes disposed in the vaults.
- Research will continue to be undertaken on issues around possible requirements to retrieve waste packages, and on techniques for closing the facility.

It is anticipated that high-profile reviews will be undertaken and published at key points of the programme.

3.4 Prioritising the Programme

In preparation for the MRWS CoRWM consultation Nirex undertook a substantial programme of work, including publication of its 'Viability Report' [3]. This covered review and collation of issues (residual uncertainties or concerns) that had been identified within the then Nirex programme of work and the Nirex Phased Geological Repository Concept (PGRC). These issues, identified by Nirex and a substantial number of external organisations and both internal and external reviews were then screened, categorised and evaluated [23]. The work had a three-fold purpose:

1. As an aid to making qualitative assessments in comparisons between different long-term management options;
2. As the basis for assessment of the viability of the Geological Repository Concept; and
3. As an aid to identifying any significant gaps in the on-going R&D programme.

The first of these was to assist with the initial options study whereby CoRWM was charged with making recommendations as to the option, or options, that Government should accept as the basis for long-term radioactive waste management policy. This exercise is now complete (geological disposal with safe interim storage: Section 2.2 above).

Studies have therefore recently been performed to evaluate a comprehensive range of the principal geological disposal concepts available internationally that might realistically be considered for implementation in the UK. In undertaking these studies, it is important to recognise that the UK is at the first stage of implementation of geological disposal, before any potential sites have been identified. The approach to these studies has, therefore, needed to balance the requirement to maintain flexibility by keeping options open with the need for the programme to focus resources on example concepts that have a realistic chance of being implemented, and can therefore be used as a basis for more detailed assessments of disposability, as well as to define research and development priorities.

Recent examples include a workshop on Geological Disposal Options for High-Level Waste and Spent Fuel held in Oxford in August 2007 [24]. This was attended by experts from the NDA, specialist consultants, the Environment Agency, the Scottish Environment Protection Agency, ANDRA (France), DBE Technology (Germany), IRSN (France), ONDRAF/NIRAS (Belgium) and SKB (Sweden).

Similarly in 2008, the NDA commissioned an expert study to collate and report information on concepts for the geological disposal of ILW worldwide [25]. This study collated information on ILW geological disposal concepts that have been developed in a number of countries.

The second purpose was to generate, for CoRWM, the Viability Report itself.

The third was utilised to review the Nirex R&D Programme then in place. As described fully in the Viability Report, identified issues were grouped and "Context Notes" for each prepared and made available to CoRWM [see [3]]. Each provided a summary of the more important issues within each grouping and a traceable basis for the information presented in the Viability Report. Context Notes of particular relevance included:

- Waste inventory [26]
- Waste package research [27, 28]
- Near-field research [29]
- Geosphere research [30]
- Biosphere research [31]
- Gas generation and its effects [32]
- Criticality [33]
- Human intrusion [34]
- Post-closure performance assessment [35]
- Safety Case arguments [36]
- Monitoring [37]
- Retrievability [38]

This approach provided the basis for ensuring the R&D programme was focused appropriately and led to development of the more intensified R&D programme now being proposed.

The various components of the programme are managed by a number of work package managers; these cover aspects such as geosphere research and waste package research. These work package managers draw up the priorities for the future programme in the light of the needs of the wider technical programme. The programme is considered at different levels of detail on different time horizons:

- The broad objectives to be achieved by the programme over a number of years are developed, in line with the outline described in Section 3.2 above.
- The programme over a three year timescale is developed in more detail. The level of detail is sufficient to enable proper planning of a coherent programme, and to ensure that the various milestones are delivered in a timely manner. It also enables the inclusion in the programme of long-term projects.
- The programme for the coming year is drawn up in detail; this ensures proper technical, project and financial management. It is constrained by the budget available.

As part of the development of the programme, there are detailed discussions to ensure that the overall programme is coordinated and coherent across the work of NDA RWMD, and that the available funds are distributed appropriately. For example there are detailed discussions between the research and assessment teams to ensure that the requirements of the assessments are met in a timely fashion by the deliverables from the research programme. The R&D programme has to be sufficiently flexible to be able to respond to revisions in the overall implementation programme, to the results of the performance assessments, and to the findings of individual R&D projects.

The programme is scrutinised and reviewed across RWMD by staff, who have been independent of the development and delivery of the programme to ensure that it is prioritised appropriately within the available funds, to ensure that the different components are coherent, and to ensure that the various drivers are being addressed. These include ensuring that consideration is given to the inputs from a range of stakeholders. In recent years this review has been undertaken by the Chief Scientific Advisor and the Head of Repository Safety & Environment. Finally, it will be scrutinised more widely, as described in Section 3.6, and views from a wide range of stakeholders are welcome.

3.5 Implementing the R&D Programme

NDA RWMD currently has a technical staff of around 40 scientists and engineers. Their role is to provide the expertise to design and define the programme, to prioritise components of the programme and to manage and coordinate the work. The work itself, however, is undertaken substantially by contractors. The quality of the work is assured through the contractors' Quality Assurance systems, and external peer review is undertaken where appropriate. This is discussed in more detail in Section 3.6.2.

3.5.1 Procurement

According to EU legislation, all contracts from the public sector valued above a certain threshold, must be published in the Official Journal of the European Union (OJEU). The legislation covers organisations and projects which receive public money. Local authorities, NHS trusts, Central Government Departments, Port Authorities are all covered by the legislation and must advertise in OJEU, where their contract falls within the scope of the legislation. If a project is in receipt of more than 50% public funds, it would also be covered by the EU legislation. All qualifying NDA contracts are published in this way as the first step in securing contracting organisations to undertake the programme.

NDA RWMD conducts its work, including R&D, essentially as a contracting organisation. This means that it has close working relations with a substantial number of national and international industrial, consulting and research organisations. Recent contracts, for example, have been placed with the following organisations either singly or as consortia:

Amec-NNC, Atkins Ltd, BNG Project Services Ltd., Brenk Systemplanung, Enviros, Forschungszentrum Julich, Frazer Nash Consulting Ltd., Galson Sciences Ltd., Nexia Solutions Ltd., Nuclear Technologies PLC., Ove Arup, Poyry Energy Ltd, Quintessa, RM Consultants Ltd., RPS Ltd., Serco Assurance, Waste Management Technology.

Some of these are single contracts for specific pieces of work. However, a significant amount of work is undertaken under framework contracts that have been awarded after an OJEU competition in defined technical areas. Further details are available on the NDA website.

The NDA has a requirement to 'promote, and to ensure, the maintenance and development in the United Kingdom of a skilled workforce able to undertake the work of decommissioning nuclear installations and of cleaning up nuclear sites'. As a consequence the competition imperative of procurement is complemented by a need to build confidence in the supplier base to ensure resources are in place. There are certain suppliers with whom the NDA develops additional relationships, and these are discussed below.

3.5.2 Strategic Relationships with Universities

The NDA remit as set out within the Energy Act includes – *"promote, and where necessary fund, generic research relevant to nuclear clean up"*. Furthermore, the NDA has a skills requirement – *"to promote, and to ensure, the maintenance and development in the United Kingdom of a skilled workforce able to undertake the work of decommissioning nuclear installations and of cleaning up nuclear sites"*. The universities, at various levels, provide much of the skilled technical workforce within both the NDA and its contractors. The NDA's approach is to foster university training links. Several research relationships with specific universities were inherited by the NDA following their establishment by BNFL: the University Research Alliances (URA) [39]. A process had been established for open competition for five university centres building capabilities in the fields of (a) Radiochemistry (b) Materials (c) Particle Science (d) Immobilisation (e) Non Destructive Evaluation. These developed towards a sustainable target level of one professor, 2-4 academic staff and between 20 and 40 postgraduate students or postdoctoral researchers. This funding enables substantially more to be attracted in matched funding from the Research Councils and the EU. The URA Programme is currently being broadened to cover radioactive waste disposal and contaminated land. In the case of geological disposal, appropriate links will be developed with NDA RWMD.

The URA model has been widely commended both nationally and internationally, for the development or redevelopment of relevant university research and training capabilities. Internationally, both the USA and Canada have recently adopted similar models in anticipation of a new programme to construct nuclear power plants.

NDA staff visit universities regularly with a view to supporting existing URAs and identifying technical areas where new ones might be appropriate to help deliver the NDA mission. University academic staff are also regularly invited to sit on research or programme advisory bodies and, as mentioned above, to undertake peer review, thereby ensuring best practice wherever possible.

3.5.3 The National Nuclear Laboratory

In 2006, the then Secretary of State for the Department of Trade and Industry, Alistair Darling announced plans for the development of a National Nuclear Laboratory. "In considering the UK's future requirements for nuclear research and development, we've recognised that much of what is needed will be provided by the private sector." he explained. "But the Government will need to act to safeguard certain capabilities, principally those services provided by Nexia Solutions and key facilities in the British Technology Centre at Sellafield."

The detail of the arrangements for the NNL and the precise way in which the NDA will be involved awaits a final statement from Government.

3.5.4 The British Geological Survey (BGS)

BGS is the United Kingdom's premier centre for applied earth science information and expertise. It holds vast and diverse arrays of data and associated knowledge and insight relating to the geology, structure, composition and stability of the UK landmass and adjacent offshore areas. Because Government Policy now stipulates geological disposal, there is clearly the requirement for close cooperation between NDA RWMD and BGS, as was previously the case when there was close and substantial collaboration between Nirex and BGS.

As a public sector organisation, BGS is responsible for advising the UK Government on all aspects of applied geoscience, as well as providing information and impartial geological advice to industry, academia and the public. The BGS is a component Research Centre of the Natural Environment Research Council (NERC), which is the UK's leading funding body for basic, strategic and applied research and monitoring in the environmental sciences. The BGS has strong links with university research through collaborative projects supported by NERC and other research councils, and also directly funds some university based research through its own BGS University Funding Initiative.

At the highest level, the relationship between UK Nirex Ltd and the BGS was embodied in a Memorandum of Understanding (MoU). BGS undertakes contract work, and competes with other specialist contractors for NDA RWMD work through the OJEU process.

3.5.5 Relationships with Waste Management Organisations in Other Countries

Relationships with waste management organisations (WMOs) in other countries have proved valuable for many years. NDA RWMD recognises this, and intends to continue and build on those relationships. The various WMOs face common challenges, and close collaboration ensures NDA RWMD builds on the experience and understanding gained elsewhere.

The NDA has the following bilateral agreements:

- USDOE (United States Department of Energy), in furtherance of the Memorandum of Understanding with DTI and through its Office of Environmental Management (agreement put in place 2007).
- EDF (Electricité de France) through its decommissioning arm.

These allow for information and staff exchanges relating to a wide variety of subject areas concerning decommissioning and clean up. The following bilateral agreements are more focused on geological disposal:

- Andra (the national waste management organisation (WMO) of France (agreement put in place in 2008).
- Nagra, the national WMO of Switzerland (1991).
- NUMO, the national WMO of Japan (2004).
- ONDRAF/NIRAS the national WMO of Belgium (2005).
- RWMC, the Radioactive Waste Management Funding and Research Centre of Japan (2004).
- SKB the national WMO of Sweden (2002).

These agreements cover information exchange on all aspects of site selection and geological disposal facility development, cover all waste types, allow for staff as well as information exchanges and enable joint R&D activities. In addition NDA is finalising agreements with JAEA of Japan.

NDA RWMD is undertaking some consultancy work (e.g. peer review) for waste management organisations in Belgium, Finland and Sweden. It is also participating in EU-funded projects within consortia aimed at providing radioactive waste management assistance to the new EU Member States and the Former Soviet Union countries. It is currently involved in projects in Ukraine and Russia aimed at developing new national WMOs.

NDA RWMD is also a member of two international organisations:

- The International Association for Environmentally Safe Disposal of Radioactive Materials (EDRAM) which began as a high level, informal forum for WMO Chief Executives for exchange of views.
- The Club of Agencies, which is a grouping of EU WMOs along with Switzerland, which discusses the progress of national programmes and Commission initiatives. It further acts as a 'horizon scanning' on proposed Directives and discussion forum on radioactive waste management R&D.

NDA RWMD are involved in a number of international collaborative projects, for example through the European Union's Framework Programmes (EU FP), and through OECD/NEA (the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development). Examples of these programmes include the FUNMIG project, which is an EU FP6 project concerned with the FUNdamental MIGration of radionuclides through the geosphere, and the NEA Sorption Project, which is concerned with demonstrating the applicability of different chemical thermodynamic modelling approaches to support the selection of sorption parameters for safety assessments of radioactive waste disposal.

The NDA has individuals with significant professional expertise in many areas. This is recognised by international organisations such as the IAEA, ICRP, EBRD and the OECD-NEA, with 'experts' being invited to provide advice directly, or invited onto groups preparing guidance documentation, or undertaking peer reviews. Specific examples where NDA staff have been involved with the IAEA include knowledge management, inventory development, radioactive waste management financing schemes, transport regulations, and safeguards support, as well as participating in the 'Joint Convention' meetings with government.

3.5.6 Learned Societies and Professional Bodies

Many NDA RWMD staff are members of the Learned Societies and Professional Chartered Bodies. These include organisations such as the Royal Society of Chemistry, the Geological Society, the Institute of Materials, Minerals and Mining, the Institute of Physics, the Institution of Mechanical Engineers, the Institution of Civil Engineers and the Institution of Engineering and Technology.

Through the meetings of these organisations and their professional programmes, NDA RWMD staff maintain immediate awareness of developing science and technology and best professional practice. The organisations are also an important source for peer review.

Some of these bodies, including the Royal Society, have regularly responded to Government consultations relating to nuclear clean up and waste management. Meetings were also arranged specifically to inform and support the MRWS consultation process and to which CoRWM members specifically contributed. The Royal Society of Chemistry, on behalf of several organisations, held a workshop in Loughborough in late 2006, and the Geological Society held a meeting devoted to the science behind long-term radioactive waste management early in 2007. Reports of both meetings have been published [40, 41,]. Several also took part directly in the CoRWM process and consultation.

3.5.7 Links to Industry R&D

Complementary research on waste management is undertaken by the Site Licence Companies (for example Sellafield Ltd, Magnox and UKAEA). The focus of their research is on packaging and making their wastes passively safe, on surface storage of the wastes, and on preparation for the Letter of Compliance process. This involves addressing specific issues for particular waste streams. On the other hand the research commissioned by NDA RWMD is focused on the long-term behaviour of the wastes and in particular disposal issues.

Coordination of the programmes is achieved through a number of industry groups. This ensures that there is no duplication of work, that issues are not neglected, and that all parties learn from the work of others.

3.6 Scrutiny of the Programme

NDA RWMD sees scrutiny of the programme by a range of external stakeholders as an important element to building confidence in the R&D programme. Such scrutiny is part of being open and transparent, which means that information will be openly shared. The aim, intent and policy of NDA RWMD is that information will be published and made available, unless there is good reason for it to be withheld. There is scrutiny both of the overall programme and of work areas and tasks within it by, for example, CoRWM Research Group, regulators, NDA staff and external experts from both the UK and overseas.

Scrutiny by the regulators, peer review, and scrutiny by a number of NDA forums is discussed below.

3.6.1 Regulatory Engagement and Review

As has been discussed in Section 2.2.2, a geological disposal facility will require a nuclear site licence from the Nuclear Installations Inspectorate (Health and Safety Executive HSE). Before wastes can be emplaced, an authorisation must be granted by the Environment Agency (England and Wales) or the Scottish Environment Protection Agency (SEPA). The Department of Transport regulates movement of wastes, and security is regulated by the Office of Civil Nuclear Security. Important international requirements must also be met. The R&D programme within the NDA RWMD is substantially influenced by regulatory dialogue and the programme is directly scrutinised.

A good example of regulatory interaction and scrutiny is that by the Environment Agency's Nuclear Waste Assessment Team (NWAT). This provides specialist technical support within the Environment Agency on the management and disposal of radioactive waste in England and Wales. Its main aim is to ensure that radioactive wastes will be disposed of in the most appropriate manner in order to protect the public, the wider environment and to contribute to the UK's aim of sustainable development. The team interacts closely with nuclear licensees, Government departments and the NDA. Much of their work is carried out in partnership with colleagues in the Health and Safety Executive (HSE) and the Scottish Environment Protection Agency (SEPA), ensuring coherence throughout.

During the latter stages of the work of the first CoRWM committee, Nirex published a comprehensive overview of the viability of its proposals for a geological repository [3] and this was submitted to NWAT. Subsequently NWAT published a response [4]. The Executive Summary concluded 'In all, whilst we have reservations about certain aspects of the report, we agree that it provides satisfactory support to the conclusion that deep geological disposal is a viable solution'. One comment was that 'We agree that no major issues have been identified that make deep geological disposal non viable. However, the report has not provided a good technical overview of many remaining key technical challenges and how they will be resolved'.

The overall scrutiny of NDA RMWD follows this pattern with many documents now subjected to review by NWAT. Subsequent NWAT reviews have included a review of the overall research programme in 2006 [42], which made the following recommendations:

- Provide a suitably detailed account of the future research programme, to enable advance external review by a suitable range of stakeholders. Be proactive in seeking such comment.
- Review the output of the research programme against predefined research objectives, in order to evaluate performance.
- Document more formally the process by which the research programme is defined and how that process is implemented.
- Document the steps that are being taken to ensure that the research programme is addressing an appropriate range of issues, given the need to accommodate possible future policy directions, for example, if the selected disposal concept were to differ from Nirex's Phased Geological Disposal Concept.

One of the purposes of this document is to take a first step in addressing these recommendations. In particular in Section 4, an outline description is provided of the current status and future direction of the different areas of the research programme. This includes a discussion of the residual uncertainties that require further research, and a discussion, where appropriate, of work on alternative materials for waste packaging.

The focus of this Section has been the identification of research needs, the different emphases in the different phases of the implementation, the prioritisation of the needs, the implementation of the programme, and the review and scrutiny of the programme. Work on considering alternative geological disposal concepts, in particularly examining the range adopted by overseas waste management organisations was discussed in Section 2.2 [24, 25].

The NWAT reviews have identified a number of key technical challenges [4, 42]:

- The need to better understand package longevity and corresponding degradation mechanisms over a long period of storage and hence any requirement to produce improved packages for certain waste streams or to make provision for reworking.
- Understanding of the gas pathway and in particular the significance of ^{14}C-labelled gases in the safety case.
- Developing a good understanding of groundwater flow and radionuclide transport at a specific site, including the representation of flow and transport in fractured rocks.
- A fuller understanding of the impact of organic complexants and colloids as well as Non-Aqueous Phase Liquids.
- Understanding the potential coupling between gas and groundwater flow.
- Developing a better understanding of the evolution of the 'near field' and its role in limiting radionuclide release, which should be closely linked to the consideration of possible design optimisation.
- The need for long-term experiments to demonstrate the behaviour of near-field components.
- Building more confidence in the safety case for criticality.
- Developing a clear strategy for repository sealing that is demonstrated to function adequately in the long term.
- Building an understanding of time-dependent effects and their consideration in a justifiable way in assessment models.
- Demonstrating an adequate understanding of the values of key parameters.

These reviews are being taken into account in the development of the ongoing programme. Some of the issues will be appropriately addressed once a site investigation programme is under way, when the detailed characteristics of the sites are investigated and site-specific materials become available. However, generic issues are being addressed as part of the research programme described in Section 4.

3.6.2 Peer Review of the Programme

The regulatory scrutiny is complemented by a programme of peer reviews. These take place at different levels. This ensures that the NDA R&D effort is guided at different levels by a wide range of technical input.

Where appropriate, individual projects are peer reviewed. Periodically work areas are also peer reviewed. As an example, there was a peer review of the work undertaken in research on criticality in 2006 [43]. This ensures that the work is coherent, that our view of the current status is externally tested, and views on the future direction are obtained.

In addition to having work reviewed after it has been completed, peer preview is also sometimes employed. This is essentially peer review of proposed work programmes, and it ensures that work is appropriately focused, and that it takes due account of previous work.

In key areas of the programme, there are external review panels. As examples, GEOCAP (GEOlogical Characterisation Advisory Panel) advises on the geological characterisation programme, and there is a Disposal System Safety Case Advisory Panel. These groups have the responsibility for previewing proposed activities and work programmes, and then reviewing completed activities and advising NDA RWMD on the extent to which these activities meet their objectives.

International scrutiny and guidance will also be employed. The Nuclear Energy Agency (NEA) is a specialised agency within the Organisation for Economic Co-operation and Development (OECD). The goal of the NEA in the area of waste management is to assist member countries in the management of radioactive waste and materials, focusing on the development of strategies for the safe, sustainable and broadly acceptable management of all types of radioactive waste, in particular long-lived waste and spent fuel. The NEA was asked in 1999 to review the technical approach adopted in the UK for the development of scenarios and conceptual models in the post-closure performance assessments and the NEA subsequently published its response: "The Nirex Methodology for Scenario and Conceptual Model Development: an International Peer Review" [9].

3.6.3 NDA Research Board

NDA has established two oversight groups to consider the wider NDA R&D programmes:

(a) The ***NDA Research Board***, which considers strategy level issues related to all the R&D carried out by NDA. From the Terms of Reference the primary objective is:

"Promote a common understanding and collaboration between relevant bodies across the UK about respective research & development needs, risks and opportunities required to enable the delivery of the NDA mission. Where appropriate these activities will be linked to long term skills and capability requirements."

Representatives on the Board include: NDA; Department for Business, Enterprise and Regulatory Reform; Department for Environment, Food and Rural Affairs; the Scottish Executive; Scottish Environment Protection Agency (SEPA); Environment Agency (EA); HSE; and the Research Councils. There are also two independent representatives (one a whom is a member of the Nuclear Safety Advisory Committee (NuSAC), which advises the Health and Safety Commission (HSC) on matters regarding nuclear safety policy and its implementation at nuclear installations).

The NDA RWMD R&D programme will be considered annually by the Research Board.

(b) The ***Nuclear Waste Research Forum***, which considers operational issues related to all R&D carried out on behalf of the NDA. From the Terms of Reference the primary objective is:

"To provide structure for UK Nuclear R&D skill base and 'common issue' specialist groups to share, collaborate & communicate, thereby enhancing safety and environmental care while reducing cost to tax-payer"

Organisations represented on the Research Forum include: NDA, NDA RWMD, the Site Licence Companies that are responsible for NDA sites, the regulators (NII, Department for Transport, EA, SEPA) and other significant producers radioactive wastes (MOD, AWE and British Energy).

4 THE R&D PROGRAMME: CURRENT STATUS AND FUTURE PROGRAMME

In this section a summary of the current status of the various areas of R&D in the programme is provided. The various areas of research concerned with waste, the facility near field, geosphere and biosphere are described in Sections 4.1 to 4.8. This is followed by a summary of the position on geosphere characterisation (Section 4.9) and engineering developments (Section 4.10). In each case, the current understanding of the area is summarised, and the main priorities over the next few years are outlined. NDA RWMD also carries out social science research but this is outside the scope of this report.

These priorities are derived from the drivers for the R&D programme discussed in Section 3.2. In summary these are:

- To prepare for future phases of the implementation programme.
- To build confidence in the concept by addressing residual technical uncertainties.
- To support 'upstream optimisation' and the delivery of cost-effective waste management solutions.
- To provide the required inputs into the Disposal System Safety Cases.
- To pursue research and development on the concept for high-level waste (HLW) and spent fuel, building on work undertaken overseas.
- To support the Letter of Compliance (LoC) process.

These drivers ensure that the safety strategy for the geological disposal facility are underpinned by appropriate R&D, and that the R&D feeds into the programme for the implementation of a geological disposal facility in a timely manner.

4.1 Corrosion Research

Most wastes will be packaged in metal containers, which provide an important physical barrier for retaining radionuclides. Consequently, understanding metal corrosion forms an important component of the research programme. This section is concerned with the corrosion of stainless steel, which is the most common material from which ILW containers are made.

Metal corrosion takes different forms. Relatively uniform corrosion covering whole surfaces is referred to as uniform or general corrosion. Localised effects, which result in the dissolution of the metal in limited areas of the surface, are commonly referred to as localised corrosion and include pitting and crevice corrosion. Other processes involving corrosion degradation are microbiologically induced corrosion (MIC) and stress corrosion cracking (SCC).

It is customary to classify metals according to the behaviour that they exhibit in most environments. Metals that tend to suffer general corrosion are termed 'active' metals, whereas metals that suffer localised corrosion are termed 'passive' metals. The origin of such a terminology derives from the fact that localised corrosion occurs in metals which are protected by a passive film, a relatively thin layer of oxide (or other stable product) that forms in contact with certain environments and prevents further general dissolution of the metal surface.

Stainless steel is the most common material used for ILW containers and is passive in a range of environments from mildly acidic to alkaline. Its good corrosion resistance derives from the stability of a protective film of chromium-rich oxide, which makes the metal surface resistant to dissolution. Due to the passive film, stainless steel benefits from extremely low rates of general corrosion in near-neutral environments (relevant to storage in atmospheric conditions underground before backfilling takes place) and alkaline environments (relevant once backfilling of the geological disposal facility has occurred). In near-neutral conditions, the rate of general corrosion is of the order of 0.1 μm per year [44, 45], whereas in alkaline conditions, the expected corrosion rate is of the order of 0.01-0.1 μm per year [45, 46]. Stainless steel also possesses good corrosion resistance to most substances contained in the waste and does not show an accelerated corrosion rate when galvanically coupled to other metals present in the waste. These considerations support the idea that, if the main degradation mechanism affecting the packages is general corrosion, the containers are likely to be able to confine the waste for a long time.

Although general corrosion is unlikely to threaten the integrity of the containment, the presence of high levels of chloride (or other aggressive species), along with water and oxygen, can lead to the breakdown of the passive film in small areas and development of localised corrosion. On free surfaces, localised corrosion takes the form of small depressions (pits), whereas in the interstices (crevices) created between contacted surfaces crevice corrosion can occur. In areas of mechanical tensile stresses (e.g. residual stresses associated with welding) and at relatively high temperatures, localised corrosion can develop into a form of environmentally assisted cracking termed stress corrosion cracking (SCC). In alkaline environments, however, localised corrosion (pitting and crevice corrosion) and SCC are inhibited by the presence of OH^- ions, even in the presence of chloride.

For these reasons, localised corrosion inside and outside the waste packages once in contact with cementitious materials is very unlikely. Localised corrosion can only occur in the unlikely event that very saline groundwaters come into contact with the stainless steel during the initial period after backfilling of the facility when relatively high temperatures may persist and before reducing conditions are established.

The risk of localised corrosion developing inside waste packages, on the other hand, is managed through the Letter of Compliance (LoC) process by ensuring that the levels of chloride contained in the encapsulated waste is kept below appropriate limits. Other specific issues associated with internal corrosion considered in the LoC process are the possible presence of acid generating materials or of materials that, in contact with stainless steel, generate the potential for galvanic corrosion to occur [47, 48, 49].

The situation is different during storage in atmospheric conditions, when the packages will not be protected by the benign alkaline environment generated by cementitious materials. Near-neutral conditions will enable localised corrosion to initiate if significant levels of chloride are deposited on the surface of waste packages and if the surfaces of the packages are moist. Evaluating the potential for corrosion damage while atmospheric conditions persist is the focus of the R&D effort in the next years.

Desk-based and experimental studies in relevant conditions have indicated that perforation of the containers due to the development of pitting corrosion during atmospheric exposure is unlikely. This is supported by evidence from 500 litre drums [50], which have been until recently stored in a characterised but uncontrolled environment at Culham Science Centre [51]; they have now moved to the Harwell Science and Innovation Campus. The measurements indicate that, despite the lack of controlled conditions, corrosion is not progressing faster than would be expected in an outdoor rural environment. Moreover, results of 35 year exposure tests in a rural environment [47, 52] have been extrapolated, and it has been estimated that 1 mm of stainless steel would not be perforated by pitting after approximately 1000 years. Considering that wall thicknesses for waste containers range from 2.5 to about 6 mm, this suggests that localised corrosion is unlikely to penetrate waste containers while they are stored in atmospheric conditions.

Although extrapolation of pit propagation rates during exposure to the atmosphere for a few decades gives some confidence that localised corrosion is unlikely to penetrate the packages, the approach adopted by NDA RWMD is to undertake studies to develop a more fundamental understanding of the corrosion mechanisms and an associated predictive capability, to enable predictions over the timescales relevant to the development of the geological disposal facility. This work is currently being undertaken through collaboration with academic institutions.

An important aspect of the development of pitting is the dependence on environmental conditions [45, 47, 52, 53]. If the environmental conditions are controlled, the risk of localised corrosion can be significantly reduced. The three principal environmental factors affecting the development of localised corrosion on stainless steels are surface chloride contamination, relative humidity and temperature. Guidance on control of environmental conditions and monitoring regimes has been produced [54, 55].

Even with the hypothesis that localised corrosion will initiate during atmospheric storage, it is important to understand whether the degradation kinetics will significantly affect package performance. Package performance may not be compromised by non-penetrating pitting or even by small, penetrating pits, particularly if the wasteform is in good condition. These issues are being addressed within the wider consideration of the identification of the performance requirements of waste packages, and of the mechanisms by which corrosion can impact on them.

Other potential forms of degradation that could adversely affect the longevity of waste packages are stress corrosion cracking (SCC) and microbiologically influenced corrosion (MIC).

Under particularly aggressive conditions, atmospheric stress corrosion cracking (ASCC) can occur and result in the formation and propagation of cracks [45, 47, 53, 56]. Atmospheric stress corrosion cracking may be initiated by the presence of chloride-containing salts, including sodium and magnesium chloride. Initiation occurs in a range of relative humidities (RH) in which formation of concentrated chloride-containing solutions can form if moisture is present on the surface. It is generally accepted, however, that occurrence of cracking is unlikely at temperatures below 50°C, if appropriate manufacturing ensures minimisation of sensitisation to corrosion, unless particularly concentrated chloride solutions are formed. Confirmatory work is currently being carried out in this area.

Microbiologically influenced corrosion could potentially damage the stainless steel, if environmental conditions support the development of a biofilm whose metabolic processes impact on the stability of the passive film and on the electrochemical processes that drive corrosion attack [57]. However, the development of conditions for MIC to occur may be incompatible with high alkaline environments, as most living species would not be active in such conditions. Appropriate storage conditions should ensure that MIC does not develop on waste containers.

The susceptibility of stainless steel to corrosion is significantly affected by the surface condition, by the presence of surface contamination, and by manufacturing practices that lead to significant alteration in the metallurgical state of the metal (e.g. welding). To assist waste producers, guidance has been produced on the design of waste containers

[58], requirements for adequate surface finish [59] and best practice in welding techniques [60].

The grades of stainless steel generally employed for the manufacture of ILW containers are 316L and 304L (Under the European standards system, 304L and 316L are known as EN 10088-2: 1995 1.4307 and EN 10088-2: 1995 1.4404 respectively.). These grades belong to the family of austenitic stainless steels because of their crystal structure (face centred cubic), which results from their chemical composition (high nickel content). The 316 grade has a higher molybdenum content providing better resistance to localised corrosion. L denotes the low carbon grades, which possess better corrosion resistance following welding. These alloys are widely used, and their corrosion behaviour is well researched. Other grades of stainless steel (e.g. duplex grades) are currently being considered for ILW packages and their higher resistance to localised corrosion and SCC supports their suitability as highly corrosion resistant materials for the encapsulation of radioactive waste.

The NDA RWMD considers that 316L stainless steel is well suited as a container material. The corrosion rates and the processes discussed above do not appear to threaten the performance of the container, providing that material selection construction techniques and subsequent environmental conditions are in line with best practice. However, further work will be carried out to build confidence in our understanding of localised corrosion and also to review the potential benefits of alternative container materials, with a view to providing further guidance to waste producers.

The main objective of corrosion research over the next few years is to provide more evidence for safety and performance of packages while the facility is operating and in the period before backfilling takes place, by improving understanding of corrosion and waste package ageing. This will include:

- mechanistic studies aimed at increasing our understanding of localised corrosion processes to develop better predictive tools or enable extrapolation of short term data;
- development of environmental control strategy necessary to minimise corrosion damage and maximise the longevity of packages during surface and underground storage;
- continued development and implementation of monitoring programmes to confirm performance of the packages and to provide data for long-term predictions;
- evaluation of the packaging materials, so that we are in a position to work with waste producers if such alternative packaging materials are proposed.

An industry wide review group, entitled the "Package Performance Industry Group", has oversight of all NDA work on corrosion of waste packages.

4.2 Waste Package Research

Waste Package Research is required to provide robust and justified input data on the performance of waste packages, with a focus on the performance in impact and fire accidents during transport and underground operations. There are a range of waste package designs and these will continue to develop to address new waste packaging proposals. Ensuring safety of workers and the public demands a combination of the robustness of the waste packages and the barriers and protection provided by the transport and repository facilities. Understanding the performance of waste packages allows robust designs of waste packages to be developed in parallel with ensuring repository operations are streamlined and simple.

Early impact and fire work used real test data from full-scale simulant waste packages. These were based on bounding mechanical and thermal loading scenarios: 25 m drop onto a flat unyielding target and 1-hour all engulfing fire duration. Figure 4.1 shows a full-scale fire test in progress.

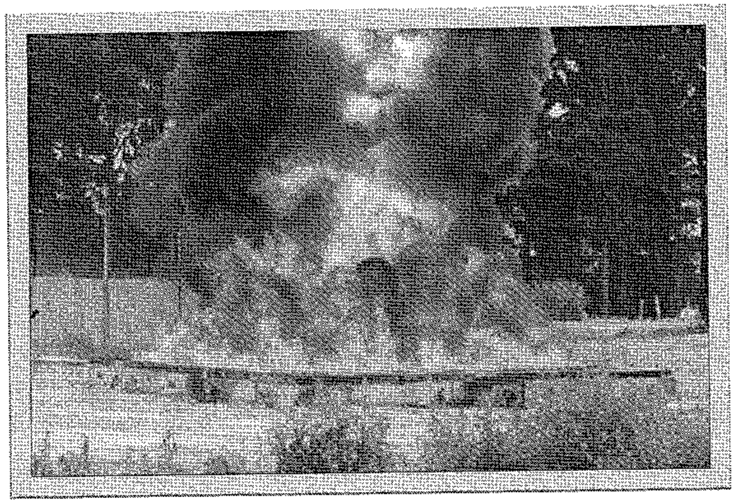

Figure 4.1 Full-scale 500 litre drum in fully engulfing pool-fire test

High costs are involved with conducting drop and fire tests, and over the last few years only a small number have been conducted. As the design of the geological disposal facility advances, faults and hazards for underground operations are identified and more clearly defined. In the light of these, better and more precise descriptions of the safety performance of waste packages are required.

The current approach is to move more towards placing greater emphasis on modelling combined with small-scale test data. In turn the approach is supported by limited full-scale testing. Figure 4.2 shows validation of modelling against full-scale drop test. Recently interest has increased in using larger waste containers with the benefit of improved volume efficiency. Figures 4.3 and 4.4 show detailed modelling of the $3m^3$ Box under impact and fire accident conditions. The advantages are that the modeller can:

- test cliff-edge effects (a situation where a small change in the experimental configuration can mean a significant change in behaviour);
- take credit for good design, e.g. thicker capping grout or inner lid;
- test small-scale samples that are more representative of real wasteforms;
- model the exact conditions identified for each fault and hazard;
- conduct sensitivity studies.

There is also a strategy to challenge pessimistic assumptions within the methodologies for evaluating impact and fire performance, so that the predictions are more representative. The tangible advantages are that more waste can be safety packaged into containers, thereby reducing the number of transport movements required and reducing the overall volume of waste in the geological disposal facility. An added benefit could be reduced costs. Impact accidents will consider drop heights, orientation, target type, adhesion and agglomeration, particulate size of concern for inhalation dose, and small-scale break-up test data. Fire accidents will consider external fire duration, cool down conditions, steam movement and small-scale release fraction test data.

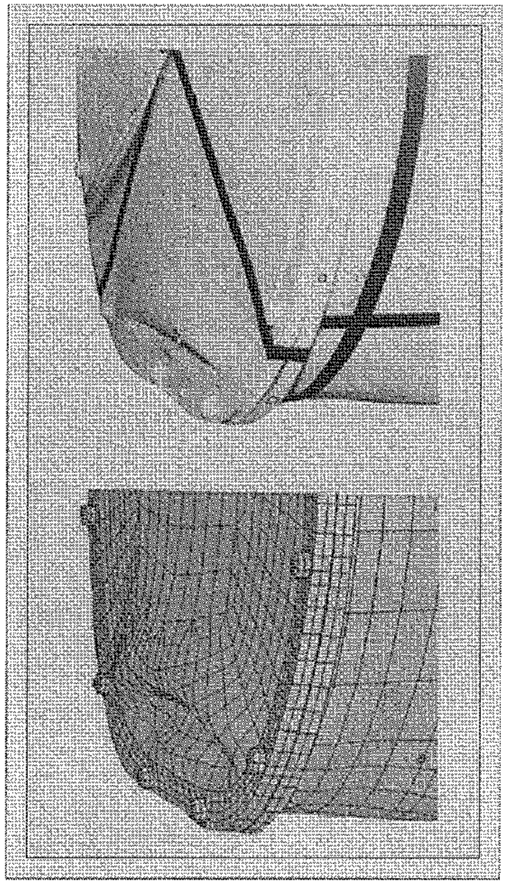

Figure 4.2 Validation of impact modelling against full-scale drop testing

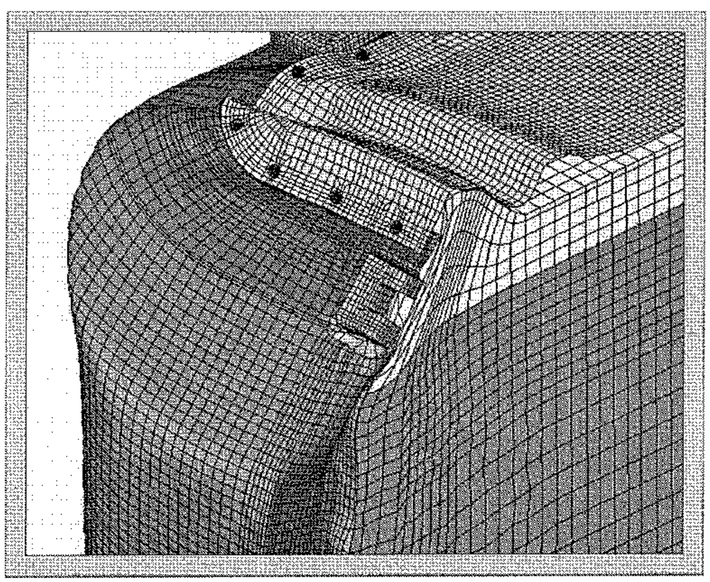

Figure 4.3 Cross section of the $3m^3$ Box showing a typical deformation after a 25m drop onto an unyielding target

The use of modelling combined with small-scale test data will enable robust release fraction data to be provided for each fault and hazard identified during transport to and operations at the geological disposal facility. These data will provide a key input to the safety cases. When combined with mitigation, barriers and protection measures, safety can be demonstrated at all stages in handling radioactive waste packages.

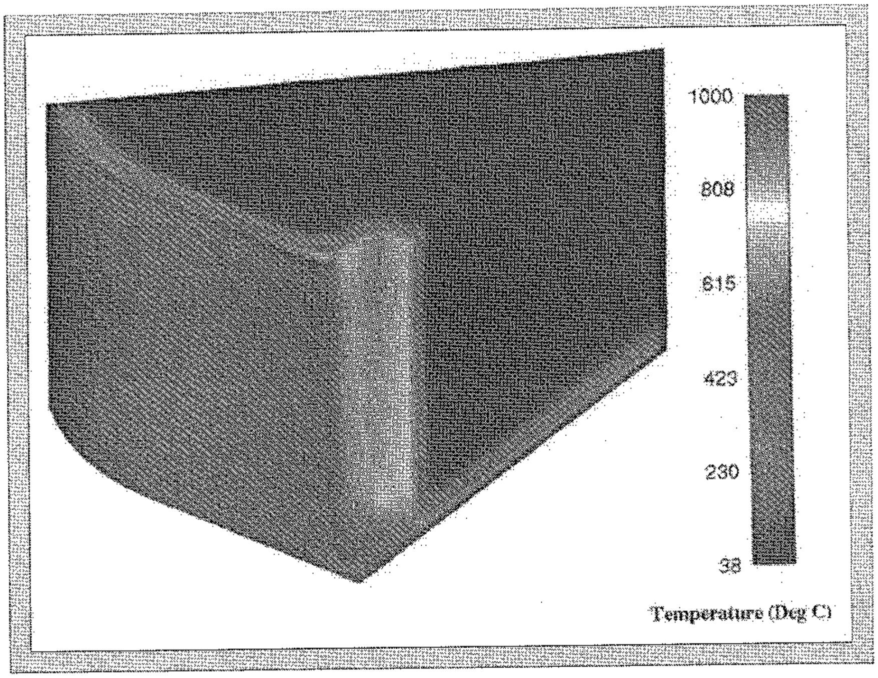

Figure 4.4 1/8th section of a $3m^3$ Box (lower half) showing a typical temperature distribution following a fully engulfing fire

4.3 ILW Wasteform Research

The packaging of radioactive wastes involves the immobilisation of wastes using a suitable encapsulant material to create a wasteform. The conversion of raw waste to an acceptable wasteform provides passive safety during storage and also contributes to the physical and chemical barriers after closure of the facility. Developing an understanding of the long-term behaviour of encapsulated intermediate-level waste is the focus of the wasteform research programme.

Many of the issues considered in this part of the research programme arise through dialogue with waste producers, particularly as wastes are assessed under the Letter of Compliance process, and details about the packaging of specific waste streams and their proposed wasteforms are provided. Waste producers conduct research aimed at developing appropriate wasteforms for specific waste streams and liaise with RWMD about this research.

Most ILW is immobilised within a cement-based matrix, which is compatible with the facility concept by design. However, for some wastes, there can be advantages in considering other immobilisation systems, which also need to be compatible with the overall concept. There are two key aspects in achieving this: the immobilisation matrix should not adversely affect the high pH environment within the geological disposal facility (e.g. by the generation of significant amounts of acidic species), and should not degrade to produce species that could complex significantly with radionuclides, making them more mobile.

Both of these aspects have been the subject of extensive research programmes for wastes in general, involving waste producers and external experts from contracting organisations. A methodology has been developed to take account of reactions that can influence the pH buffering behaviour of the near field (e.g. the presence of potential acid-generating material within wasteforms) when calculating the amount of backfill needed in a geological disposal facility [61], and this work can be used as a basis for considering the impact of non-cement based immobilisation matrices. The impact of complexants is discussed further under near-field research below.

To date, in performance assessment risk calculations, no credit has been taken for containment of radionuclides by the wasteform once the geological disposal facility has been closed. However, the majority of the initial radioactivity would decay inside the container in the thousand years following closure of the facility. This issue is being addressed in current modelling work, and this will focus requirements for further research, to build on the current understanding of wasteform evolution.

The key themes of the wasteform research programme are:

- Package performance over longer timescales (often referred to as package longevity [62]). The issues around the corrosion of stainless steel have already been discussed in Section 4.1. The evolution of the wasteform is considered in Section 4.3.1 and the specific aspect of corrosion of waste metals is covered in Section 4.3.2.
- The generation of gas from waste packages (Section 4.3.3); and
- The use of alternative encapsulants for certain wastes (Section 4.3.4).

Section 4.4 considers further topics in the context of near-field issues.

4.3.1 Evolution of Wasteforms

There is a need for unconditioned wastes to be processed to achieve passive safety. In the cases of liquid and sludge wastes, for instance, this is achieved by converting them into a solid wasteform. Similarly, solid wastes that contain particulate matter or exist in a fragmented form also require immobilisation. Cement grouts are found to be versatile, reliable and convenient immobilisation media and their use in waste packaging is physically and chemically compatible with the design of the facility, which uses cementitious material as vault backfill and in the engineering of the facility. The cementitious facility that would result offers a number of significant benefits in terms of physical and chemical containment of radionuclides [63].

The long–term management of the packaged wastes consists of a number of phases involving: interim storage at the site of packaging; transport to the repository; emplacement in underground vaults; an option for extended retrievable storage in the underground vaults; backfilling of the vaults, followed by sealing and closure of the repository; a possible further period of post-closure monitoring.

The design of waste packages and the materials used in their construction must be sufficiently robust to ensure the integrity of the packages, allowing safe handling, including transport through the public domain. The Generic Waste Package Specification [64] requires that the integrity of the waste package shall be such that it is capable of being moved and handled safely and efficiently, as required, during all the phases. A target of 500 years has been identified for the integrity of the waste container. The Environment Agency review [4] of Nirex Report N/122 [3] concluded that one of the areas needing further investigation was the longevity of waste packages over this timescale. Subsequent to the EA review, further discussions with EA and SEPA have taken place [65], and this provides an input to the research programme strategy addressing this issue.

An understanding of the wasteform matrix material, and its evolution with time without the addition of any waste, provides a background from which evolution of a wasteform can be predicted. Grouts used for the conditioning of radioactive waste in the UK are usually based on formulations containing blast furnace slag (BFS) or pulverised fuel ash (PFA) with ordinary Portland cement (OPC). These grouts are found to be:

- Tolerant to a wide range of chemical constituents.
- Suitable for immobilisation of solid, slurry and liquid wastes.
- Capable of being designed to be free-flowing when fresh so they give good penetration into drummed solid waste.
- Able to produce (after curing) wasteforms that have low voidage combined with adequate strength and low permeability.

The cement grouting processes developed by the nuclear industry in support of its proposals for waste immobilisation fall into three broad categories:

- Mixing of liquid or sludge wastes with the cement constituents to form a relatively homogeneous wasteform, which is then allowed to set.
- In-drum grouting, where solid waste items are placed in a drum and then infilled by pumping in a fluid cement grout.
- Annular grouted wasteforms where the waste, often in the form of high-force compacted drums (or 'pucks'), is surrounded by an inactive protective annulus of grout or concrete material.

PFA and BFS have been used in construction concrete for approximately 50 years. Therefore, direct observation of the long-term behaviour of cement formulations containing these materials is limited to this timescale. In addition, construction materials tend to be concretes (i.e. including aggregate), rather than mortars, so that studies of their behaviour may not be directly related to encapsulation grouts. However, the general physical properties of encapsulation grouts are understood, as are the conditions that could be detrimental. Samples taken from 12 year old simulant wasteforms containing grouted ferric floc have confirmed that the wasteforms were physically stable, with no evidence of degradation due to waste/grout interactions [66].

One of the major mineral phases in hydrated cement is calcium silicate hydrate (C-S-H). Part of the work to develop the Nirex Reference Vault Backfill (NRVB) included study of the evolution of C-S-H systems [67]. In freshly-cured cements, these are poorly crystalline or amorphous and could become more crystalline over long periods of time. At ambient temperatures, the rate of crystallisation is very slow. Recent examination of 20 year old samples of OPC and 9:1 BFS/OPC has shown that C-S-H has evolved over this period with changes in the Ca/Si ratio and increasing aluminosilicate chain length compared to data obtained when the samples were 14 months old [68]. Crystallisation of C-S-H gels can be accelerated in the laboratory by the use of high temperatures and, at 80 to 120°C, minerals similar to those found in nature are formed [69]. Although the mineralogy of the C-S-H phase differs depending on the cement type used (BFS or PFA), such results give some confidence in cement properties over an extended storage period.

Additional evidence of the longevity of cementitious materials comes from both natural and archaeological analogues for Portland cement [70, 71]. It is recognised that some of the information is not directly relevant to the wasteform grouts, but many of the mineral phases are the same, which allows legitimate comparisons to be drawn. Considered in isolation, the physical properties of wasteform grouts may be expected to remain relatively unchanged based on evidence from several archaeological analogues:

- Old Portland cement mortars.
- Ancient lime mortars, which retain their high permeability and porosity even when carbonated.
- Concretes used for Roman baths, which retain their low permeability; and from still-intact Roman buildings, which show long-lasting strength.

These analogues give timescales at least as long as those being considered for the operation of the geological disposal facility, even if there were a prolonged operational period before backfilling takes place.

Understanding of the reactions of typical waste components with cementitious matrices has developed as wastes have been considered through the LoC process, which assesses the acceptability of packaging proposals and includes an assessment of the implications of wasteform ageing. The mechanisms for chemical attack on cements and concretes are generally well understood from the need to determine the long-term performance of construction concretes. Thus, reactions of cements with many of the most likely chemicals to be released from wastes has been examined in the past, for example:

- Sulphate reacts with $Ca(OH)_2$ to form calcium sulphate, and with calcium aluminates to form ettringite in expansive reactions. Although BFS may improve resistance to sulphate attack, this is dependent on the source of the slag.
- Chloride reacts with $Ca(OH)_2$ to form soluble calcium chloride, which may increase porosity. Expansive reactions may occur, forming additional hydrated calcium aluminate.
- Many inorganic and organic acids react with cement components, particularly $Ca(OH)_2$, to form water-soluble salts.
- Carbonation may lead to a reduction in permeability due to the formation and precipitation of calcium carbonate. Carbonation from the "inside out" could occur from degradation of CO_2-generating wastes. Carbonation from the "outside in" would mainly affect the grout on top of the waste close to the vent. If the permeability of this grout were significantly reduced, it would be expected that gas generated inside the package would find an alternative pathway to the drum vent around the container / grout interface. Experimental work is planned to investigate whether these assumptions are valid and, if not, the potential, impact of these processes on wasteform performance. Carbonation of the wasteform offers a benefit in the overall safety case in that it represents a sink for any $^{14}CO_2$ that is generated by reaction or degradation of components of some wastes [72].

The possibility of these and other reactions is considered during the LoC process and they are investigated in more detail if thought to be significant for a particular waste stream. Although the majority of wasteforms are expected to perform satisfactorily in the longer term, there will be some whose likely evolution contains uncertainties. Examples of those considered to date include:

- *Wasteforms containing iron hydroxide flocs.* It was initially considered that iron hydroxide flocs would crystallise with time and cause problems with dimensional stability of the wasteform. However, recent work indicates that, although there is some initial shrinkage, it is likely to be acceptable. Studies carried out at Sheffield University have seen no change in crystallinity of a cemented simulant floc up to 2 years after conditioning and 12 year old samples supplied by Nexia Solutions also showed no change (related work can be found in [66]).

- *Wasteforms containing plutonium contaminated material (PCM).* PCM has a relatively high concentration of organic material, which is increased by supercompaction. The degradation of organic materials can result in production of acidic species: either acidic organic compounds such as carboxylic acids or stronger (mineral) acids such as hydrochloric acid generated from chloride present in the parent polymer. Because such acids could have an impact on the evolution of the waste package, the package has been designed with a cement annulus, which protects the outer container from corrosion. Consideration of the post-closure impact of the degradation of organic materials within supercompacts suggests that although transient acidic conditions may occur within compacted pucks during storage, high pH conditions would be established after facility closure and resaturation [73]. Further work is being undertaken to understand in more detail the likely significance of chloride release from wastes on internal corrosion of the waste container.
- *Wasteforms containing reactive metals.* This is an important issue and is discussed in more detail in Section 4.3.2 below. Guidance on the quantities of reactive metals that may be allowed in individual waste packages without the requirement for further justification from the waste producer is included in waste form specifications [74,75]. The values are for guidance only, and waste producers are invited to justify higher values if the corrosion rates are demonstrably slow or other mitigating factors can be invoked.

A spreadsheet-based tool has been developed to enable the qualitative screening of packaged waste streams for possible package performance issues. This will allow important generic processes, which may be significant for package performance, to be identified and included in future research. In addition, it will identify waste packages where the provision for future reworking may be required. Package-scale mathematical models that will allow consideration of the implications of ageing effects, such as wasteform cracking, on post-closure performance in the future are also being developed. There has previously been little emphasis on the performance of the waste package in post-closure assessment modelling, since the overall impact on risk is likely to be small. However, developing such models will contribute to future assessments by describing the performance of individual barriers as part of a multi-barrier safety case. This approach is more realistic and will enhance confidence in the system overall.

4.3.2 Corrosion of Waste Metals

Various metals are present in the waste [76, 77]. The inventory is dominated by stainless steels and other ferrous metals (e.g. mild steel). However, aluminium, lead, magnesium alloy components and cladding swarf (referred to hereafter as Magnox) from Magnox reactor fuel elements, Zircaloy cladding from uranium oxide fuel pins and uranium also make a significant contribution. Examples of Magnox swarf simulants used in experiments are shown in Figure 4.5.

As discussed above, it is envisaged that most waste will be immobilised within waste containers using a cementitious grout, either by intimate mixing or by surrounding pucks of compacted waste with a grout annulus. The good resistance of stainless steel to general corrosion under alkaline conditions has been discussed above and available information suggests that Zircaloy may be considered to be similarly corrosion-resistant under alkaline conditions [78, 79].

In contrast aluminium, Magnox and uranium are reactive metals that can corrode rapidly under high pH conditions and are present in several waste streams in relatively large amounts. The high pH corrosion of aluminium, Magnox and uranium (under anoxic conditions) results in the formation of hydrogen gas and solid corrosion products. The corrosion products occupy a greater volume than the original metal and have the potential to cause cracking of the wasteform and deformation of the waste container on timescales similar to those considered for the long-term storage of waste packages in an underground facility. Excessive gas generation from rapid corrosion could also lead to pressurisation and damage of the wasteform. Therefore, understanding the long-term behaviour of wasteforms containing appreciable amounts of grouted reactive metals is important in evaluating their package longevity and in identifying those waste streams where alternative conditioning methods may be required or existing waste packages for which re-working in the long term may possibly be necessary.

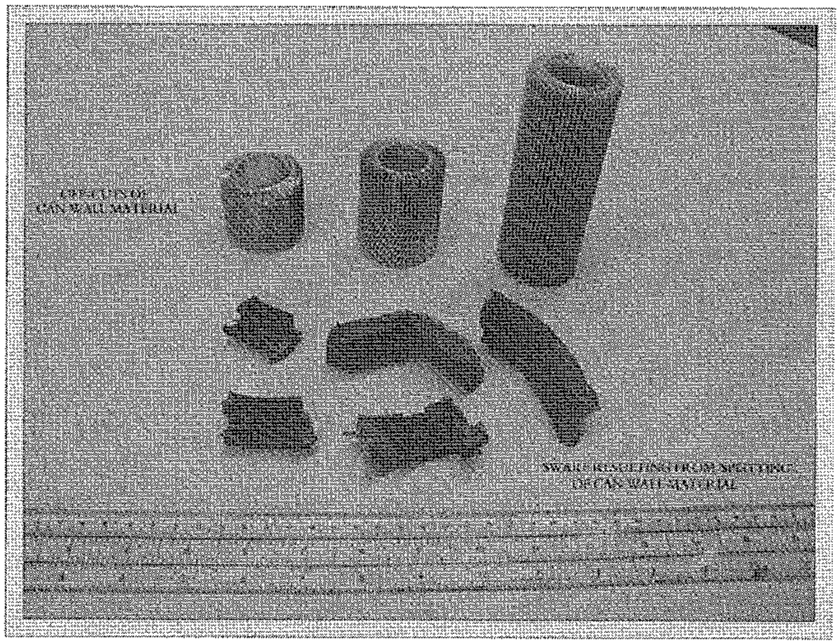

Figure 4.5 Examples of Magnox swarf simulant

Existing work on the corrosion of Magnox and application to estimating the longevity of packaged waste has been reviewed [80]. Early predictions of the longevity of packages containing large amounts of Magnox were based on short-term experimentally determined corrosion rates from small-scale samples. Although 500 litre drums of encapsulated swarf from the decanning of irradiated Magnox fuel elements do show high short-term corrosion rates during grouting and curing, these rapidly decrease to a low long-term rate. This behaviour may be explained by consideration of the grout microstructure and the state of the water held within. Corrosion rates are determined by the availability of water to take part in the corrosion reaction. Water availability is reduced at the grout/Magnox interface as the grout microstructure develops and this leads to a consequent reduction in the rate of corrosion of the metal. The formation of corrosion product at the surface of the metal also brings about a reduction in the corrosion rate. As long as the encapsulation of the Magnox cladding swarf ensures good infiltration and intimate surface contact, the properties of the grout should provide a significant contribution to the longevity of the product. Figure 4.6 shows some Magnox swarf being prepared as a simulated wasteform.

The encapsulation of metallic uranium in grout raises similar issues to Magnox. To some extent, the availability of water and understanding of the microstructure of the grout may help to predict the behaviour of a cemented package. The corrosion behaviour of uranium shows more variability than Magnox, not always decreasing to a slow rate. There are fewer data available for uranium corrosion in grouts than for Magnox. The corrosion behaviour appears to be more sensitive to conditions than that of Magnox. The use of encapsulants other than the current OPC-based formulations may offer an alternative means of packaging wastes containing uranium metal.

Aluminium corrodes rapidly under alkaline conditions due to the dissolution of the protective oxide layer. This exposes the metal surface which corrodes to give hydrogen and aluminates which, in a similar manner to the corrosion of Magnox, can form a corrosion product layer and reduce to some extent the rate of corrosion [81]. Corrosion is less rapid under less alkaline conditions, and the possibility exists for reducing the rate of aluminium corrosion by the use of less alkaline encapsulants.

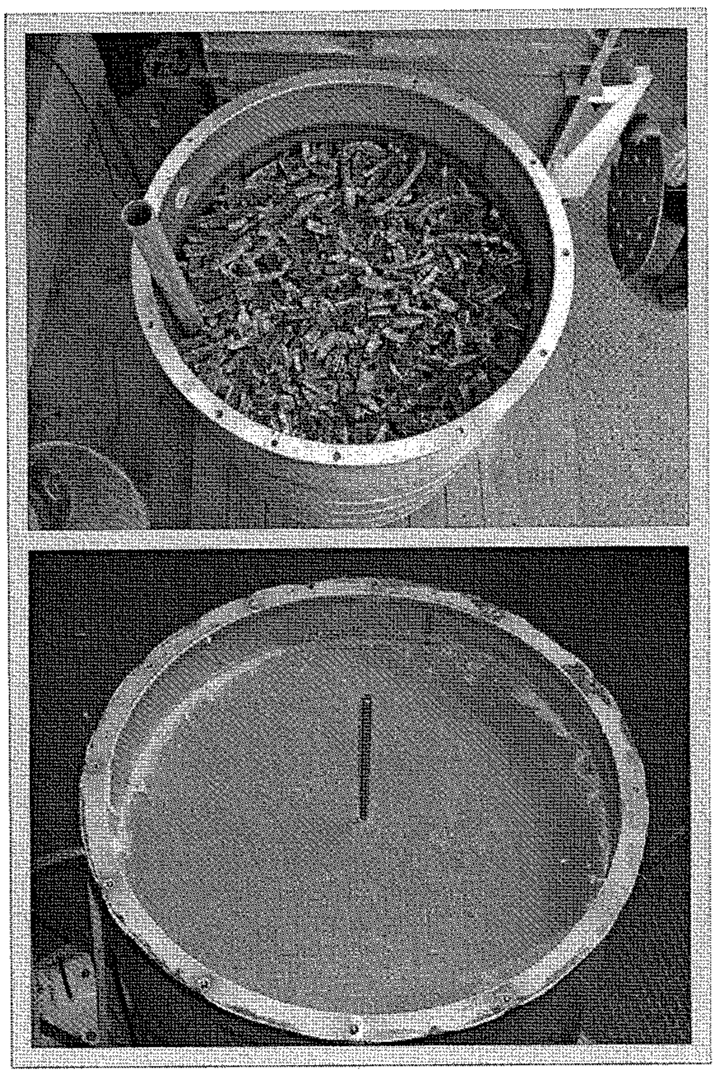

Figure 4.6 Magnox swarf being prepared as a simulated wasteform

Lead is present in wastes through its use in the nuclear industry as a shielding material. Although lead is generally considered to be fairly resistant to corrosion, this is partly due to the formation of protective surface coatings and lead will corrode in alkaline solution due to dissolution of the surface coating (in a similar manner to aluminium). However, the reaction rate is expected to be much slower. Lead will mainly be present in a fairly massive form (e.g. lead blocks) and the low surface area to mass ratio may also limit the overall rate of corrosion.

Contact between dissimilar metals has the ability to increase the corrosion rates of the reactive metals due to the formation of an electrical (galvanic) couple. This will result in accelerated corrosion of a reactive metal in contact with stainless steel, lead, mild steel or graphite while the electrical couple is maintained (e.g. until the amount of corrosion is sufficient to break the contact) and sufficient water remains available [81]. The corrosion of mild steel also results in the formation of solid corrosion products occupying a greater volume than the parent metal, although hydrogen is only produced under anaerobic conditions. The corrosion of grouted mild steel wastes is analogous to the corrosion of steel reinforcing bars in concrete [82]. Corrosion rates depend upon a number of parameters including pH, relative humidity, concrete porosity, cement type and chloride concentration. Corrosion rates increase in carbonated materials, due to the decrease in pH at the metal surface, and with increasing temperature. It has been considered previously that the corrosion of grouted mild steel items is unlikely to be significantly detrimental for wasteform performance during storage for one hundred years [83].

It is recognised that we need to develop a better understanding of the effects of corrosion of grouted Magnox on wasteform expansion as this has been identified as a potential mode of failure of the waste packages [80]. Further experimental and modelling studies of the rate of corrosion of grouted Magnox and consequent effect on wasteform swelling are being undertaken, in order to understand the circumstances where some form of re-working might be required for such waste packages if they were stored for a prolonged period, either on the surface or underground before backfilling of the facility. Re-working could take the form of repair, over-packing or re-packaging.

It will be apparent from the above discussion that the corrosion of some metals is promoted in highly-alkaline aqueous conditions. In some cases, e.g. aluminium, reducing the alkalinity of the grouted environment may reduce the rate of corrosion. However, the availability of water is a common controlling factor in determining the rate of corrosion. For some metallic wastes, there may be benefits in employing alternative encapsulants, based on non-aqueous systems (e.g. organic polymers) or grouts with reduced water content, to limit water availability at the metal surface and hence control the rate of corrosion. Such alternative encapsulants may also offer benefits (e.g. better infiltration) for the packaging of other problematic wastes and are discussed in Section 4.3.3 below.

4.3.3 Alternative Encapsulants

The majority of wastes can be conditioned to meet the waste package specification requirements through the use of current grout formulations e.g. those based on OPC/BFS or OPC/PFA. However, it is becoming clear that the challenges presented by some wastes may be better addressed through the use of alternative encapsulants. Much less information is available, in general, on the properties and long–term behaviour of potential alternative encapsulant materials, whether based on inorganic or organic systems, in comparison to the cumulative knowledge developed over several decades on the use of grout formulations based on OPC. Such knowledge is being acquired through investigation under the research programme and dialogue with waste producers.

One class of alternative encapsulants under investigation is polymeric organic encapsulants [84]. The potential advantages offered by organic polymers include the capability to infiltrate fine voidage, immobilise fine particulate material and, of particular relevance to wasteform ageing, control the corrosion of embedded metals by essentially eliminating free water from the encapsulant and minimising water transport through the wasteform. A number of organic polymers have been considered for packaging radioactive wastes around the world with bitumen, polyethylene, epoxy resins, polyester resin and urea formaldehyde the most extensively investigated [85]. Each has particular properties which may offer benefits in some applications.

The main themes of the current research programme on alternative encapsulants are as follows:

- *Long-term performance of organic polymer encapsulants.* The use of organic polymers has potential benefits for the encapsulation of some problematic wastes where there is incompatibility with OPC-based grouts (e.g. reactive metals) or where infiltration is difficult. Further studies will be initiated to improve understanding of the long-term stability of polymer encapsulants under geological disposal conditions and compatibility with a cementitious near field. A programme of experimental studies is being undertaken on the stability of potential organic polymeric encapsulants under geological disposal conditions. These studies will also enable any significant degradation products formed to be identified, and their effects understood. Figure 4.7 shows some possible polymer encapsulants being subjected to gamma irradiation in contact with aqueous solutions.

- *Development of an understanding of the properties and performance of alternative inorganic waste encapsulation processes.* Future waste conditioning methods for ILW may employ alternative inorganic encapsulants (e.g. low pH cements) or novel processes (high temperature processes producing slag or vitrified wasteforms) offering potential benefits over conditioning with OPC-based grouts. These may raise issues of potential compatibility with a cementitious near field. In order to allow such issues to be addressed studies are required to establish a basis for assessing their performance. Experimental studies will be undertaken to enable these issues to be understood.

- *Examination of the long-term impact of superplasticisers on near-field performance.* The use of superplasticisers is likely to be proposed for encapsulation of certain wastes in order to reduce grout water content or improve flow properties. In addition, it is likely that there may be a requirement for their use in constructional concrete within the geological disposal facility. Such additives may adversely affect the retention of radionuclides within the near field. Experimental and modelling studies are being undertaken to provide information towards developing arguments to understand when the use of such materials is appropriate. This work will include studies on radionuclide complexation and the effects on radionuclide solubility and sorption, on their long-term degradation and on the rate of release from grouts.

4.3.4 Gas Generation

A feature of intermediate and low-level wastes is that they can contain metal and organic materials that may produce gas when they corrode or degrade. The metal containers, in which wastes typically are packaged, will also eventually corrode over thousands of years, producing gas. Gas is generated by corrosion of metals, by microbial degradation of organic wastes (particularly cellulose) and by radiolysis. Minor quantities of gas would also be generated by radioactive decay. A small proportion of the generated gas could be radioactive, mainly containing the isotopes tritium and carbon-14.

Wastes that are expected to generate gas are packaged in vented containers in order to prevent pressurisation of the waste container. The disposal facility will be designed with features that mitigate the potential consequences of gas generation. During the operational phase, the disposal vaults, and other parts of the facility, will be ventilated, which will prevent the build-up of gas. Gas concentrations and discharges would be monitored, filtered and controlled to ensure compliance with authorised discharge levels as is the case in surface stores. Such levels are set to ensure that any discharges do not pose an unacceptable risk to man or the environment.

Issues related to gas generation have been the subject of research over many years, both in the UK and internationally. This has established an understanding of these issues sufficient to guide the design of the concept and to develop a model of gas generation within the facility, although some uncertainties remain about the amount of gaseous carbon-14 that would be generated from the waste. The possible impacts of gas generation have been reviewed in a recent EC-funded project [86].

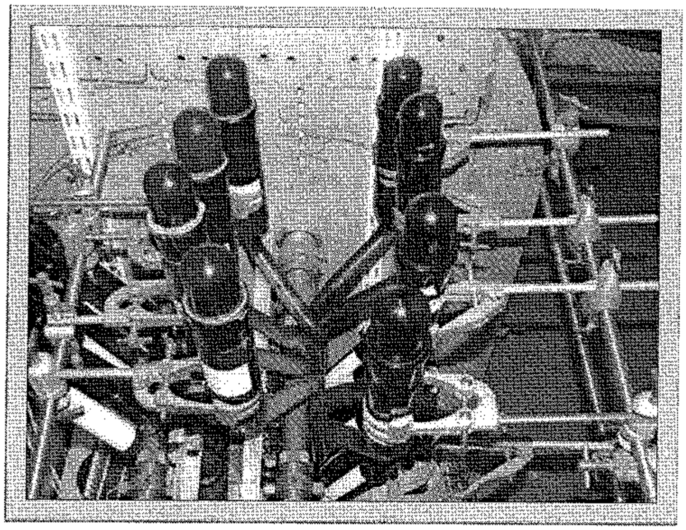

Figure 4.7 Gamma irradiations of possible polymer encapsulants in contact with aqueous solutions

Current research on bulk gas generation aims to improve the understanding of gas generation rates in order to refine data input to the gas generation model SMOGG [87] used as part of post-closure and waste package assessments. Knowledge of the rates of gas generation from waste packages during transport to the facility and operations of the facility, including radiolytic production of hydrogen and oxygen and possible release of radon, is required as input to assessment calculations. The research includes modelling, review and experimental studies of rates of gas generation.

The vault backfill has a relatively high porosity, which will allow gas to disperse in the vault volume. The vault backfill and the grout within waste packages are cement-based and will react with carbon dioxide to form low solubility carbonates, limiting the release of gaseous carbon dioxide from the geological disposal facility. Further work is being undertaken to demonstrate that the carbon dioxide would have sufficient access to backfill and that there would be sufficient time for the carbonation reaction to occur. However, scoping calculations presented in Volume 4 of Nirex 97 [88] indicate that sufficient equilibration would be achieved and that therefore negligible gaseous carbon dioxide would be present in the facility.

A remaining key issue is the potential radiological consequences of gases containing carbon-14 [72]. Work to address this issue includes studies to assess the extent to which gas would dissolve in groundwater and the potential for different geological environments to retard gas migration. Within the wasteform research programme studies the focus is on work to reduce uncertainties in the rates and quantities of gaseous C-14 generated.

There are three potential major sources of carbon-14 containing gases in the UK radioactive waste inventory: irradiated graphite; irradiated metals; and some waste streams containing organic materials [89, 90]. The main focus of the current research work is to build a sounder understanding of the first two sources. In these wastes the majority of carbon-14 arises from the neutron irradiation of nitrogen-14, which can be present in forms such as adsorbed molecular nitrogen on surfaces or as nitrides within materials such as steels. An experimental rig to measure the release of volatile carbon-14 from irradiated graphite is shown in Figure 4.8. Experimental programmes to measure release from irradiated materials are seen as an important part of developing the required understanding. These programmes include experiments to obtain:

- *Data for the rates of release of gaseous carbon-14 from irradiated graphite in contact with alkaline water.* This area of work is concentrating on obtaining data relevant to understanding the generation (potential quantities and rates) of volatile C-14 from irradiated graphite in the near field. Although carbon-14 released in the form of carbon dioxide would be likely to be retained within a cementitious near field, other possible carbon-14 containing species such as methane may be mobile in a gas phase. There is currently a lack of data and insufficient understanding of processes involved to allow a robust position to be established for treatment in performance assessments. Some preliminary experiments have already been undertaken [91, 92]. These detected the release of a small amount of volatile carbon-14 from samples of irradiated graphite from the Windscale Advanced Gas-cooled Reactor (WAGR) in contact with alkaline solution over a period of a few weeks. Further experiments will be undertaken to extend the range of irradiated graphite samples studied and to investigate longer-term release rates.

- *Data for the rates of release of gaseous carbon-14 from irradiated steels in contact with alkaline water.* This area of work will concentrate on obtaining data relevant to understanding the generation (potential quantities and rates) of volatile C-14 from irradiated mild steel and stainless steel in the near field. Work has begun by investigating the products of the reaction of metal carbides with aqueous solutions. This will then be extended to study the release of volatile carbon-14 from the corrosion of samples of irradiated steels in alkaline solutions (in an analogous programme to that for irradiated graphite). This will enable a robust position to be established for treatment in assessments.

The work on gas generation is complemented by work on carbonation reactions described in Section 4.4.1. A description of the work on gas migration is given in Section 4.7.5.

This effectively limits the quantity of radionuclides that could be dissolved in the groundwater.

- The calcium in the cement porewater reacts with carbonate in the inflowing groundwater, precipitating calcium carbonate.
- The backfill provides a high surface area for the sorption of radionuclides from solution [94]. This reduces their ability to migrate out of the geological disposal facility in groundwater.
- The backfill provides physical stability surrounding each container.
- At closure, the facility access routes would be backfilled and sealed to prevent these acting as preferential pathways for contaminated water [96].

4.4.1 The Chemical Environment

The near-field chemical environment is an important safety function in the NDA concept for disposing of low and intermediate-level wastes; it provides a number of additional benefits over and above those provided by the waste package alone. A large programme of research has been carried out in this area, including experimental and modelling work. However, it should be demonstrated that the chemical environment would indeed provide conditions in which the solubility of radionuclides would be low and that the high pH environment would last over the timescales required. This is, therefore, considered to be an important issue and is the subject of ongoing research.

The evolution of the pH of the backfill is affected by processes including leaching, reactions with groundwater solutes, reactions with waste encapsulation grouts, wastes and their degradation products. Leaching and ageing of the backfill will also affect its buffering behaviour and sorption characteristics.

The backfill requirement is specified on the basis of calculations of pH buffering in a homogeneous near field, taking full account of all the expected detrimental reactions with the waste and inflowing groundwater [61, 97]. In addition, variations in the composition of inflowing groundwater, and in particular the magnesium and sulphate concentrations, could be of significance in determining the pH evolution of the near field. As a consequence current work is concerned with extending the model to cover a range of typical groundwater compositions in the UK. In future, more realistic representations could include a treatment of the spatial distribution of groundwater reaction products and the migration of the evolving pH front in a vault.

Current models of the chemical conditioning provided by the near field treat the vault contents as a homogeneous medium with uniform waterflow throughout. In reality, cracking of the backfill and wasteform grouts may occur and provide preferential flow paths in the engineered system. This, together with the possible formation of relatively impervious groundwater reaction products on the crack surfaces, may affect the conditioning of water in these features. Modelling and supporting experimental studies are being undertaken to develop an understanding of crack formation in both the backfill material and wasteform grouts and the effect on the physical and chemical barrier performance of the grouts and backfill.

The carbonation of the backfill and wasteform grouts represents an important sink for the removal of ^{14}C-labelled CO_2 from gas generated in the near field. However, carbonation of the backfill may affect conditioning of the near-field pore water. Experiments and modelling of the carbonation of the backfill and wasteform grout, will address these two aspects.

4.4 ILW Near-field Research

This section again focuses on the part of the geological disposal facility containing intermediate-level wastes, and those low-level wastes that are not to be disposed in a shallow facility.

The near field of the facility consists of the vaults and the immobilised waste within them, as well as the cement-based vault backfill.

The engineered barrier system is designed to provide the following benefits:

- Wastes are immobilised in cement within a stainless steel container. This package provides passive safety during the operational period [58] and also contributes to the physical and chemical barriers after closure of the facility.
- Once the vaults are backfilled and sealed, oxygen will be consumed (mainly by metal corrosion and organic degradation reactions), so that anaerobic or reducing conditions are established [93]. Reducing conditions limit localised corrosion of stainless steel waste containers and maintain some radionuclides in low oxidation states, which have low solubility.
- Incoming groundwater will dissolve small quantities of the cement-based backfill, becoming alkaline (high pH) as it fills the vault [94]. The high pH environment ensures that the rate of corrosion of the stainless steel containers is very slow [47].

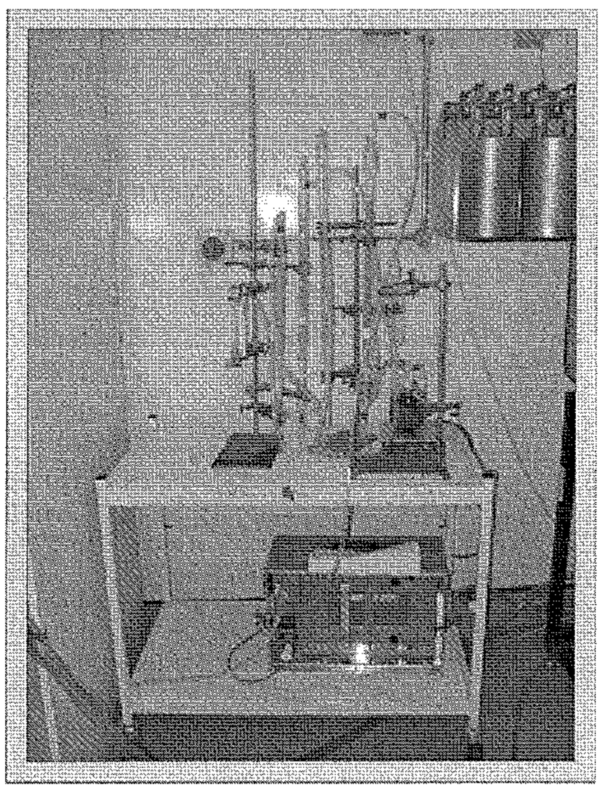

Figure 4.8 Measurement of release of volatile ^{14}C from irradiated graphite

- The high pH of the cement porewater ensures that the chemistry of the near field is dominated by the hydroxyl ion (OH^-), which favours the formation of metal hydroxides. Hydroxides of some key radionuclides have very low solubility [95].

For redox-sensitive elements, it is important to understand the expected oxidation state in the geological disposal facility near field. Models that describe our understanding of the redox-controlling processes at different times during the facility lifetime are important for demonstrating confidence in the concept of chemical containment. A model for evolution of the redox conditions in the near field has been developed. It considers the consumption of any residual oxygen, the anaerobic corrosion of stainless and mild steels and the eventual establishment of redox control by near-field solid phases. The distribution of wastes and the nature of the redox active solid phases will also play a role in determining the actual redox potential in regions of a vault [98, 99]. The model assumes that the system is in equilibrium. Although there are some uncertainties, it is considered to be a reasonable approximation, given the long timescales involved.

The model is reviewed as new information becomes available, for example, the NEA updates to uranium thermodynamic data [100]. The NEA is currently considering thermodynamic data for iron, and again the impact of these data updates will need to be considered.

The principle of chemical containment has been demonstrated by short-term laboratory experiments complemented by modelling studies. It is seen as important to build confidence in the performance of the system through long-term experiments or larger-scale tests to demonstrate key aspects of expected processes in the geological disposal facility. Planning of such experiments is underway, with a view to setting some demonstration experiments running in the near future.

4.4.2 Basis for Key Near-field Chemical Parameters

The research programme provides data and process understanding to support the safety case.

An important focus of the research programme is therefore to conduct laboratory and field experiments under conditions relevant to the geological disposal facility. Such experiments will be complemented by studies of natural systems, which enable longer timescales to be studied.

There has been an extensive research programme over a number of years measuring the solubility of important radionuclides in the high pH and reducing environment of the geological disposal facility [101, 102, 103]. There has also been an extensive programme measuring sorption onto NRVB, focusing in particular on fresh materials and pure solids [104]. However, there will be a need for further measurements and modelling studies of the evolution (ageing) of the NRVB and the wasteform grouts and the effects on radionuclide sorption, and the sorption of inorganic toxic species. In addition it may be necessary to obtain additional solubility data for certain important radioelements and inorganic toxic species.

Process models have also been developed to ensure the results can be placed in context and an appropriate understanding developed [94,105, 106]. The experimental data and interpretive models are not used directly in assessment models. The approach adopted is to elicit key parameters using expert groups. These groups take into account the available experimental data (obtained either as part of our programme or as part of programmes overseas) and the appropriateness of the conditions under which they are obtained. They also take into account supporting modelling work, and the understanding that has been developed. The elicited data includes an estimate of the uncertainty in the parameters by defining a probability density functions (PDF) [107]. This enables the uncertainty to be incorporated into performance assessments in a structured way, so that there is an understanding of the robustness of the results. In their review of the near field [108], the Environment Agency commented 'whilst we have not reviewed in depth the detailed justification for the PDFs adopted by Nirex in the GPA, it is clear that the data ranges are generally comparable with those adopted in certain other disposal programmes world-wide'.

4.4.3 Non-aqueous Phase Liquids

Non-aqueous phase liquids (NAPLs) may be present in radioactive wastes in the form of organic compounds [109]. Any compound considered to be a NAPL is by definition immiscible with water and therefore may migrate separately from groundwater. NAPLs can be either denser (DNAPL) or lighter (LNAPL) than water. LNAPLs have the potential to migrate more rapidly than groundwater. Some radionuclides, particularly those present as uncharged or less-polar species could partition into the LNAPL and thus be transported with this phase. The ability of lubricating oil to extract plutonium from alkaline solution and its effect on sorption has been examined [110, 111].

LNAPLs would only leave each vault if there were sufficient pooled in a reservoir in the roof space to overcome the forces that prevent such materials entering narrow fractures or pore structure in the host rock. Given that the amounts of NAPLs such as oil and grease in wastes are controlled by the LoC process, this source does not represent a significant uncertainty. Furthermore, materials such as oils are known to break down under radiolysis to give water-soluble or immobile products over timescales as short as 100 years, the timescales being subject to the precise conditions under which radiolysis occurs. It has been shown that small quantities of oil may be retained within cement matrices [112].

However, the possibility exists that further NAPLs could be created in the facility as breakdown products of the organic polymers in wastes [113]. Their possible breakdown to NAPLs contributes a considerable uncertainty in the size of the LNAPL reservoir that may collect in the roof space of a vault. Therefore, work is underway to define the realistic potential yield of NAPLs from this source and the nature and rates of production of such NAPLs. Synthetic polymers may degrade by chemical, radiolytic, thermal and microbial processes. Radiolytic degradation is seen as the most important process for such polymers under disposal conditions as, in general, most are not susceptible to alkaline degradation. An experimental programme to study the degradation of a range of organic polymers under gamma irradiation and the analysis of the resulting products has started recently. To date, a limited number of polymers have been irradiated at high dose rates to 10 MGy. A fuller range of materials are being irradiated at a lower dose rate in order to evaluate any dose rate effects. The polymers are being irradiated dry and in contact with deionised water and high pH solution. Typical effects of gamma irradiation on solid PVC polymer are shown in Figure 4.9.

4.4.4 Challenges to Near-field Performance

Complexants make radionuclides more mobile by increasing their solubility and reducing sorption. One of the most significant sources of complexants within the geological disposal facility is cellulose (present in the waste) which degrades over time under alkaline conditions [114]. The increases in solubility and decreases in sorption caused by the presence of cellulose degradation products have been measured in experiments and a methodology has been developed to include the effects in performance assessments [115]. It is expected that further data may be required as part of the input to data selection for future performance assessments of the groundwater pathway.

Because of the focus on cellulose degradation, less work has been undertaken on the effects of 'as-disposed' complexants (e.g. EDTA, citrate) on radionuclide behaviour at high pH [115]. With the development of performance assessment modelling to demonstrate the contribution of the waste package after closure of the facility, and in order to provide support to the LoC process, experiments are being undertaken to examine the effect of common complexants on the solubility of elements/radionuclides at high pH.

Sorption onto cementitious materials within the near field contributes to the retardation of some radionuclides within the geological disposal facility. To date, performance assessments have only considered the role played by the vault backfill and thus data have been acquired for sorption to the NRVB. The sorption of radionuclides to waste encapsulation grouts has not been considered. In order to support package scale assessment modelling, a programme of work has commenced this year to measure data for the sorption of key radionuclides onto wasteform grouts. In addition, ongoing work is measuring sorption onto leached and hydrothermally-treated samples of NRVB to simulate 'aged' vault backfill.

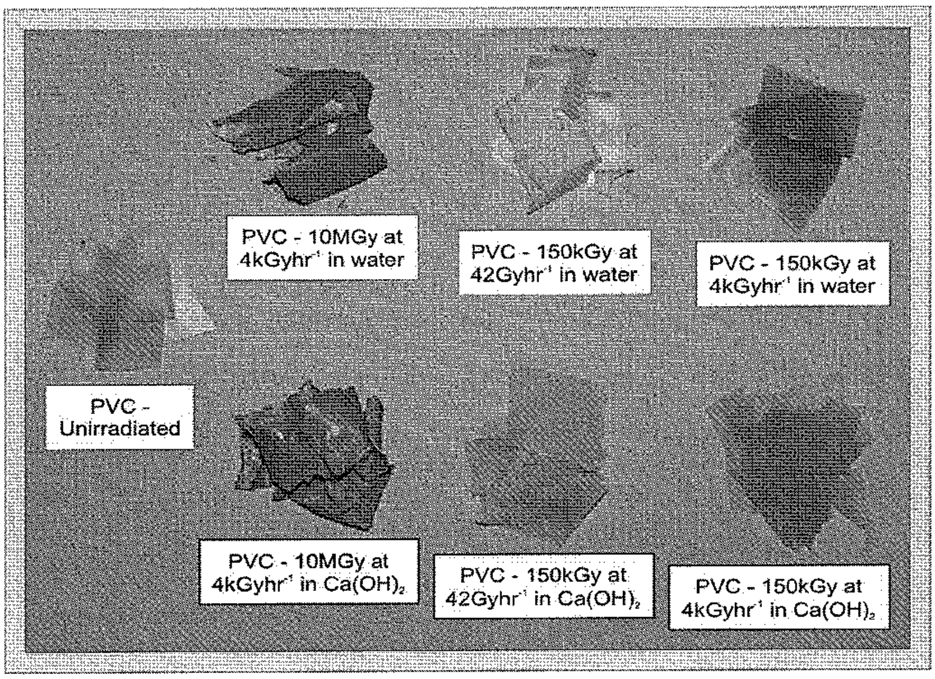

Figure 4.9 Effect of Gamma irradiation on PVC

Colloids offer a means by which the aqueous concentration of radionuclides in the near field may be increased. Previous work in this area related to the near field has included experimental studies of colloid generation in mixed waste equilibrium leach tests and from the NRVB [116, 117]. The approach to treating colloids in performance assessments is being reviewed, along with the capacity for colloid production in the near field, the stability of such colloids, their ability to migrate and their capacity for uptake of radionuclides. This will enable the future treatment in the safety assessments and any consequential data requirements to be identified.

4.5 Research on High-level Waste and Spent Fuel

Historically, Nirex's remit was focused on the long-term management of solid intermediate-level waste (ILW) and that low-level waste (LLW) that is unsuitable for disposal in near-surface facilities. The majority of Nirex's work has therefore been devoted to the long-term management of these wastes. In response to the revised

Government policy, a research programme is being developed by NDA RWMD for HLW and any spent fuel that is deemed in the future to be waste.

One of the steps that has been made has been to undertake two reviews. In the first the properties of UK HLW were discussed [118], and the second considered the current status of other countries' programmes for the geological disposal of vitrified HLW, and provided information on recent issues and developments in the long-term behaviour of the wasteform in a geological disposal environment [119]. Together these will help ensure that our future research builds on the work done elsewhere, and focuses on the issues particular to UK wastes and UK disposal environments.

One way in which NDA RWMD has gained knowledge about overseas programmes on high-level waste and spent fuel is by participating in NF-PRO, which formed part of the 6^{th} Framework Programme of the European Commission. The project improved the understanding of safety relevant processes in the near field of repository concepts for HLW and SF currently under investigation within the European Union, and the integration of these processes in performance assessment [120]. There were 40 participants in NF-PRO representing all the major radioactive waste management organisations in Europe. UK participants included the NDA, Serco Assurance, Cardiff University, the University of Sheffield, the British Geological Survey and Quintessa Limited.

In the light of this work, the strategic direction of the HLW and SF research programme falls under the following three headings:

1. *Investigations of the behaviour of UK highly radioactive wastes*

UK nuclear power generation has mainly been based on operation of Magnox reactors and Advanced Gas-cooled Reactors (AGR); the UK operates only one Pressurised Water Reactor (PWR) at Sizewell. The Magnox reactor and AGR designs are specific to the UK, and the wastes which result have different chemistries and irradiation histories from wastes produced from power generation overseas. Work is proposed to measure the key parameters which underpin wasteform stability such as long-term dissolution rates, and secondary phase formation. As an example, the specific formulation of Magnox glass may mean that the surface alters in a different manner over very long timescales in comparison to overseas glasses, and hence the dissolution control may be different [121]. Key radionuclides may or may not be sealed in different secondary surface products formed on Magnox glass. Two micrographs showing the formation of secondary phases in HLW are shown in Figure 4.10.

2. *Investigation of physical and chemical interaction between near-field barriers, the wasteform, and surrounding groundwater in the HLW and SF near field.*

The engineered barrier system makes an important contribution to the safety of many HLW and SF disposal concepts. Barriers need to be designed so that they perform during the initial thermal period and also in the longer term, while the wastes retain significant radioactivity. Again there is a need to obtain UK-specific data on engineered barrier performance, in order to build confidence in the concept. The main topics for study are the interaction between groundwater and buffer materials, the rate and routes of water ingress into HLW or SF packages, the physico-chemical interactions between materials resulting from groundwater/waste interaction, and the consequent implications for engineered materials. Later research will focus on parameter values for significant radionuclides and associated uncertainties for a range of scenarios.

3. *Support to the DSSC on the HLW and SF concept*

The UK concept for HLW disposal is still under development. It is important to ensure that research is in place to demonstrate that key processes relevant to the chosen concept are appropriately captured in the safety case.

The focus will be on filling gaps in data and mechanistic understanding, and to improve confidence in extrapolation to long timescales and different scenarios. It is worth noting that the substantial copper and steel containers favoured by SKB offer an extremely high level of physical containment.

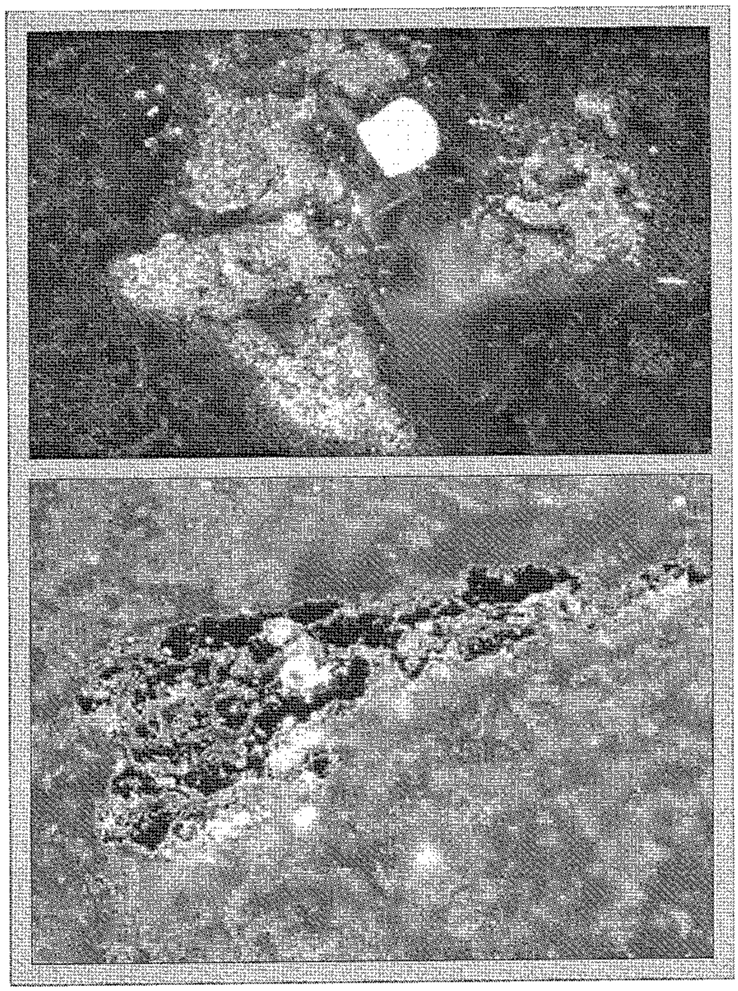

Figure 4.10 Two micrographs showing investigations of UK HLW glasses. In the top micrograph the light brown zones show a precipitated magnesium (Mg)-enriched phase in a glass matrix. Higher Mg content is typical for Magnox HLW glasses. In the lower micrograph the black regions contain high levels of ruthenium (Ru).

4.6 Criticality Research

The intermediate-level wastes include a wide range of materials and radionuclides. Some radionuclides are fissile, i.e. they can cause a critical chain reaction with slow neutrons, which have thermal energies, assuming that sufficient mass of the radionuclides is present in the right conditions. The most significant fissile radionuclides in the waste inventory are the plutonium isotope ^{239}Pu and the uranium isotope ^{235}U.

Engineering measures are available to prevent criticality for such time as the waste packaging affords a high level of containment. In particular, limits are being established on the amount of fissile material that can be incorporated into individual waste packages of intermediate-level waste. These limits will ensure that a criticality cannot occur during any credible configuration of waste packages and conditions that could occur during waste storage, transport and emplacement in a repository. In the long term, however, after deterioration of the physical containment provided by the waste packages, there would be the possibility of movement of fissile material out of the waste packages and subsequent accumulation into new configurations that could in principle lead to a criticality. It is conceivable that a criticality could adversely affect the performance of a repository after closure because, for example, of the heat that would be produced affecting the engineered barriers.

The criticality research programme is aimed at demonstrating an understanding of the geological disposal facility system and the possibility and consequences of a criticality. The work to date and the resulting understanding of the likelihood and consequences of criticality are sufficient to conclude that these issues do not pose a significant threat to the viability of the concept. However, criticality is an important topic from a regulatory perspective [122], and because of public concern criticality will continue to be a key component of the Nirex research programme.

Waste will be packaged and emplaced in the facility in a manner that ensures that criticality will not occur while the facility is being operated, and in the periods immediately thereafter. However, there is a very small chance that as the packages corrode, fissile material in the facility may migrate and be re-distributed. Then there is a very small probability that a criticality occurs.

In the repository environment, fissile radionuclides would migrate slowly through materials that would be saturated with water and they would be more likely to be dispersed than to be accumulated.

The criticality research programme is investigating the effects of such criticalities arising from a wide range of hypothetical configurations of fissile materials. The consequences of these effects and their impact on subsequent performance are then being identified for configurations that could potentially arise. Initial work concluded that even if a criticality did occur, it would only affect a small volume of the facility and the impact on the overall performance of the facility would not be significant [123]. However, not all types of post-closure criticality event were considered in this initial work. Further work has been commissioned to improve our understanding of criticality in post-closure environments, to enable testing of the robustness of the initial conclusions, involving development of two different types of model to allow independent testing.

The work to date and the resulting understanding of the likelihood and consequences of criticality are sufficient to conclude that these issues do not pose a significant threat to the viability of the concept.

A number of aspects are being addressed in the current criticality safety research programme.

The criticality transient models that have been developed have been applied to hypothetical scenarios. Validation of the complete models against demonstration experiments is not feasible. However, the extent to which parts of the models can be verified and validated is to be investigated.

In addition, the extent to which the models can predict features of the Oklo natural reactors will be explored. Oklo is in Gabon in Africa, and around fifteen natural fission reactors have been found in three different ore deposits. Two photographs of the Oklo system are shown in Figures 4.11 and 4.12. The reactors are around 2 billion years old. Information deduced from Oklo [124] will be compared with predictions from Quasi-Steady State (QSS), one of the models developed for the NDA. For example, Figure 4.13 illustrates, for a range of assumptions on the rate of accumulation of uranium, the predicted temperatures and timescales of a Quasi-Steady State criticality of the type that arose at Oklo.

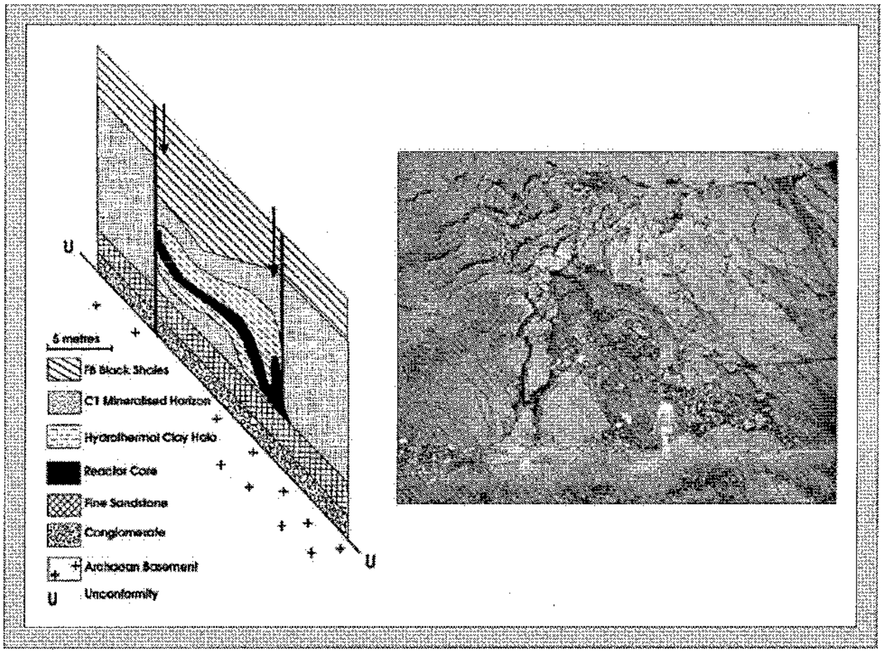

Figure 4.11 Reactor zone in the Oklo open-pit (right) showing the etched out imprint of the reactor core and the surrounding hydrothermal channels in the host sandstone; note the residual clay (darker colour) which coats the core area and the channels. Idealised cross-section (left) of a fossil reactor (modified after Gauthier-Lafaye et al [125]).

A small number of improvements are being made to the criticality transient models. These include improvements in the way the numerical models run, in particular to ensure that they run smoothly without the need for intervention, and also in the manner in which physical processes are represented. To ensure their potential applicability in future assessments, the documentation will be improved, for example by producing User Guides.

The criticality transient models that have been developed require thermal and mechanical properties for the materials in and around the facility. Independent peer reviewers [43] have commented that idealised materials have been modelled in some cases, e.g. ignoring the effect of existing cracking in rock. In other cases, properties have had to be estimated, theoretically or by analogy with similar materials. Sensitivity studies will help inform the need for obtaining material properties data.

To date, criticality safety and research studies have concentrated on the fissile material content of the wide variety of ILW wasteforms. Following a preliminary criticality safety assessment, part of a study aimed at demonstrating the viability of disposal of

HLW/SF[126], further confidence needs to be built for Spent Fuel; on the other hand High Level Waste will generally contain only low levels of fissile material.

Figure 4.12 The remains of underground reactor 15 from Okélobondo. The visible yellow spots are uranium oxide of 70% concentration in sandstone.

Commercial AGR fuel is routinely de-fuelled when the residual enrichment is close to natural levels, and is then separated from the graphite moderator that enabled criticality to be sustained. Such fuels are therefore very unlikely to lead to a criticality. However, the final, and any early discharges of AGR fuel, are expected to require additional consideration. LWR fuels, particularly PWR fuel, are discharged at higher residual enrichments and again further consideration is expected to include engineering solutions through design of the container and repository concept. With such engineering solutions, the canister and wasteform integrity and performance will be key features in reducing the risk of criticality from their fissile contents. While the fissile material remains in the canister, there is no risk of criticality. Because of low failure rates, there is a very low probability of adjacent canisters failing, and therefore a low probability of getting an accumulation of sufficient fissile material.

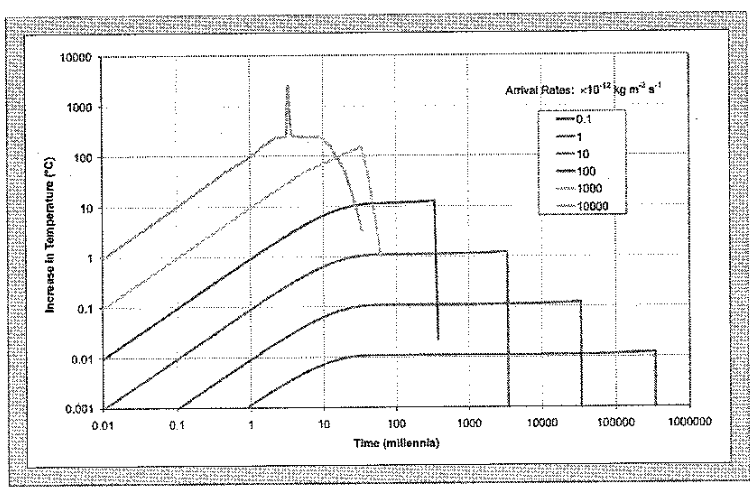

Figure 4.13. QSS model predictions of the temperature rise and duration of criticalities for a range of rates of accumulation of uranium in a sphere of radius 0.105 m.

4.7 Geosphere Research

The geosphere comprises the rocks in which the geological disposal facility is constructed and those that surround them, extending to the surface. This natural environment provides a number of key safety functions:

- A physical barrier that protects the geological disposal facility from natural disruptive events such as weathering, glaciations, erosion and earthquakes.
- A mechanically stable environment for the geological disposal facility.
- Long and slow groundwater return pathways from the geological disposal facility to the surface environment, along which retardation processes, dilution and dispersion act to reduce the concentration of radionuclides in groundwater.
- A stable and benign geochemical environment to maximise the longevity of the engineered barriers, such as the waste containers and backfill in the facility.
- An environment which reduces the likelihood of inadvertent human intrusion.
- Protection from deliberate human interference.

Geosphere research addresses the following themes, which relate to the safety features described above:

- Geosphere stability – consideration of natural processes over the very long timescales of relevance to safety such as volcanic activity, tectonic uplift and seismic events, as well as future climate, including ice ages, global warming and changes in seawater level which may all affect flow, and thus groundwater return times, from the geological disposal facility to the surface.
- Spatial variability – includes developing methods for representing the natural variability of the geosphere in groundwater flow models. Models of fracture flow have been based respectively on knowledge gained from experiments of flow in individual fractures and at experimental sites, such as those at Reskajeage in Cornwall and Äspö in Sweden, while models of flow in porous rocks used experience from the water and oil industry [127].
- Retardation processes – processes that retard the transport of radionuclides in the geosphere. Of these the most important process is sorption of radionuclides to rock surfaces. A large number of laboratory measurements has been collected, demonstrating that sorption is an effective way of retarding many radionuclides across a wide range of rock and groundwater types. Retardation by diffusion under a concentration gradient into small pores in the rock matrix can also be important for retardation, particularly for non-sorbing nuclides.
- Perturbing factors – understanding the expected scale and consequences of the impact of the presence of a disposal facility on the surrounding geology, hydrogeology and geochemistry. It is important to have an understanding of the expected changes and their consequences, to provide confidence that the safety of the facility will not be compromised.
- Gas migration – processes involving two phase (gas-water) interactions that may impact on the migration of radionuclides in the gas and groundwater phases.
- Modelling – approaches to the development of and confirmation of mathematical models of the various processes noted above.

Current tasks focus on updating the understanding of key safety-relevant processes. Site-specific research will be required again once a site or sites have been carried forward into the surface-based investigation phase of the Government's process.

The main topics for future research are described below.

4.7.1 Geosphere Stability

At a well-chosen site, the geosphere provides a stable environment in which to construct a geological disposal facility. This is especially true in the United Kingdom which is located in a very stable location remote from active tectonic plate margins. However, the high latitude location of the United Kingdom does mean that during the next million years a geological disposal facility could be subjected to the direct or indirect influence of glaciation. The latest modelling would suggest that anthropogenic warming of the atmosphere may delay the onset of the next glaciation until more than 100,000 years into the future.

During a glacial event deep permafrost develops first followed by the accumulation and migration of ice sheets more than a kilometre thick. Deglaciation results in the thinning and retreat of the ice sheet followed by a period of permafrost due to the loss of the insulating effect of the ice sheet. Thus during a glaciation the rock is subjected to changes in temperature and in-situ stress (loading) which in turn alter the forces responsible for groundwater movement. Evidence for such changes at depth can be quite subtle and difficult to detect. There is evidence from Scandinavia, Canada and, more equivocally, in Scotland for a short period of enhanced earthquake activity following deglaciation [128, 129].

Earthquakes may also be caused by release of normal tectonic stresses. In the United Kingdom earthquakes tend to be both of small magnitude and widely dispersed [130]. Earthquakes if located close to the geological disposal facility could, at least theoretically, disrupt the facility or cause localised transient groundwater movement. Increased hydrostatic pressures beneath an ice sheet may also alter the groundwater flow pattern and cause shallow groundwaters to penetrate more deeply than would otherwise be the case. However, it is important to note that earthquake damage is very much less severe at depth than it is at the surface.

A seismic hazard assessment survey will be undertaken during the surface-based site investigation phase at any future geological disposal facility location. This will include detecting present-day earthquakes in the vicinity of the geological disposal facility and seeking historical, archaeological and neotectonic evidence for past earthquakes. A key component of this will be the installation of a seismic monitoring network during site characterisation.

In the period before specific sites are chosen for investigation, the research tasks will be directed towards updating understanding of the scientific arguments, specifically:

- **Developing an approach to estimating and applying groundwater ages.** Long groundwater return times are beneficial to safety. One of the most effective ways of providing confidence that the groundwater return times are long is by providing evidence that current groundwaters are very old and therefore move very slowly. Techniques such as isotope ratios and fracture infill morphologies can provide this confidence. Progress has been made in measurement and interpretation during the last 5 years or so through studies such as the EC PADAMOT project [131] (see Figure 4.14), and it is important to ensure we can apply the most-recent developments.

- **Defensible representation of impact of future climate change on the environment in the geological disposal facility**. The facility must be demonstrated to be safe over a very long timescale. Evidence from history shows several cycles of climate change, including ice ages and warmer inter-glacial periods, over the last few million years. It is important to understand the effect of these changes on groundwater flow.

- **Representation of the likely scale and consequences of future seismicity**. Seismicity in the vicinity of a disposal facility is a key concern for the public. Even though the UK is tectonically very stable, it is important to build confidence that the current concepts are robust with respect to any likely future seismic events in the area.

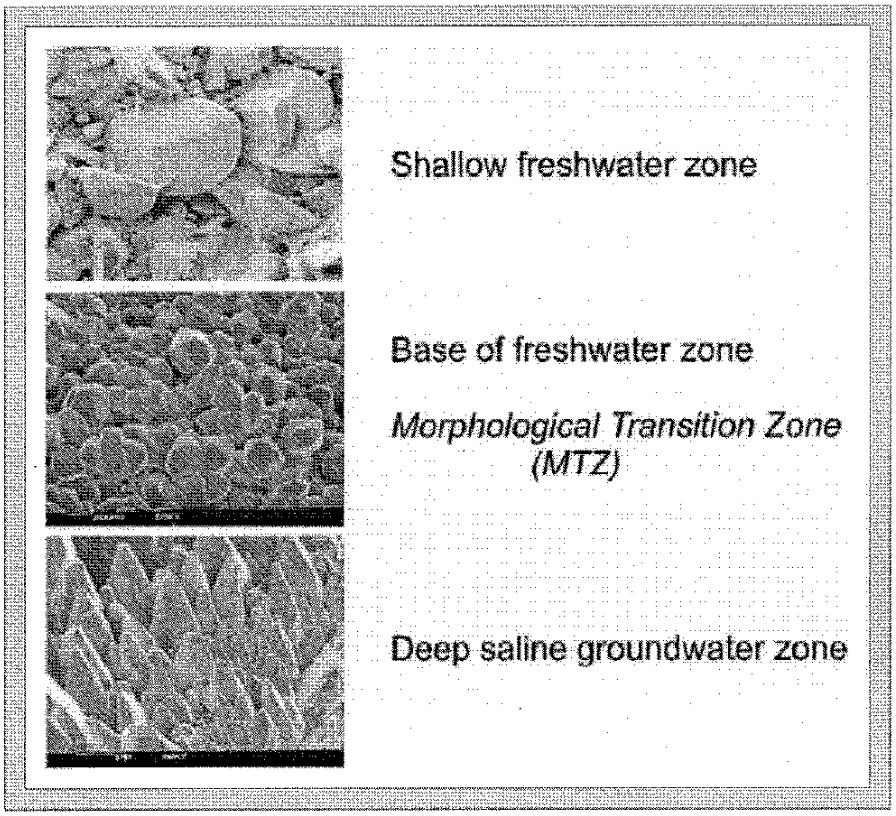

Figure 4.14 Calcite crystals grown in a freshwater environment display a blunt 'nailhead' form whilst those grown in a saline environment have a much sharper 'dog tooth' shape. Correlations between present-day water compositions and crystal morphologies of minerals lining the fracture walls from which they have been collected provide confidence that the groundwater flow system has changed very little over geological timescales

Geological, geochemical and mineralogical evidence obtained during the site characterisation programme will provide evidence relevant to the stability of the local rock mass. It is anticipated that such information will be acquired and analysed within the auspices of the site characterisation programme to ensure that the performance of the system is robust.

4.7.2 Radionuclide Retardation by Sorption

In radioactive waste disposal, sorption is used as a generic term for the partitioning of a dissolved radioelement between groundwater and the surfaces of minerals in contact with the groundwater. It is an important process in retarding the transport of radionuclides and other solute species in the geosphere and has been included explicitly in all of our performance assessment calculations [89, 132, 133, 134]. The results of performance assessments guide which radionuclides are studied.

The extent to which a solute sorbs to a mineral surface depends on a large number of variables including:

- the chemical form of the solute in solution, in particular its oxidation state and complexation;
- the groundwater chemistry, in particular pH, ionic strength, concentration of the sorbing species and competing species for sorption sites, presence of inorganic and organic ligands;
- the nature of the mineral surface, in particular the types of minerals present, their crystallinity, surface area, sorption site density, solute accessibility, crystallographic orientation etc.

Taken together it is clear that the extent of sorption is highly site specific and depends on details of the nature of the rocks and groundwater. Changes in the direction of the groundwater pathway or the chemistry of the groundwater may affect sorption. For these reasons it is also necessary to consider sorption to rocks within the alkaline disturbed zone (ADZ) around the facility, as well as changes in sorption introduced by the presence of facility-derived and naturally occurring organic complexants. Changes in the groundwater flow path and water chemistry induced by changes in driving forces in the future (e.g. glaciations) may also affect sorption. Figure 4.15 shows the impact of different groundwater compositions on the sorption of U(VI) onto rock samples from the matrix and from fracture walls. The three alkaline waters correspond to the range of waters that are expected to be leached from the engineered system (from early to later stages). The figure shows that sorption in the ADZ is at least as strong as on unperturbed host rock.

In the period before surface-based site characterisation, the research programme will be generic in nature. There will be a focus on studying simplified systems in order to build further confidence in the understanding of the factors influencing sorption, ensuring that our modelling approach is in line with international best practice (in part through participation in the OECD/NEA Sorption Project) and that our databases are maintained and up to date. Cellulosic degradation products from the near field can reduce the retardation of radionuclides in the geosphere. It is important to have a robust position on the scale of this perturbation. An experimental programme is underway to measure the effect and also provide data for modelling of the processes.

During the surface-based site characterisation programme, a major campaign of sorption experiments onto crushed and intact rocks will be undertaken on site-specific materials to acquire data to inform selection of parameter ranges for performance assessment. The minimum requirements for such experiments are access to fully characterised core samples and co-existing groundwater samples.

The following potential areas of surface-based site-specific sorption research have been recognised:

- Sorption measurements on crushed and intact site-specific rock samples and unperturbed groundwater chemistries in the presence of appropriate radionuclides to determine the likely sorption behaviour along the expected groundwater flow path(s) in the geosphere.

- Sorption measurements on crushed and intact site-specific rock samples altered under high pH conditions in the presence of appropriate radionuclides to determine the likely sorption behaviour in the ADZ.

- Studies of radionuclides sorbed onto site-specific minerals using techniques such as EXAFS to give evidence of the nature of the surface site and the stoichiometry of the sorbing species.

- Partitioning of naturally occurring radionuclides between groundwater, mineral surfaces, colloids and humics and fulvics.

- Developing a mechanistic understanding of the controls on radionuclide and heavy metal sorption at the site.

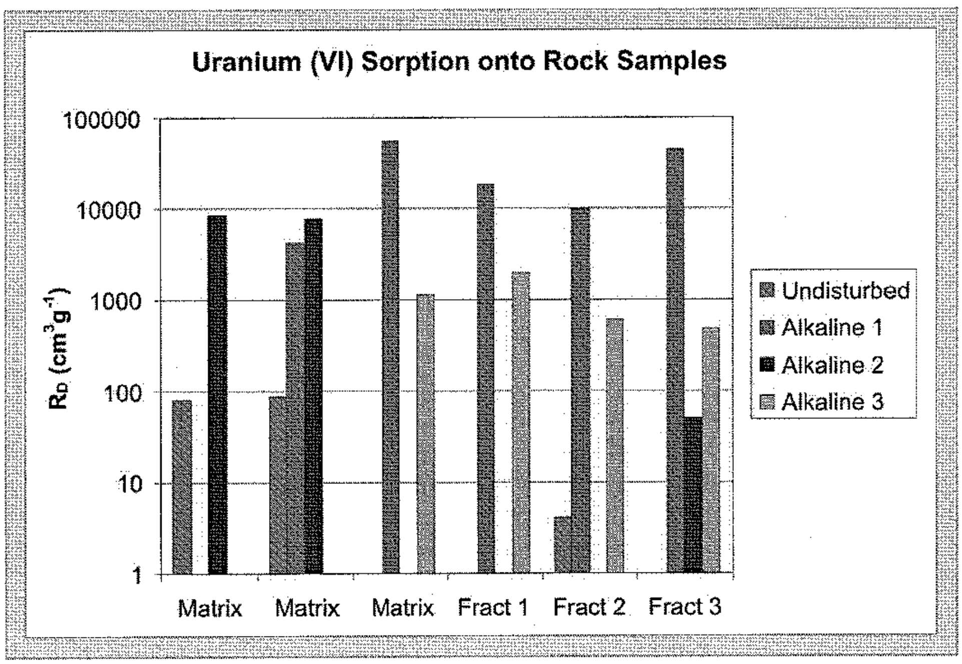

Figure 4.15 The impact of alkaline waters on the sorption of U(VI) onto rock sample from the matrix away from samples and onto sample from fracture walls

4.7.3 Retardation of Radionuclides by Rock-Matrix Diffusion

Molecular diffusion is the process whereby solutes in the aqueous phase move from regions of high solute concentration to regions of lower solute concentration. Originally recognised for the diffusion of solutes in bulk liquids the process can also operate in porous rocks provided that the following criteria are met:

- There is water filling the interconnected porosity in the rock.

- There is a solute concentration gradient.

In unfractured low permeability rocks, such as mudrocks diffusion, is the principal process by which solute transport occurs. At the other extreme in high permeability porous rocks, such as some sandstones, advection dominates solute transport with diffusion playing only a minor part. In the case of fractured low-permeability rock, such as granites, the majority of solute transport occurs by advection in a subset of fractures. Diffusion may occur into stagnant water in the fractures and away from the fractures into the pore space of the rock matrix. This latter process is termed 'rock matrix diffusion' [135]. Rock matrix diffusion and diffusion into stagnant water both lead to a retardation and dispersion of solutes. They are particularly important processes for the retardation of non-sorbing species.

Permanent negative charge on the surfaces of minerals may prevent access of anions to some rock porosity; a process known as 'anion exclusion'. Similarly some large organic complexes and colloids etc may be excluded due to size effects; a process known as 'steric exclusion'. Reactive solute species tend to sorb to mineral surfaces as they diffuse. Diffusion in any particular rock therefore depends on the solute species concerned, and for reactive species, sorption and diffusion are likely to occur together and may be difficult to distinguish.

The main focus of this area of the geosphere programme will be in the site characterisation phase, once site-specific materials, including fully characterised core samples and co-existing groundwater samples are available.

4.7.4 Colloids, Natural Organics and Microbes

Colloids are particles in the size range 1nm – 1μm and are larger than true solutes but smaller than suspended particles. Most natural groundwaters contain an indigenous colloid population, comprising mineral particles, organic macromolecules (including humics) and viruses. This may be enhanced by colloids formed in the geological disposal facility or ADZ. Colloids can be stabilised by the sorption of organic molecules (humics). However, colloids may be retarded by filtration in pore throats and lost through growth (settling), dissolution or microbial digestion and destabilised by sorption of polyvalent cations. They become less stable with increasing salinity, a process known as 'salting out'. The salinity of groundwater also normally increases with depth.

The significance of colloids from a radioactive waste perspective stems from possession of a negative surface charge. Repulsion from negatively charged mineral surfaces results in colloids concentrating towards the centre of fractures and pores where groundwater velocities are higher. Thus colloids can be advected faster than conservative solutes, a process termed 'hydrodynamic chromatography'.

The relatively large size of colloids and their charge may lead to the steric and/or electrostatic exclusion of colloids from smaller pores reducing the effectiveness of retardation due to rock matrix diffusion.

Radionuclides can form, or can be sorbed onto, colloids and so potentially, colloids may provide a fast transport pathway for attached radionuclides provided a number of conditions are met [136]. These include:

- The presence of a significant indigenous or facility-derived colloid population.
- The stability (longevity) of the colloids.
- The extent and nature of the sorption of radionuclides to the colloids, in particular whether colloid sorption is reversible or irreversible.
- The extent to which the colloids are mobile in the groundwater system.

Humic and fulvic acids form part of the indigenous colloid population and are known to complex radionuclides under certain conditions. Data and understanding relevant to the behaviour of these materials is being gathered through participation in the EC FUNMIG Integrated Programme.

Microbes may affect the groundwater chemistry by speeding up reactions which otherwise proceed very slowly. A diverse population of micro-organisms is capable of surviving within varied rock types to depths of several kilometres. These micro-organisms appear capable of utilising many different metabolic pathways. Further, it now appears likely that communities of certain types of micro-organisms in the deep geosphere may be capable of surviving for time periods measured in millions of years. In addition to indigenous micro-organisms others may be introduced into the geosphere during site characterisation and from the geological disposal facility or wastes during the operational and post closure phases [137, 138].

In advance of sites being selected for surface-based site characterisation, the priority will be updating the understanding of the state of the art on the potential role of colloids and microbes in affecting radionuclide migration. Once site characterisation commences, appropriate samples will be required, and will be used to develop a site-specific understanding of their importance for radionuclide migration.

4.7.5 Gas Migration

A key feature of the UK's ILW/LLW wasteforms is that some are potentially reactive, releasing gas in quantities sufficient to persist as a separate phase by metal corrosion, microbial degradation of organic materials, release of ^{14}C in active metals, irradiated steels and graphite and by radiolysis. The gases formed are expected to comprise mixtures of the flammable gases hydrogen and methane plus carbon dioxide. A portion of these gases will be radioactive due to the substitution of ^{14}C and / or ^{3}H. Smaller quantities of the radioactive gas radon and toxic gases such as hydrogen sulphide may be produced.

The migration of gases depends on site specific aspects of the geosphere. It is a feature of gas migration that the gas will preferentially enter the larger pores and fractures in rocks. In highly fractured rocks gas migration is localised into the larger fractures and provided that these are connected, highly localised migration may occur. Under such circumstances the nature of the gas-water interactions within the fracture network become important in determining gas solution and the entrainment of gas or water slugs. In porous rocks a more dispersed migration of gas is possible with enhanced opportunities for gas dissolution and subsequent transport in the direction of groundwater movement. For porous rocks with very small pores, such as mudrocks, high gas pressures are required to overcome the capillary pressures before the gas can enter the rock. In practice such rocks act as barriers to gas flow until sufficient gas pressure has built up to overcome the capillary forces. It is evident from the above discussion that the nature of gas migration is highly site dependent.

In the period before sites are selected for site characterisation, the main themes of the gas migration research programme are:

- Developing a more detailed understanding of gas migration. One aspect of this work is involvement in the international Large-scale Gas Injection Test LASGIT experiment (see Figure 4.16).
- Developing an improved understanding of gas migration at a field scale in order to build confidence in our modelling approaches.
- Understanding the implications of radon-stripping. Gas derived from the geological disposal facility has the potential to strip radon gas from the overlying strata and thus increase the rate of radon release from the natural environment.

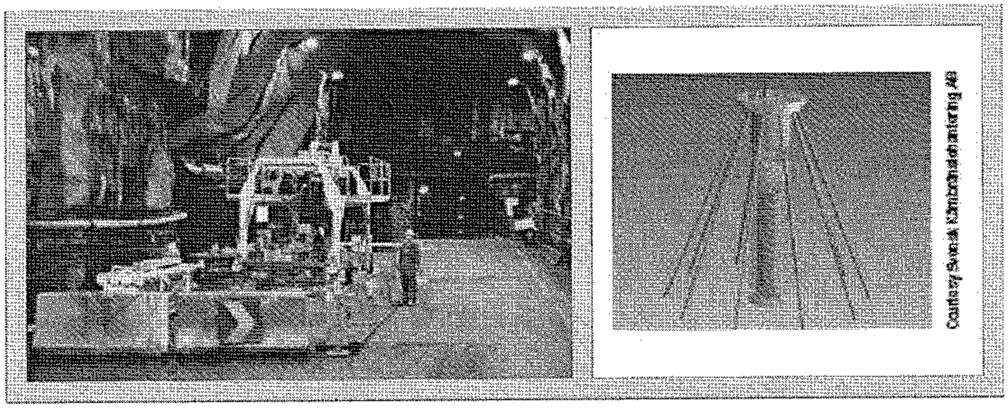

Figure 4.16 The LASGIT experiment in the Äspö Underground Laboratory provides information on gas migration at a field scale

Once site characterisation starts, it will be important to develop an understanding of gas migration at the site(s), and to build confidence in the robustness of that understanding.

4.7.6 Non-aqueous Phase Liquids (NAPLs)

As light NAPLs may migrate under buoyancy and represent a mechanism for transporting radionuclides at a more rapid rate than as part of the groundwater pathway, research is underway to understand their migration.

In the period before surface-based site characterisation, research on migration of NAPLs is generic and focused on using multi-phase flow models to improve understanding of the key geological parameters and processes affecting NAPL migration.

During the surface-based site characterisation programme, confirmatory modelling will be undertaken as specific geological information becomes available.

4.7.7 EDZ

Following excavation of an underground cavern reorientation of stresses adjacent to the excavated openings, coupled with excavation-induced damage, and in some cases chemical reaction, leads to the development of a zone of modified hydraulic and mechanical properties in the rock mass immediately adjacent to the excavation. This is known as the Excavation Disturbed Zone (EDZ). It includes both permanent changes and reversible changes that can be recovered once support is re-established following backfilling.

The extent of the EDZ depends on many factors including the nature of the host rock, its properties, in-situ stress and fracture state, excavation method, and the depth, size, spacing and orientation of the excavations etc. It will also depend on the length of time that the excavation remains open and any remediation required to keep the excavation open prior to backfilling.

The EDZ raises issues of constructability and safety during the operational phase of the facility. In the long-term the key concern relating to the EDZ is that stress reorientation may lead to the dilation of some fractures close to the excavations which in turn may provide pathways for radionuclide migration. In the worst case scenario the EDZ may short circuit the facility seals. Modelling the extent of permeability modification in the EDZ is challenging since fracture dilation involves consideration of coupled hydro - mechanical processes which in some instances may require a consideration of chemical processes as well [139].

Full-scale experiments into the nature of the EDZ have been undertaken in purpose-built excavations in crystalline rocks, indurated mudrocks, and plastic clays. These have been reviewed by [140 141, 142]. In parallel with developing an understanding of the nature and extent of the EDZ from full-scale experiments there have been international initiatives in the DECOVALEX and BENCHPAR projects to develop a capability to model the fully coupled thermo – hydro - mechanical system in crystalline rocks relevant to the EDZ and the post-closure state of a SF/HLW geological disposal facility.

The nature of the EDZ is a site-specific issue. Further research will be undertaken once it becomes clear what type of host rocks are present at candidate sites. At this point a review of appropriate software will be undertaken.

During surface-based site characterisation properties such as the in-situ stress and mechanical properties of the rock mass will be obtained by the Site Characterisation Programme, which will be valuable in designing later experimental work.

4.7.8 Alkaline Disturbed Zone (ADZ)

The rocks adjacent to the geological disposal facility may be chemically altered by the presence of the facility. Prior to backfilling and sealing the major aspect of such alteration is likely to involve localised mineral oxidation. The nature and extent of such oxidation will be highly dependent on the mineralogy of the facility host rock, in particular the presence of sulphide minerals (e.g. pyrite), but is likely to be quite restricted in most host rocks [143].

The NDA ILW/LLW geological disposal facility concept incorporates large volumes of cement-based material. Following resaturation, leaching of the cement phases will yield a high pH alkaline plume which may react chemically with the surrounding rock mass. The volume of reacted rock and zone of elevated pH is termed the alkaline disturbed zone (ADZ). Hydro-chemical coupled reactions (H-C) will occur in the ADZ which may alter the porosity, permeability and diffusivity of the rock mass by the dissolution of existing mineral phases and the precipitation of newly formed phases. These may also alter the sorption properties of the rock.

An extensive programme of laboratory and field work was carried out during the 1990s to study alkaline water/rock interactions [144]. During that time, there was a collaborative international natural analogue project [145] at the Maqarin site in north east Jordan;. This is a unique site because it has a naturally occurring portlandite and an active groundwater system. Therefore it provides an opportunity to study the interactions between cementitious waters and the surrounding rock. Figure 4.17 displays some hand specimens showing fractures through which a high pH water has flowed. Water/rock interactions produce secondary phases analogous to those that may be found around a geological disposal facility.

Future research will be focused on a number of areas:

- Measuring thermodynamic and kinetic data relevant to alteration of minerals by high pH water for use in models of alkaline water/rock interactions. This will focus on data for the key chemical processes and components, where the current datasets are incomplete.
- Undertaking laboratory experiments of high pH water/rock interactions for a range of rock types.

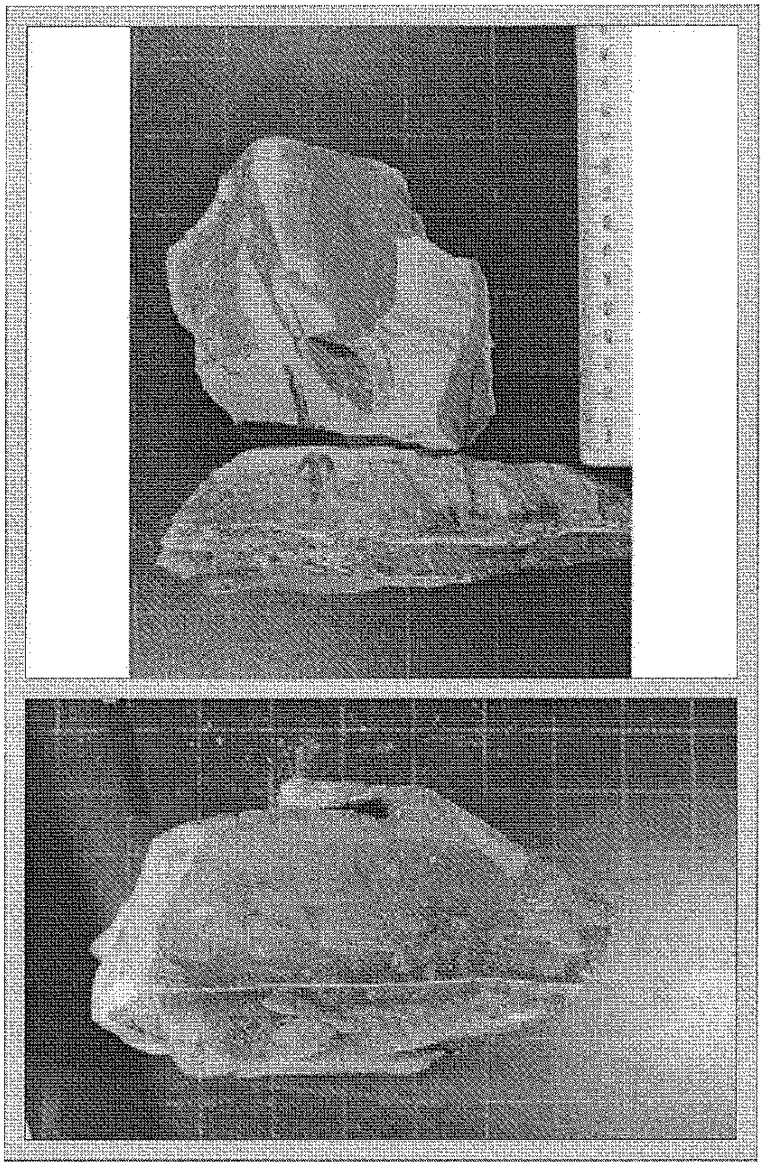

Figure 4.17 Hand specimens showing the fractured morphology of rocks from the Eastern Springs area, Maqarin Natural Analogue Site, northern Jordan. Hyperalkaline waters are observed to discharge from fractures and fracture-rich zones in the area

- Examining natural systems for the effect of high pH water on rock, particularly for silica-rich high pH water, to gain evidence from natural systems that will build confidence in the processes relevant on timescales of the safety case.
- Modelling of alkaline water/rock interaction to demonstrate understanding of the processes.

4.8 Biosphere Research

The biosphere is the near-surface and surface environment. It includes the atmosphere, rivers, lakes and their underlying sediments, soil and the underlying subsoil to depths below which life does not exist. Whereas the geosphere acts as a definite barrier to radionuclide migration, the biosphere is a receptor for any eventual releases that might occur. On the long timescales of relevance to performance assessment calculations, typically up to one million years, small quantities of waste-derived, as well as naturally occurring, long-lived radionuclides may be released from the repository system, migrate through the geosphere and reach the surface environment. Performance assessment calculations aim to assess the risk to humans and other biota from the subsequent radiological exposure to the release of waste-derived radionuclides. Biosphere research provides data and understanding about how radionuclides are dispersed or accumulate in the environment and how they enter the food chain.

Because of the long timescales over which the repository must function, it would be simplistic (and almost certainly wrong) to assume that the future biosphere will be the same as now. It will evolve over time. Human influence on climate is a topic of current scientific debate. In long-term safety assessments, the biosphere is represented by stylised scenarios, based on our understanding of current and past environments. The future biosphere conditions that are assumed are hypothetical and much of the ongoing work is to ensure that models encompass the range of conditions that could reasonably be expected to occur.

The biosphere research programme has been divided into a number of project areas:

- Climatology (evolution of climate)
- Geomorphology (landform evolution)
- Ice sheet modelling
- Near-surface hydrology and radionuclide transport
- Soil-plant radionuclide transfer and uptake into the food chain
- Description of potentially exposed groups (PEGs)[2].

The scope of the research work has included literature reviews, laboratory and field experimentation, and numerical modelling studies of subsystem components. Most of these areas are discussed further below.

The biosphere research programme has had, and continues to have, close links with work carried out in overseas radioactive waste management organisations. Many biosphere-related issues are of common interest and several are being addressed in international forums such as BIOPROTA [146].

In respect of climate, the landscape evolution scenarios that have been developed [147] are underpinned by the climate evolution scenarios that were developed in BIOCLIM [148]. These climate evolution scenarios were also used in the update of the 2002 Post-closure Radiological Safety Assessment for the LLWR, near Drigg [149]. The climate scenarios are based on long-term climate calculations undertaken using Earth Models of Intermediate Complexity (EMICs) complemented by results from Atmosphere-Ocean

[2] In the Glossary of the Guidance and Requirements for Authorisation [15], Exposed Group is defined in the following statement "For a given source, any group of members of the public within which the exposure to radiation is reasonably homogeneous; where the exposure is not certain to occur, the term potentially exposed group is used."

General Circulation Models (AOGCMs) and Regional Climate Models (RCMs), with the results from those models downscaled using a variety of statistical and rule-based techniques.

Since the earlier work was completed, there have been substantial developments in EMICs and downscaling techniques, while the large-ensemble studies have demonstrated a wider range of climate sensitivities to greenhouse-warming than had previously been identified. Furthermore, the sensitivities of ice sheets to increasing temperatures have been re-evaluated.

Organisations involved in geological disposal of radioactive wastes have interests in future climate change covering much longer timescales than most other organisations. Given the rapid pace of research developments in this area, it is prudent to defer consideration until more information is available on the sites that are carried forward.

In respect of landform evolution, the pace of research is much less rapid than in climatology, and a recent account [147] provides a defensible context within which biosphere assessment calculations can be undertaken. Therefore, no initiatives in geomorphological research are proposed.

The existing approach to modelling large-scale, land-based ice sheets is considered justified. Previous work on ice sheets tested the validity of the existing small-slope approximation that is used in all large-scale, 3D ice-sheet modelling. The small slope approximation was shown to be good at relatively steep bed slopes. The results of this work have been documented in a series of reports and journal papers [150, 151, and references contained therein]. Furthermore, the BIOCLIM studies described above have determined that the current interglacial episode is likely to persist for many tens of thousands of years. Therefore, detailed modelling of a future glacial episode has a lower priority than was previously the case. Other waste management organisations, for example SKB (the Swedish waste management organisation), are continuing to pursue ice-sheet modelling, including appropriate representation of sub-glacial hydrology, but further NDA RWMD research on this topic is not proposed at this time.

A primary reason for undertaking landscape evolution studies was to define the types of surface-water catchments that might exist in the future in the UK. It was intended that this work should be complemented by physically based, catchment-scale modelling of water flows and contaminant transport pathways for the surface-water catchments identified through this approach. In the period before sites are selected for surface-based site characterisation, a programme of catchment-scale modelling is envisaged, to explore the usefulness of alternative approaches and evaluate the resource requirements that would be needed to undertake such modelling for one or more actual sites. It is noted that this work is closely related to determining the type and extent of surface and near-surface hydrological and hydrogeological measurements that would be required for site characterisation. Thus, this is work that can be usefully undertaken in a generic context to underpin future site-specific investigations.

An extensive programme of research on radionuclide migration in soils and uptake by plants, lasting some 20 years, was conducted by Imperial College of Science, Technology and Medicine. That work concentrated on the key radionuclides determining radiological impacts of geological disposal (for example ^{36}Cl). There is now a very extensive database available from the experimental studies and future work will focus on further interpretation and analysis of the data for upscaling from the point scale of the experiments to the grid scale of a catchment model [152].

A related issue is assessment modelling of the biogeochemical cycling of ^{36}Cl in soils and plants, taking into account the influence of different concentrations of stable chloride and the influence of organic chlorine. This is present in soils in comparable quantities to chloride. Research will be undertaken to integrate the assessment-level modelling approach with the more detailed, process-based models. In the late 1980s and early 1990s, a series of literature reviews was undertaken. These covered individual radionuclides and specific topics of relevance to biosphere assessments, (for example bioturbation by deep-rooting plants). These reviews have not been updated subsequently. Although extensive reliance can be placed on reviews conducted internationally, there is a need to consider whether some of the radionuclide specific or topic-based reviews need to be updated in the light of more recent literature.

Finally, with respect to the gas pathway, it has been established that the microbial metabolism of ^{14}C-labelled methane in the soil zone and uptake of the resultant ^{14}C-labelled carbon dioxide by plants is of potential radiological significance. An experimental programme to address this issue is under consideration.

4.9 Geosphere Characterisation

Geosphere Characterisation comprises detailed surface and sub-surface investigations and is required to acquire and interpret information on the geological, hydrogeological and environmental conditions at one or more candidate sites throughout all stages of the development and implementation of a geological disposal facility for the long-term management of the higher activity radioactive wastes.

During the desk-based siting studies phase of the project, the geosphere characterisation project will identify the information needed about a site and the means by which that information can be obtained. It will identify measurement techniques and site characterisation technology that will most efficiently provide the information needed about a Geological Disposal Facility site. Initially, this work will cover a range of generic geological settings. Following the identification of candidate communities and subsequently candidate sites, the output will be progressively more detailed plans for investigation and characterisation of a potential Geological Disposal Facility site.

In order to ensure the credibility of work in this strategic area, the work programme and its outputs will be reviewed throughout the desk-based siting studies phase by an advisory panel of UK and international experts in relevant disciplines.

In preparation for site investigations, a procurement strategy will be developed and contract documents prepared. Specific attention will be paid to the capacity of the supply chain to meet the requirements of the site characterisation programme, and in particular the capacity to undertake the required analysis programme. As there are certain aspects of the work where the requirements are significantly in excess of the work currently undertaken in the UK, planning will be required, involving the contractors who will undertake the work, to ensure that the capacity to undertake the work is available.

Once candidate sites are identified by Government and appropriate permissions obtained for undertaking surface-based investigations at these selected sites, contracts will be awarded and a programme of surface-based investigations undertaken at each of the candidate sites. These investigations will comprise a wide range of surveys conducted from the surface, including a programme of deep borehole drilling and testing. The results of the investigations will be interpreted and reported. Information derived from the investigations will be used as an input to the development of the safety case and the engineering design and construction of the disposal facility.

Characterisation of the geosphere will continue throughout the subsequent construction and operation of the facility to confirm that the as-found ground conditions meet the requirements as set down in the safety case and to allow the engineering design and construction of the facility to be optimised.

There is a substantial amount of international experience of characterising sites for geological disposal facilities. Characterisation programmes have been undertaken in Belgium, Canada, Finland, France, Germany, Japan, Sweden, Switzerland, the UK, the USA and elsewhere. These programmes have considered a wide range of geological environments, including fractured rock, clays and evaporates.

The current status of work by the NDA in this area is described in two recent reports [21, 22]. The current focus of the programme is to ensure we are abreast with developments of approaches and measurement techniques, for example in repository development programmes overseas.

4.10 Engineering Developments

The development of engineering solutions has been based on sound engineering principles and, as far as practicable, upon established and proven technology, for example from the mining industry worldwide. The development of the solutions has had to address the provision of safety over long timescales of operation and incorporate flexibility into the conceptual designs. Further details on the engineering foundations are provided in [20].

The primary objective of engineering development is to provide for the safe and cost effective long-term management of the higher activity radioactive wastes. In satisfying this objective, engineering solutions need to address all phases of the concept from construction and operation of a repository through to sealing and closure. The operational period may include a period of maintained storage between last waste emplacement and a decision to commence closure of the facility. In addition the facility may need to have the flexibility to enable certain wastes to be retrieved during the period while it remains open. To achieve this, there are a number of stages to be taken into account, which include:

- Wastes have to be transported to the facility in appropriate containers, which may be re-used or may be disposed into the facility.
- There will need to be surface receipt facilities at the geological disposal facility.
- Access routes from the surface to the underground vaults will have to be provided for wastes, personnel, utilities, ventilation etc. Such access could be provided by drifts and/or shafts.
- Provision to emplace wastes in their final location will be required.
- There will be a requirement to monitor emplaced wastes while the facility is still operational and there may be a requirement to take remedial action on waste packages that are not performing to specification.
- There will be a requirement to maintain the facility (e.g. rock supports, infrastructure, cranes, tracks, locomotives).
- As the vaults or the whole facility move towards closure, systems will be required to backfill the vaults, and then to seal and close the facility.
- There may be requirements for post-closure monitoring.

The engineering work converts the multi-barrier concept discussed earlier in the report, and turns it into a realisable design, which will take into account the nature and quantity of wastes, the UK geological conditions, regulatory requirements and results of the R&D. To provide a realistic basis, the designs are based on proven technology. The designs provide the basis for the assessment of repository performance, costs and programme. At appropriate stages the detailed designs will be incorporated into the Disposal System Safety Case.

The designs can only make limited progress in the absence of a preferred site. The design work can show what the implications are for different geological environments, and one of the key tasks is to feed into the requirements for site characterisation. It will also ensure that preparatory work has been undertaken before data become available, to facilitate timely developments from conceptual designs at the start of site characterisation to detailed design towards the end.

Some of the current priorities for the engineering work are:

- The development of the design of Standard Waste Transport Containers to transport HLW/SF waste streams to the disposal facility, the development of outline designs for Transport Flasks to transport HLW/SF on site, and the development of Standard Waste Transport Containers to transport ILW to the disposal facility.

- The design of waste package for HLW and SF, in particular considering the options for the package materials (e.g. copper and steel), and the options for standard designs.

- The design and operational outline of HLW/SF Receipt and Transfer Facilities for HLW/SF and for ILW.

- The development of designs for different host geological environments. This will progress as the voluntarist process develops. Factors to be taken into account include: different geological environments; consideration of the operability at a range of depths; vaults and deposition area designs; and access arrangements. Initially the development of design options will support the optioneering reviews for the various waste streams.

- The development of methods for inspection and operational monitoring. This will include emplaced waste packages prior to backfilling and all infrastructure systems.

- Consideration of methodologies for the retrieval of emplaced wastes; including ILW and HLW/SF.

- Consideration of methodologies for the backfilling, sealing and closure of the facility. This will include supporting the long-term post-closure safety requirements.

NDA RWMD is a member of the ESDRED project (Engineering Studies and Demonstrations of Repository Designs). This is an EC 6th Framework project involving 13 organisations from 9 countries, including 7 waste management organisations. It is valued at about €18M, and lasts for 5 years starting in 2004. It is an integrated project, concerned with ensuring European waste management organisations work together, and share experience in the field of engineering design. The overall aim is to move from research to demonstration, providing information on performance and building confidence in what is achievable. There are four technical modules concerned with buffer construction technology, waste canister transfer and emplacement technology, heavy load emplacement technology, and temporary (low pH) sealing. A test undertaken as part of the first module is shown in Figure 4.18. NDA RWMD has led a programme on developing non-intrusive monitoring techniques.

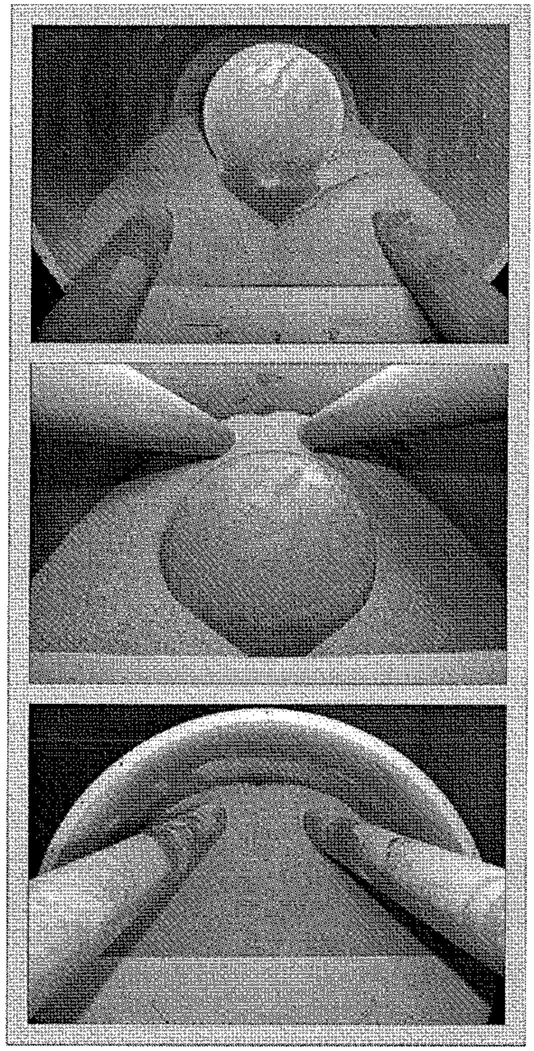

Figure 4.18 Test undertaken by Nagra as part of the EC ESDRED Project – showing the gradual filling (from the top picture to the bottom) of the gap around a demonstration container.

5 NEXT STEPS

The UK now has a clear policy for the long-term management of its higher activity radioactive wastes through disposal in a geological facility following intermediate safe and secure surface storage. Responsibility for developing the facility has been assigned by Government to the Nuclear Decommissioning Authority: this duty having been added to the NDA's existing responsibility for decommissioning and clean-up at redundant nuclear sites. The work will be undertaken by the Radioactive Waste Management Directorate.

Designing the facility, demonstrating compliance with strict health, safety, security and environmental regulations, finding a suitable site with necessary permissions and construction will take many decades and involve numerous scientific, technical and socio-economic disciplines. Although there is now a wealth of knowledge and experience both within the UK and internationally, such a programme will be underpinned by a substantial R&D programme. Indeed, this was specifically called for in the recommendations to Government upon which current Government policy is based.

A crucial requirement of sound implementation planning is to build up skills and resources in a timely manner, consistent with the timetable set out by Government. These activities are very much part of the RMWD's project management programme.

The NDA RWMD welcomes feedback on this proposed R&D strategy from all stakeholders. The research and development programme has been developed within the Radioactive Waste Management Directorate. Views are being sought more widely in NDA, and in particular from the (corporate) NDA Research Board. Looking outside the NDA, the views of the Regulators and of the CoRWM Research Group will be specifically sought. It is hoped, however, that there will be a wide and diverse response from many different organisations and interested individuals. The plan is to publish a revised version of the R&D Strategy at the end of March 2009.

In time, as the MRWS programme develops, engagement with local communities will be welcomed. The Research and Development Strategy and its associated work programme will be periodically revised and updated throughout the lengthy period of the geological disposal facility's development, operation and closure.

The R&D programme is broad, addressing a wide range of issues. In the next three to five years, particular attention will be paid to undertaking work to constrain and reduce uncertainties in a number of areas. These include developing a better understanding of the longevity of different waste packages in different settings. Work here, as in most elements of the R&D programme, will complement related international research.

The R&D programme will support development of all safety cases, particularly the post-closure disposal system safety case. In this case, for example, regulators internationally have called for 'supporting arguments' to be included alongside classical risk/time analysis. This calls for the assembly of historical, archaeological and geological evidence, which will add confidence to predictions as to the behaviour of individual containment 'barriers' or in some cases, the behaviour over very long timescales of natural systems analogous to the disposal system overall.

Appendix: Final Recommendations made by CoRWM

CoRWM [1] made the following recommendations:

1: Within the present state of knowledge, CoRWM considers geological disposal to be the best available approach for the long-term management of all the material categorised as waste in the CoRWM inventory when compared with the risks associated with other methods of management. The aim should be to progress to disposal as soon as practicable, consistent with developing and maintaining public and stakeholder confidence.

2: A robust programme of interim storage must play an integral part in the long-term management strategy. The uncertainties surrounding the implementation of geological disposal, including social and ethical concerns, lead CoRWM to recommend a continued commitment to the safe and secure management of wastes that is robust against the risk of delay or failure in the repository programme. Due regard should be paid to:

i. reviewing and ensuring security, particularly against terrorist attacks
ii. ensuring the longevity of the stores themselves
iii. prompt immobilisation of waste leading to passively safe waste forms
iv. minimising the need for repackaging of the wastes
v. the implications for transport of wastes.

3: CoRWM recommends a flexible and staged decision-making process to implement the overall strategy, which includes a set of decision points providing for a review of progress, with an opportunity for re-evaluation before proceeding to the next stage.

4: There should be a commitment to an intensified programme of research and development into the long-term safety of geological disposal aimed at reducing uncertainties at generic and site-specific levels, as well as into improved means for storing wastes in the longer term.

5: The commitment to ensuring flexibility in decision making should leave open the possibility that other long-term management options (for example, borehole disposal) could emerge as practical alternatives. Developments in alternative management options should be actively pursued through monitoring of and/or participation in national or international R&D programmes.

6: At the time of inviting host communities to participate in the implementation process, the inventory of material destined for disposal must be clearly defined. Any substantive increase to this inventory (for example creation of waste from a new programme of nuclear power stations, or receipt of waste from overseas) would require an additional step in the negotiation process with host communities to allow them to take a decision to accept or reject any additional waste.

7: If a decision is taken to manage any uranium, spent nuclear fuel and plutonium as wastes, they should be immobilised for secure storage followed by geological disposal.

8: In determining what reactor decommissioning wastes should be consigned for geological disposal, due regard should be paid to considering other available and publicly acceptable management options, including those that may arise from the low level waste review.

9: There should be continuing public and stakeholder engagement, which will be essential to build trust and confidence in the proposed long-term management approach, including siting of facilities.

10: Community involvement in any proposals for the siting of long term radioactive waste facilities should be based on the principle of volunteerism, that is, an expressed willingness to participate.

11: Willingness to participate should be supported by the provision of community packages that are designed both to facilitate participation in the short term and to ensure that a radioactive waste facility is acceptable to the host community in the long term. Participation should be based on the expectation that the well-being of the community will be enhanced.

12: Community involvement should be achieved through the development of a partnership approach, based on an open and equal relationship

13: Communities should have the right to withdraw from this process up to a pre-defined point.

14: In order to ensure the legitimacy of the process, key decisions should be ratified by the appropriate democratically elected body/bodies.

15: An independent body should be appointed to oversee the implementation process without delay.

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