CORWM

Committee on Radioactive Waste Management

CoRWM REPORT TO GOVERNMENT

REPORT ON NATIONAL RESEARCH AND DEVELOPMENT FOR INTERIM STORAGE AND GEOLOGICAL DISPOSAL OF HIGHER ACTIVITY RADIOACTIVE WASTES, AND MANAGEMENT OF NUCLEAR MATERIALS

OCTOBER 2009

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INTRODUCTION BY THE CHAIR

This is one of three CoRWM reports to Government in 2009. The reports are about:

- interim storage of higher activity wastes (including waste conditioning, packaging and transport, and the management of materials that may be declared to be wastes)
- the implementation of geological disposal of higher activity wastes
- research and development for interim storage and geological disposal (this report).

The reports cover the three strands of the UK Government's *Managing Radioactive Waste Safely* programme. They contain the results of CoRWM's scrutiny, during 2008 and much of 2009, of the work of the Government, the Nuclear Decommissioning Authority, other nuclear industry organisations, the regulators, local authorities and various organisations that carry out research. The recommendations in the reports are to Government but also affect others.

Robert Pickard
30 October 2009

EXECUTIVE SUMMARY

1. CoRWM's remit is to provide independent scrutiny and advice to Government on the long-term management, including storage and disposal, of higher activity radioactive wastes and materials that may be declared to be wastes. This is the last of three reports produced in 2009 that describe the results of the Committee's scrutiny and provide advice to Government.

Scope of Report

2. This report is about CoRWM's work during 2008 and much of 2009 on:

   - the UK's process for providing research and development (R&D) in the management of higher activity wastes
   - the skills requirements to support R&D in the Managing Radioactive Waste Safely (MRWS) programme, in particular those R&D skills to enable implementation of geological disposal
   - the infrastructure requirements, in particular those facilities supporting R&D on highly radioactive materials and R&D that will need to be carried out underground
   - public and stakeholder engagement on the above topics.

3. For each topic, the current position is summarised and advice is given for use in making plans for the R&D to be carried out over several decades and beyond. CoRWM intends to monitor whether and how this advice has been acted on by Government and others.

How CoRWM Worked

4. CoRWM worked by gathering information from the Nuclear Decommissioning Authority (NDA), its Site Licence Companies (SLCs), other nuclear site licensees, the Research Councils, Learned Societies and other organisations in the UK involved in R&D of relevance to the MRWS programme. It looked at the processes used to define R&D strategies in other countries. It held meetings with all the major organisations and it helped to organise meetings on the current state of national R&D in storage and geological disposal with the Radioactive Waste Immobilisation Network. It also sought the views of stakeholders and the public *via* its website and at CoRWM stakeholder events in October 2008, February 2009 and September 2009. A draft of this report (without conclusions and recommendations) was sent to key stakeholders for comment and a full draft placed on the CoRWM website for public comment. Responses to all the requests for comments were taken into account in preparing the final version of the report.

Overall Conclusions and Recommendations

5. This report sets out the information CoRWM gathered on each topic, references CoRWM and other documents for more details, and gives CoRWM's conclusions on each topic. The overall conclusions and recommendations are as follows.

Strategic Co-ordination of UK Radioactive Waste Management R&D

6. CoRWM considers that there is a need for more strategic co-ordination of R&D for the management of higher activity wastes throughout the UK. This strategic co-ordination is required within NDA (including its SLCs), between NDA and other parts of the nuclear industry (including the Ministry of Defence), amongst the Research Councils, and between the nuclear industry, its regulators and the Research Councils.

7. Within NDA, the need is for more strategic co-ordination of R&D carried out by its SLCs, its Radioactive Waste Management Directorate (RWMD) and within its Direct Research Portfolio (DRP). It is particularly important to co-ordinate RWMD's R&D for implementation of geological disposal with SLC and DRP R&D for waste conditioning, packaging and storage and for the management of spent fuels, plutonium and uranium that may be declared to be wastes. The lack of such co-ordination would lead to a poor use of NDA's resources (effort, time and money).

8. Between NDA and the nuclear industry there is a need for strategic co-ordination of R&D and agreement on national priorities. As well as enabling better use to be made of resources, this would ensure that key issues are tackled in a timely way.

9. Of the five Research Councils that could potentially fund research relevant to the management of higher activity radioactive wastes, only two are doing so at present and only one at a substantial level. Research Councils do not seem to have recognised the need to come together to identify the fundamental research required to underpin the MRWS programme. They should work together in an open and transparent way and involve prospective researchers in all the relevant fields, as well as the nuclear industry and its regulators. All these stakeholders should agree national priorities for the research to be funded by the Councils. This will maximise the benefits of the Research Councils' resources to the MRWS programme.

10. CoRWM does not wish to be prescriptive about the co-ordination mechanisms to be used in any of these cases. However, it has identified a number of attributes it thinks that the mechanisms should have in all cases. The mechanisms should:

   - cover the R&D needs of all the relevant UK organisations
   - be open and transparent
   - involve researchers, the nuclear industry, its regulators and other stakeholders
   - agree national priorities for R&D
   - encourage innovation
   - foster collaboration with other countries
   - ensure R&D is carried out in a timely manner
   - involve independent national and international review
   - ensure R&D results are disseminated and acted upon.

11. In CoRWM's view no single existing body, as presently constituted, is capable of overseeing the necessary strategic co-ordination mechanisms. Either several

bodies would need to work together or an existing body would need to be augmented in order to fulfil the oversight role.

12. It is essential that future UK R&D programmes for the management of higher activity wastes contain sufficient fundamental research, as well as applied research and development. In deciding which R&D to fund and when, account should be taken of the needs of the overall programme for the management of higher activity wastes, the needs for safety case development and the lead times and durations of R&D projects.

> ***Recommendation 1***
>
> *CoRWM recommends to Government that it ensures that there is strategic co-ordination of UK R&D for the management of higher activity wastes. Such co-ordination is required within the NDA, between the NDA and the rest of the nuclear industry, amongst the Research Councils and between the whole of the nuclear industry, its regulators and the Research Councils.*

Regulatory Research

13. The Health and Safety Executive (HSE) has a responsibility to ensure that appropriate nuclear safety research programmes are carried out, including nuclear safety research related to the management of higher activity waste. It has a well-established mechanism for fulfilling this responsibility. HSE commissions its own research and sets out the research topics that nuclear site licensees should address.

14. The Environment Agency (EA) and the Scottish Environment Protection Agency (SEPA) have relatively modest research programmes on topics of regulatory interest in the areas of radioactive waste management and related health and environmental protection issues. CoRWM believes that EA will need to commission more independent research as the MRWS programme proceeds in order to carry out its role as a regulator of geological disposal of higher activity wastes. CoRWM also expects that SEPA will need to commission research to assist it in the regulation of the management of higher activity wastes in Scotland.

> ***Recommendation 2***
>
> *CoRWM recommends to Government that it ensures that the Environment Agency and the Scottish Environment Protection Agency obtain the resources that they need to access and commission the additional independent research required to support them fully in their regulation of the management of higher activity wastes.*

R&D Skills to Support the MRWS Programme

15. The importance of maintaining nuclear skills in the UK was recognised some years ago and steps have been taken to reverse the decline that was occurring. In recent years there has been a significant improvement but there is some way to go, particularly for R&D skills.

16. CoRWM has found that responsibility for the provision of R&D skills is split between many organisations. Although each organisation is playing its part, there

seems to be a lack of national leadership and strategic direction. CoRWM thinks that this would be best rectified by assigning a single organisation the responsibility for providing this leadership and direction. This organisation should be capable of taking a clear overview of the R&D skills needs of the whole of the nuclear industry, existing and new, civil and defence. CoRWM believes that the Cogent Sector Skills Council, with additional expertise, could fulfil this role.

> ***Recommendation 3***
>
> *CoRWM recommends to Government that it assigns to a single organisation the responsibility for providing national leadership and strategic direction for provision of R&D skills relevant to the long-term management of radioactive wastes.*

Infrastructure Required for R&D – Facilities for Research with Highly Radioactive Materials

17. CoRWM considers that the UK's existing civil facilities for research with highly radioactive materials are inadequate and in need of improvement. In addition, new facilities need to be established in order to support the full spectrum of research relevant to the management of higher activity wastes, including geological disposal.

18. Almost all of the existing facilities for research with highly radioactive materials are operated by the National Nuclear Laboratory (NNL). There are plans to widen access but at present the only R&D that can be performed in these facilities is that funded by NNL customers, primarily the NDA and other nuclear industry organisations. It is essential that funders and providers of fundamental research can access the facilities they need in order to contribute to R&D for the management of higher activity wastes, both now and in the future.

> ***Recommendation 4***
>
> *CoRWM recommends to Government that it ensures that facilities for research with highly radioactive materials are improved and their capability enhanced so that they can be used for the full spectrum of research relevant to the long-term management of higher activity wastes. These facilities should be accessible to all researchers who need them.*

Infrastructure Required for R&D – Underground Research Facility

19. Underground investigations will be needed at the site of any proposed geological disposal facility (GDF) in the UK. These investigations need to include both underground site characterisation work and underground R&D if they are to provide sufficient input to GDF design and safety case development. CoRWM is of the view that this R&D should be carried out in an underground research facility (URF) at any site where it is proposed to construct a GDF.

20. An R&D programme should be carried out in the URF prior to the decision as to whether or not to proceed with GDF construction. This programme should be discussed with a range of stakeholders, including the community local to the site and independent scientists, and agreed with regulators. The geological disposal programme should allow time to carry out the required underground R&D and to

disseminate and assimilate its results. It should be recognised that this underground R&D may take decades. The URF should continue to be used for as long as is necessary while the GDF is open.

21. Until a URF is available in the UK, generic R&D should be carried out in underground facilities in other countries. This would allow UK researchers to gain the necessary experience, as well as providing information and techniques to be used in the UK geological disposal programme.

> ***Recommendation 5***
>
> *CoRWM recommends to Government that an underground research facility be constructed at any site where it is proposed to construct a geological disposal facility.*

Public and Stakeholder Engagement for R&D

22. At present, as in the past, stakeholders who are outside the organisations that fund and carry out R&D have little opportunity to influence UK R&D programmes on radioactive waste management. There is a general lack of transparency in establishing R&D requirements and commercial reasons are often cited as a reason for not publishing results.

23. CoRWM believes that this situation must change. As implied in Recommendation 1, a wider range of stakeholders should be involved in establishing R&D requirements. It is also necessary to make accessible information available to the public about R&D needs, progress and plans.

> ***Recommendation 6***
>
> *CoRWM recommends to Government that mechanisms are put in place to ensure that a wider range of stakeholders than to date will be involved in establishing R&D requirements for the long-term management of higher activity wastes and that accessible information will be made available to the public about R&D needs, plans and progress.*

Specific R&D Issues

24. In addition to arrangements for providing R&D and the skills and infrastructure needed for it, CoRWM also considered some of the topics on which further R&D is likely to be required for the long-term management of the UK's higher activity wastes. In doing so, it recognised that future R&D programmes will need to build on the substantial body of knowledge that already exists as a result of past R&D in the UK and other countries. This current knowledge base is sufficient to be confident that geological disposal is the right way forward. In future R&D it will be necessary to focus on knowledge gaps and uncertainties that are important for UK wastes and, in the case of geological disposal, for the types of rocks in which a GDF may be located. The results of CoRWM's consideration of specific topics are in Section 6 and Appendix A of this report. CoRWM did not attempt to identify, consider or prioritise every topic on which R&D may be needed. The material in Section 6 and this appendix is only intended to illustrate the range of R&D that could be required over the next few decades.

1. INTRODUCTION

Scope of the Report

1.1 This report describes CoRWM's scrutiny of current provision and future research and development (R&D) needs for interim storage and geological disposal of higher activity radioactive wastes, and management of nuclear materials that may be declared to be wastes. It covers a number of tasks in CoRWM's work programme for 2008-09 (CoRWM doc. 2266) and much of 2009-10 (CoRWM doc. 2515.2). These tasks can be grouped into the following areas.

Development of a UK R&D programme

- Advising on mechanisms for developing a UK R&D programme on interim storage and geological disposal.
- Scrutinising mechanisms for oversight, review and peer review of R&D.
- Contributing directly to the identification of key technical areas that have fundamental research requirements.

Provision of the skills and infrastructure required for R&D

- Scrutinising current proposals for acquiring and maintaining the skills needed for R&D on storage and geological disposal, over decades.
- Evaluating existing capabilities for R&D, including facilities for work on radioactive materials and capability for investigation of potential sites for a disposal facility.

1.2 In June 2008, as part of the Managing Radioactive Waste Safely (MRWS) programme, the Government published a White Paper on the framework for implementing geological disposal and an invitation to communities to participate in discussions to host a geological disposal facility (GDF) (Defra *et al.*, 2008). The White Paper highlights the need for more R&D to support both storage and implementation of geological disposal and describes the role of the Nuclear Decommissioning Authority (NDA) in carrying out R&D:

> *"The NDA has statutory responsibility under the Energy Act 2004 for carrying out research to support the activities for which it is responsible. The UK Government believes, in the light of CoRWM's work and wider international experience, that there is already sufficient research work available to be confident that geological disposal is technically achievable. In line with CoRWM's recommendation 4 (CoRWM doc. 700) and responses to the MRWS consultation, the NDA will undertake further research during the geological disposal facility development process in order to refine concepts, improve understanding of chemical and physical interactions in a disposal facility, address specific issues raised by regulators, support development of site-specific safety cases and to optimise facility design and delivery.*
>
> *Whilst Government policy is to pursue the geological disposal of higher activity radioactive waste, Government recognises the need to take account of developments in storage and disposal options, as well as possible new technologies and solutions. Future R&D may identify new options for dealing with some wastes, which under application of the waste hierarchy could reduce the amounts of waste requiring disposal…."*.

1.3 CoRWM's Work Programme for 2008-09 (CoRWM doc. 2266) and the R&D Working Group's work plan (CoRWM doc. 2323), stated that CoRWM would be seeking to reassure itself that the R&D carried out would be:

- of appropriate scope and breadth to underpin the MRWS programme
- at the forefront of innovation and international developments in the field
- performed by the most appropriate people and institutions
- cost-effective
- aligned with the needs of the MRWS programme
- able to access the specialised infrastructure needed to work safely with radioactive materials
- of quality at least comparable to that in countries with similar waste inventories and demonstrated through a well-defined independent peer review process
- integrated into skills development activities as an essential component in developing high level skills
- funded openly and transparently, and performance monitored objectively
- appropriately resourced
- an appropriate mix of applications-focused applied and underpinning fundamental science programmes
- conducted in a manner that ensures effective co-ordination between different funding bodies (*e.g.* NDA, nuclear site licensees, Research Councils) and activities (waste conditioning, packaging, storage, disposal).

1.4 CoRWM's 2006 report also stated (CoRWM doc. 700):

> *"If the public is to have confidence in the proposals for the long-term management of radioactive waste, it is essential that the areas of uncertainty and the plans for addressing them are clearly identified from the outset. Wherever possible, uncertainties should be reduced through further research. Where this is not possible, the implications for the success of the programme should be explained along with proposals for managing the programme in the face of these uncertainties."*.

1.5 It was evident at the outset that, to achieve all these requirements, the UK needs co-ordinated R&D that facilitates strategic planning, is open to independent scrutiny, and encourages engagement of talented researchers from a diverse range of fields across fundamental research and applied R&D. The report focuses on these aspects. It covers the UK's current programme and future R&D needs across all research providers and funding bodies; it is not restricted to the NDA.

1.6 CoRWM emphasises that this report is not intended to be exhaustive in the sense of identifying each and every topic on which R&D may be required or describing every R&D project that is in progress or planned. Its focus is the mechanisms and arrangements for specifying R&D needs, carrying out R&D and ensuring the results are utilised fully in managing higher activity wastes and nuclear materials that may be declared to be wastes. Where R&D on specific topics is discussed this is solely for illustration of the breadth and depth of the work required in future;

the omission of any topic does not imply that CoRWM is unaware of it or that it is unimportant.

1.7 Technical topics that are outside the scope of this report include wastes from new build reactors, which CoRWM is addressing in its 2009-10 work programme, and transport of higher activity wastes, which CoRWM plans to address in future. A further omission is the effects of radiation on the health of human beings and other living organisms. The report does not deal in any detail with research in the social sciences that is relevant to radioactive waste management. This was because there was insufficient time to do so. CoRWM intends to return to this topic in future.

1.8 Issues associated with the provision of interim storage and implementation of geological disposal are addressed in two other CoRWM reports published in 2009 (CoRWM docs. 2500, 2550). A position paper (CoRWM doc. 2389) on R&D for conditioning, packaging and storage of higher activity wastes, and the management of nuclear materials, formed the core of sections on these topics in this report.

Context

1.9 In 2006, CoRWM (CoRWM doc. 700) recommended geological disposal as the long-term management option, the provision of safe and secure interim storage, an intensified programme of R&D to support both disposal and storage and a site selection process that is based on the willingness of communities to participate. Government accepted the bulk of CoRWM's recommendations and gave the responsibility for implementing geological disposal to the NDA (UK Government *et al*., 2006). The positions of the Devolved Administrations are given below.

- In June 2007, the Scottish Government rejected geological disposal, opting instead for long-term, near-site, near-surface storage. At the time of publication of this report the Scottish Government is developing a policy framework to take this forward.
- The Welsh Assembly Government reserves its position on geological disposal; it attaches particular importance to ensuring safe and secure interim storage and to carrying out R&D to support the optimised management of higher activity wastes.
- The Department of the Environment in Northern Ireland supports the MRWS programme.

1.10 Many organisations have an interest in, or obligation to, carry out R&D relevant to the management of higher activity wastes. Specifically, under the Energy Act 2004, NDA must ensure that R&D relevant to its remit for decommissioning and clean up is carried out. When the NDA was additionally given responsibility for implementing geological disposal, this included commissioning appropriate R&D. NDA was also required to engage with, and learn from, relevant overseas R&D programmes (UK Government *et al*., 2006). R&D on waste conditioning, packaging and interim storage is largely the responsibility of nuclear site licensees; NDA has a strategic role for its sites.

1.11 The R&D requirements for the long-term management of higher activity wastes are complex and cover the full spectrum from fundamental underpinning scientific research to highly focused applied research. An example of the former is determining the local atomic co-ordination around uranium in particular crystals, an example of the latter is defining the size, shape and manufacturing route of waste containers. NDA's R&D programme is extensive, ranging from techniques to separate and sort contaminated materials during decommissioning to computer model development to simulate the migration of gases through the rocks surrounding a GDF. It necessarily consists of R&D targeted to fulfil specific needs in support of NDA's mission and objectives. More fundamental research in the UK is generally performed by universities and national research centres and is funded mainly through the UK Research Councils.

1.12 This report provides a summary of the current R&D situation. There will undoubtedly be changes in future.

Approach to the Work

1.13 The work described in this report has focused on the provision of technical R&D for support of interim storage and geological disposal of existing and committed UK higher activity wastes. In particular, at this early stage in the MRWS programme, it is critical that the R&D programme includes:

- a system for identifying, prioritising and meeting key R&D needs for interim storage of radioactive wastes
- a robust process of R&D strategy development to identify and prioritise R&D requirements for geological disposal
- a robust and independent peer review process for all R&D
- a long-term programme of skills and infrastructure development that will meet the requirements for long-term waste management including eventual implementation of geological disposal.

1.14 Much of the information required by CoRWM to assess the current extent of R&D programmes, the provision of existing infrastructure and the existing skills development programme was not readily available in any documented form. Consequently, a substantial amount of investigation, conducted by individual members of CoRWM, has proved necessary. This has taken a number of forms, as described in our position paper on storage R&D (CoRWM doc. 2389), including meetings with relevant stakeholders and the interrogation of on-line databases.

1.15 Drafts of this report and of the position paper on storage R&D were issued to stakeholders for comment, placed on CoRWM's website for public comment and discussed at stakeholder workshops (CoRWM docs. 2563, 2581, 2630, 2677). All the comments received have been considered in finalising this report.

Report Layout

1.16 The following sections address each of the topics listed below in turn:

- establishing R&D requirements (Section 2)

- the UK R&D programme relevant to the management of higher activity wastes (Section 3)
- R&D skills (Section 4)
- infrastructure required for R&D (Section 5)
- some specific R&D issues (Section 6 and Appendix A).

1.17 The overall conclusions and CoRWM's recommendations are in Section 7.

2. ESTABLISHING R&D REQUIREMENTS

What is meant by R&D?

2.1 R&D activities for the management of higher activity radioactive waste are diverse. They range from experiments in a small laboratory or development of mathematical and computational methods to design and operation of multi-million pound pilot plants or the construction of underground research laboratories (URLs). Defining exactly what is meant by research and development in diverse fields is difficult. CoRWM has had extensive discussions with NDA and others over these terms and has not been able to reach agreement on definitions.

2.2 CoRWM has devised its own definitions for use in the context of radioactive waste management and these are stated in the Glossary (Appendix C). Key definitions are as follows.

- *Applied Research*: investigation directed primarily towards a specific practical aim or objective, which can involve using existing knowledge and understanding or acquiring new knowledge.
- *Fundamental Research*: original, exploratory investigation involving experimental or theoretical work undertaken primarily to acquire new knowledge and understanding of phenomena and observable facts without necessarily having any immediate application or use in view.
- *Development*: progressive, systematic use of knowledge and understanding gained from research directed towards the production or improvement of materials, devices, systems or methods.

2.3 CoRWM believes strongly that a full range of fundamental and applied research is required for the management of higher activity wastes. The requirement for applied research is the more obvious and it is on this that current R&D programmes in the UK tend to focus. Fundamental research is essential for long-term radioactive waste management, where an ability to demonstrate good understanding of underlying mechanisms and processes is required to provide sound inputs to decisions and make a robust defence of a proposed course of action.

2.4 In particular, CoRWM believes that fundamental research is important for geological disposal, where the safety case must demonstrate to the satisfaction of regulators, the host community, other stakeholders and the public that it is very unlikely that significant quantities of radionuclides will be released from a GDF and travel to the surface over periods of tens of thousands of years or more. Uncertainties over such long times can only be addressed if there is a sound understanding of the processes that underlie potential release and transport of radionuclides. Fundamental research may also reveal unknown issues or phenomena that have not yet been considered but which may be of crucial importance.

2.5 It is clear to CoRWM that the UK needs an R&D programme on the management of higher activity waste that contains fundamental research, applied research and development, with an appropriate amount of effort on each.

2.6 Other terms that are often used to describe different types of research are "needs-driven" and "curiosity-driven". CoRWM has not found these terms to be useful. "Needs-driven" is too general a term in the context of management of higher activity wastes. It covers both applied and fundamental research but says nothing about the balance between them. "Curiosity-driven" is an ambiguous term. In one sense it can be used instead of "fundamental". However, it is often used to refer to research that appears to have no relevance at the time to any practical application (also called "blue skies" research).

Scope of R&D Required

2.7 Radioactive waste management is usually taken to cover a wide range of topics in addition to *conditioning*, *packaging*, *storage* and *disposal*, which are addressed in paragraph 2.14 *et seq.*. Management activities include:

- minimising arisings of all radioactive wastes (solids, liquids and gases), *e.g.* through appropriate designs of nuclear facilities and appropriate operating and decommissioning procedures
- waste characterisation, *i.e.* determining the radionuclide content of waste, its non-radioactive content, and the physical and chemical forms in which radionuclides and other potentially harmful constituents are present
- minimising arisings of each type of solid radioactive waste (low, intermediate and high level), *e.g.* through sorting, segregation, decontamination and allowing radioactive decay
- treatment of liquid and gaseous effluents prior to discharge to the environment
- retrieval of wastes from legacy facilities
- transport of wastes, *e.g.* between stores and disposal facilities
- near-surface disposal
- geological disposal.

2.8 Wastes will follow a sequence of conditioning, packaging, storage, transport and disposal. R&D can be used to provide confidence that the waste packages will be storable, transportable and disposable. This sequence, from the initial processing of raw waste to final sealing into a closed disposal facility, is likely to take many decades, so the durability of the packaged wastes is critical. The waste packages must retain sufficient integrity during interim storage to allow them to be transported to a GDF and emplaced. They then may have to remain intact during a period before the disposal facility is backfilled and sealed. Lastly, they may fulfil important safety functions in the long-term, post-closure safety of the disposal facility. R&D related to many of these topics is covered in this report. In particular, CoRWM has investigated how research requirements related to these topics are established and prioritised, how R&D is co-ordinated and how the R&D results are used in radioactive waste management programmes.

2.9 R&D relevant to radioactive waste management is also carried out in two other technical contexts: nuclear safety, and health and environmental protection. Nuclear safety R&D is mainly about preventing accidents, minimising their consequences, and protecting workers and the public, during the construction, commissioning, operation and decommissioning of nuclear facilities, including radioactive waste management facilities. In the UK nuclear safety research is co-ordinated by the Health and Safety Executive (HSE); this is discussed further in Section 3. Health and environmental protection research related to radioactive waste management is about the movement of radionuclides through the surface and near-surface environments, and the effects of radiation on people and other living systems. This research was briefly discussed in CoRWM's position paper on storage R&D (CoRWM doc. 2389). For both nuclear safety research and health and environmental protection research, CoRWM's concern is with links and overlaps with radioactive waste management research, and gaps that may need to be filled.

2.10 It should also be mentioned that OCNS (Office for Civil Nuclear Security), which regulates the security of civil licensed nuclear sites, nuclear materials and sensitive nuclear information, is connected into national groups considering R&D on wider security issues, such as those led by the Home Office Scientific Development Branch (CoRWM doc. 2414).

2.11 R&D in support of the management of higher activity wastes is both multi-disciplinary and inter-disciplinary. The disciplines involved include chemistry, geology, materials science, biology and engineering. When establishing R&D requirements it is essential to take a holistic view within each discipline and across the boundaries of disciplines.

The Context for R&D – UK Higher Activity Wastes

2.12 The UK has a vast array of various types of radioactive waste, a legacy of its early lead in military and civil power generation nuclear programmes. In this respect, it is similar to the USA, Russia and France, but it is unlike countries such as Sweden, Finland and Switzerland. Higher activity wastes currently being stored (Defra & NDA, 2008a, b) include vitrified high level waste (HLW) in over 4,300 1.34m high x 0.43m diameter steel canisters in a specialist store at Sellafield. There are also about 40,000 packages of conditioned intermediate level waste (ILW) in store, mostly at Sellafield. These include several thousand 500 litre drums of Magnox Encapsulation Plant (MEP) wastes containing reactive metals such as Magnox (a magnesium-aluminium alloy used to clad uranium metal fuel in Magnox reactors) and some uranium. Other ILW includes ion exchange resins, graphite, steels, plutonium contaminated materials (PCM) and some soils. In addition, there are some ill-characterised legacy wastes (predominantly at Sellafield), many as sludges for which immobilisation routes are being developed. In due course some spent fuels, plutonium and uranium may be declared to be waste.

2.13 The diversity, complexity and, in some cases, poor level of characterisation of the UK's higher activity wastes mean that fundamental and applied research, specific to the complex UK inventory, is required to support waste conditioning, packaging, storage and disposal programmes. R&D must be directed to those UK-specific wastes for which other countries are unlikely to develop appropriate treatment processes. The effects of these unusually diverse waste streams on R&D needs are discussed in more detail below and in Section 6 and Appendix A.

Waste Conditioning and Packaging R&D Requirements

2.14 Less than 10% (in terms of volume) of the total predicted UK arisings of ILW have been conditioned to date (CoRWM doc. 2459; NDA, 2008a). The volume of conditioned ILW in store is about 21,000m^3; this is in about 40,000 packages. The volume of raw ILW in store is about 71,500m^3 (Defra & NDA, 2008a). Conditioning and packaging options have been identified for many of the remaining wastes but R&D is needed to choose between the options and to enable the chosen option to be implemented in the most appropriate way. There are also some wastes for which no appropriate conditioning method has yet been developed and for which, research of a more fundamental nature is needed to develop options. Examples of the issues on which R&D is in progress are as follows.

2.15 Most of the ILW that has been conditioned so far has been encapsulated in cement. This matrix could also be used for many other types of ILW but there are other conditioning options that may be better. For example, in the case of ion exchange resins and so-called “wet wastes” (*e.g.* sludges), techniques that involve dewatering and/or high temperature processes may be able to produce more durable wasteforms with lower volumes, and hence lower storage and disposal costs. These techniques are being investigated by several waste producers, who are evaluating their technical advantages and disadvantages and their development, capital and operating costs. There are also wastes such as reactive metals for which many formulations of cement are not ideal and for which alternative treatment and encapsulation methods are being sought.

2.16 To date, most waste containers have been made of various types of stainless steel. There are questions as to whether more corrosion-resistant steels should be used in future for some ILW containers. There are also proposals to use thicker steel containers, which would have a longer life simply through their size. The various possibilities are under investigation at a number of nuclear sites. For vitrified HLW, a number of potential over-pack canister materials for disposal have been proposed and will be investigated by the NDA.

2.17 A further area of research is into the behaviour of some waste packages that are already in store. This is needed to improve understanding of the evolution of the wasteforms and their containers, and hence both to predict their likely performance and to learn lessons for future conditioning and packaging.

2.18 A related area is R&D on the remediation of waste packages, either because they have deteriorated in some way during storage, or because they were not manufactured to the correct specifications. Remedial actions could range from a simple repair of a waste container (*e.g.* re-sealing a lid), to placing the container in a new one (overpacking), to removing the waste, reconditioning it and placing it in a new container (sometimes called “reworking”).

2.19 Much of the above R&D informs the drawing up and the review of waste package specifications. These are set by the NDA, which operates the “Letter of Compliance” system (CoRWM docs. 2459, 2688; NDA, 2008b). This system is designed to make sure that wastes are conditioned and packaged in ways that enable them to be stored and disposed of. It does not provide guarantees but should mitigate the risks of finding in the future that packages are unsuitable in some way (CoRWM docs. 2389, 2500).

Waste Storage System R&D Requirements

2.20 It is necessary to ensure the whole storage system is stable for a long enough period (including any potential delays in the geological disposal programme) so that, when desired, the waste packages can be transported and emplaced in a GDF and remain stable until closure and beyond. CoRWM defines the storage system as encompassing the wasteform, its container, the building or other structure in which the packaged waste is housed, the environment in the building, the means of controlling that environment, other equipment in the building such as cranes and other handling equipment, and the monitoring, inspection and maintenance regime. The reason for defining the storage system in this holistic way is that all these factors interact to govern the safety, security and robustness of storage (CoRWM doc. 2500).

2.21 The most modern purpose-built stores are the new ILW stores at Trawsfynydd and Hunterston A. These are large concrete buildings that are designed to hold ILW in steel drums or boxes. The stores are seismically qualified and designed for ease of maintenance over their entire lifetimes (100-150 years). The Trawsfynydd store uses passive environmental control (natural ventilation *etc.*) while the Hunterston store is actively controlled. The stores also have good arrangements for the monitoring and inspection of waste packages. R&D requirements for such stores include improving predictions of the lifetime of the concrete structure.

2.22 Some future ILW stores will be similar to those at Trawsfynydd and Hunterston. However, various nuclear sites are considering other types of storage system in which wastes are placed in very robust containers that are then housed in relatively simple buildings (Section 6 and Appendix A). Such systems are being developed to the point where a safety case could be made for them.

2.23 Existing stores vary from the relatively modern and purpose-built to older facilities, some of which were only intended as temporary. There are a number of topics on which applied research or development is required to improve these facilities or predict or extend their lives. These topics include atmospheric control systems, monitoring and inspection regimes, means of recladding buildings, and means of replacing cranes, ventilation systems and other equipment.

Geological Disposal R&D Requirements

2.24 R&D is required to support the siting, design, construction, operation and closure of geological disposal facilities and the preparation of safety cases for all these stages and for the long post-closure period. The UK has carried out research on geological disposal since the late 1970s. This initially focused on HLW and was largely funded by the Government and by the European Commission. After Nirex was established in 1982, the focus moved to ILW. Research on geological disposal of ILW was funded by Nirex and also by Her Majesty's Inspectorate of Pollution (which became part of the Environment Agency in 1996) (EA, 2003). Since the failure to acquire planning permission for a Rock Characterisation Facility (RCF) at Sellafield in 1997, relatively little geological research specific to radioactive waste disposal has been conducted in the UK. It has continued to participate in European Commission R&D programmes, but at a relatively low level of effort compared to other countries. It has also followed developments in countries outside the European Union and participated in some work in such countries.

2.25 There is a need now to have a UK R&D programme to support geological disposal that has the appropriate amounts of fundamental research, applied research and development. This will involve making use of past UK R&D, carrying out new R&D and applying relevant overseas knowledge to UK wastes and geologies.

2.26 Much of the new R&D will be site specific and can only begin once one or more candidate sites have been identified. There are, however, a number of areas where generic (*i.e.* not site specific) research would be useful. Examples of these areas are: temporal changes (both transient and permanent) to the hydraulic, chemical and mechanical properties of a rock mass; sorption processes on likely surfaces; microbial interactions with wasteforms; and the transport and fate of waste-emitted gases in the geosphere (including from chemical and microbial reactions). Such research 'grand challenges' have been highlighted in the US (USA) Department of Energy (USDOE) Workshops (USDOE, 2006, 2008a).

2.27 Preparation of a post-closure safety case for a GDF will require numerical models to describe a range of processes over the lifespan of the facility. Applied research will be needed to develop state-of-the-art models, at a range of spatial and temporal scales, leaving sufficient time within the geological disposal programme for these models to be robustly tested. Fundamental research will be required to understand, for example, chemical and microbial interactions over long timescales between the backfill material, wasteform containers, the surrounding geosphere and contaminant plumes migrating from different wasteforms; and coupled thermal-hydraulic-chemical-mechanical behaviour of any GDF and surrounding geosphere over time. Research will also be required to develop and validate up-scaling methodologies over space and time, to relate detailed process-based model predictions to simplified probabilistic calculations within the framework of a post-closure safety case (EA & NIEA, 2009).

2.28 Once candidate sites have been identified, and the desk study and site investigation stages begin, a range of fundamental and applied research will be required to support site characterisation, engineering design and the development of site specific safety cases. Site characterisation will relate both to design and construction of the GDF (including depth, construction techniques and waste emplacement geometry) and to characterising the heterogeneous physical, chemical, hydraulic and mechanical properties of the surrounding geosphere. Much of this research will have to be carried out underground (Section 5).

Knowledge Management

2.29 Knowledge management is an important aspect of establishing R&D requirements. Effective knowledge management entails making full use of existing information so that R&D can be planned to advance knowledge and there is no unwarranted repetition of previous work. It also includes ensuring that the results of R&D feed through into the design, construction and operation of radioactive waste management facilities, and into the development of safety cases for facilities and operations.

2.30 UK knowledge management needs to encompass relevant radioactive waste management work worldwide. The activities and publications of international organisations have a useful role to play. The United Nations International Atomic Energy Agency (IAEA) and the Nuclear Energy Agency (NEA) of the Organisation for Economic Co-operation and Development (OECD) organise meetings and compile information and experience. The European Commission funds projects that provide overviews of past R&D on particular topics. Some countries seem to be much more advanced than the UK in developing and using knowledge management procedures and systems in the context of radioactive waste management. For example, Japan has developed a knowledge management system specifically for geological disposal of HLW [1].

2.31 CoRWM will return to the topic of knowledge management in its future work programme. For the present, it notes that there are several issues that need to be addressed with some urgency. These are (CoRWM doc. 2630):

- preservation of documents that describe past R&D (so that knowledge is not completely lost and work has to be repeated)
- declassification of as many existing R&D documents as possible, including documents that are marked "restricted" or "commercial" (so that R&D results are widely available)
- capturing the tacit knowledge of senior experts who are approaching retirement
- development of a suitable knowledge management system for all radioactive waste management R&D in the UK (so that understanding from past and future R&D can be shared, used and passed on to subsequent generations).

Timescales and Priorities for R&D

2.32 It is clear that R&D needs to be timed so that it fits in with the overall programme for the management of higher activity wastes. For example, it is unnecessary to begin R&D on methods for conditioning a particular waste if that waste will not arise for several decades. On the other hand, if facilities for storage of existing raw wastes are reaching the end of their useful lives, R&D is needed in the near future on methods for conditioning and packaging those wastes for further storage and eventual disposal.

2.33 In the case of geological disposal, there should be a progression from generic to site specific R&D. For example, generic R&D on site characterisation techniques must precede the start of investigations of prospective sites for a GDF. However, site specific underground R&D can only begin once a site for detailed investigation has been selected.

[1] *http://www.jaea.go.jp/04/tisou/english/forum/forum_index.html*

2.34 It is also necessary to consider the durations of the R&D projects needed for the management of higher activity wastes. These range from a few months to several years and in some instances to a few decades. Some projects can begin almost immediately while others have long lead times, for example because of the need to build up the skills base or to develop new facilities.

2.35 A further very important issue in setting research priorities is safety case development. This is an iterative process. An initial design for a facility is devised and a safety case is developed for that design. Then an analysis of that safety case is carried out to identify those areas of uncertainty that have most impact on the safety of the GDF. R&D is then performed to investigate these areas of uncertainty, with a view to reducing them or producing a better quantification of them. The design is then improved and the safety case revised accordingly. The iterations continue until the safety case is sufficiently robust to satisfy regulators and other stakeholders. For a GDF, the R&D includes site investigation, from the surface and underground, and the analysis of safety case results helps to guide the site investigations. Throughout the iterative process, time needs to be allowed for R&D results to be promulgated, assimilated and discussed.

2.36 In the current economic climate, it is particularly important to set clear R&D priorities. CoRWM believes that this is best done in an open and transparent way, involving the people who will do the R&D as well as those who will use the results.

Key Points on Establishing Research Requirements

2.37 Both applied R&D and fundamental research are needed to support the management of higher activity radioactive wastes. The applied research addresses practical safety and design issues in the development and operation of facilities for waste conditioning, packaging, storage and disposal. The fundamental research provides the detailed understanding that underpins safety cases and facility designs. It can also reveal hitherto unknown issues that need to be considered. It is essential that future UK R&D programmes for management of higher activity wastes contain the full spectrum of fundamental research, applied research and development, with appropriate amounts of effort devoted to each.

2.38 Research requirements for the management of higher activity wastes span a large number of disciplines. These include engineering disciplines as well as physics, chemistry, biology and earth sciences. The research needed is both multi-disciplinary and inter-disciplinary.

2.39 There are a number of knowledge management issues that should be addressed in the near future. These include the preservation and declassification of documents describing past R&D for higher activity wastes and the development of a UK knowledge management system for all radioactive waste management R&D.

2.40 Priorities for R&D to support the management of higher activity wastes should be set in an open and transparent way, involving researchers themselves as well as programme managers and users of results. It is also important to involve a wide range of stakeholders, including local communities (Section 3). The needs of safety case development, the overall programme for the management of higher activity wastes, project lead times and project durations should all be taken into account in deciding which R&D to fund and when.

3. UK R&D FOR MANAGEMENT OF HIGHER ACTIVITY WASTES

3.1 In this section of the report, the organisations that provide R&D for the management of higher activity wastes are identified and their roles described. There is then a description of the mechanisms used in the past to co-ordinate UK radioactive waste management R&D and a discussion of public and stakeholder engagement in past and current UK R&D programmes. This is followed by some examples of how other countries organise their radioactive waste management R&D. The section ends with CoRWM's conclusions about future UK R&D for the long-term management of higher activity wastes.

Overview of Organisations Responsible for Providing R&D

3.2 Figure 1 shows the organisations responsible for providing R&D relevant to the long-term management of higher activity wastes and the links between these organisations. The organisations that fund R&D are:

- NDA, including its Site Licence Companies (SLCs)
- other civil and defence nuclear industry organisations (*e.g.* British Energy, AWE plc)
- regulators of the nuclear industry (HSE, Environment Agency (EA), Scottish Environment Protection Agency (SEPA))
- Research Councils
- the European Commission.

3.3 The organisations that carry out R&D are:

- universities
- the National Nuclear Laboratory (NNL)
- research institutes (*e.g.* the British Geological Survey)
- nuclear industry organisations
- consultants and contractors.

3.4 As an indication of the current scale of R&D and the contributions of the various organisations, Table 1 shows approximate annual funding levels for the organisations for which CoRWM has been able to obtain figures.

NDA

R&D on Waste Conditioning, Packaging and Interim Storage

3.5 The NDA is required by the Energy Act 2004 to undertake R&D relevant to its mission. It funds research directly *via* its Direct Research Portfolio (DRP) and other means. However, most of its funding for R&D is indirect, *via* its SLCs. It is difficult for NDA to estimate its indirect expenditure on R&D because R&D spend is included in SLC project costs rather than being recorded as separate items. NDA's Annual Report and Accounts for 2008-09 state that it spent about £101M in total on R&D, of which £11M was direct spend and £90M was the estimated SLC spend. For perspective, NDA's total operating expenditure in 2008-09 was £2.7B (NDA, 2009a).

Table 1. Approximate annual levels of funding for R&D on management of higher activity wastes

Funding provider	Approximate maximum annual spend (£M)
NDA Radioactive Waste Management Directorate	3*
NDA Direct Research Portfolio	4**
NDA Site Licence Companies	60***
Engineering and Physical Sciences Research Council	2
Natural Environment Research Council	0.25
British Geological Survey (non-NERC)	0.6
European Commission	2
Total	Less than 72

*The NDA RWMD and DRP figures are its spend on contractors. They exclude costs associated with NDA R&D staff and support functions.
**Total DRP budget is £6M; CoRWM estimates the proportion relevant to higher activity wastes and materials that may be declared to be wastes to be this amount.
***Total SLC R&D budget is about £90M; CoRWM estimates the proportion relevant to higher activity wastes and materials that may be declared to be wastes to be this amount.

3.6 The figures for NDA shown in Table 1 were derived from CoRWM's estimates of the proportion of NDA's spend that was for R&D specifically to support the implementation of geological disposal. All of the SLC spend shown in Table 1 is for R&D on waste conditioning, packaging and storage, as is much of the DRP spend. CoRWM estimates that less than 5% of NDA's £101M R&D expenditure in 2008-09 was for geological-disposal-related R&D.

3.7 The SLCs are responsible for decisions on their own radioactive waste management R&D. They have their own programmes of work; these are driven by the task in hand, including meeting regulatory requirements for safety and environmental protection. The SLCs' R&D programmes are defined in Technical Baseline and underpinning R&D documents (TBuRDs) linked to the SLC Life Time Plans (LTPs). The TBuRDs set out the technical baselines for the site, describe the technical challenges that the SLCs face and summarise the R&D that is deemed necessary to meet them. For each NDA site, it is the contractual responsibility of the SLC to develop an LTP and assess the associated timescales and costs. The LTP includes the reference means of conditioning, packaging and storing wastes. Where there are unknowns or significant uncertainties, the need for R&D is identified. The R&D requirements are compiled in the TBuRD, which is updated annually (NuSAC, 2008).

3.8 The "NDA Research and Development Needs, Risks and Opportunities" (NDA, 2006a) document is a compilation produced before the development of the

TBuRD system in its current form. It states that "Historically, the short-term benefits gained from carrying risks associated with the technical underpinning of projects led to significant cost implications and delays to projects and programmes. Today, we believe the technical baselines and identification of R&D requirements will help the SLCs to focus on overall programme delivery and not just short-term activities". This document is being revised to reflect the creation of the NDA's Radioactive Waste Management Directorate (para. 3.17) and provide an updated description of NDA's non-site R&D.

3.9 The NDA role is primarily one of strategic and contract management, helping to avoid duplication of similar work over its seven SLCs. The NDA Research Board on Nuclear Decommissioning and Waste Clean Up (NDARB) is an advisory body which provides high-level oversight, and has members from government departments, regulators and Research Councils. It also has two independent members including one from HSE's Nuclear Safety Research Review Group (previously a sub-committee of the Nuclear Safety Advisory Committee (NuSAC), which has been disbanded). The primary objective of NDARB, which meets every four months (see NDARB Terms of Reference [2]), is to:

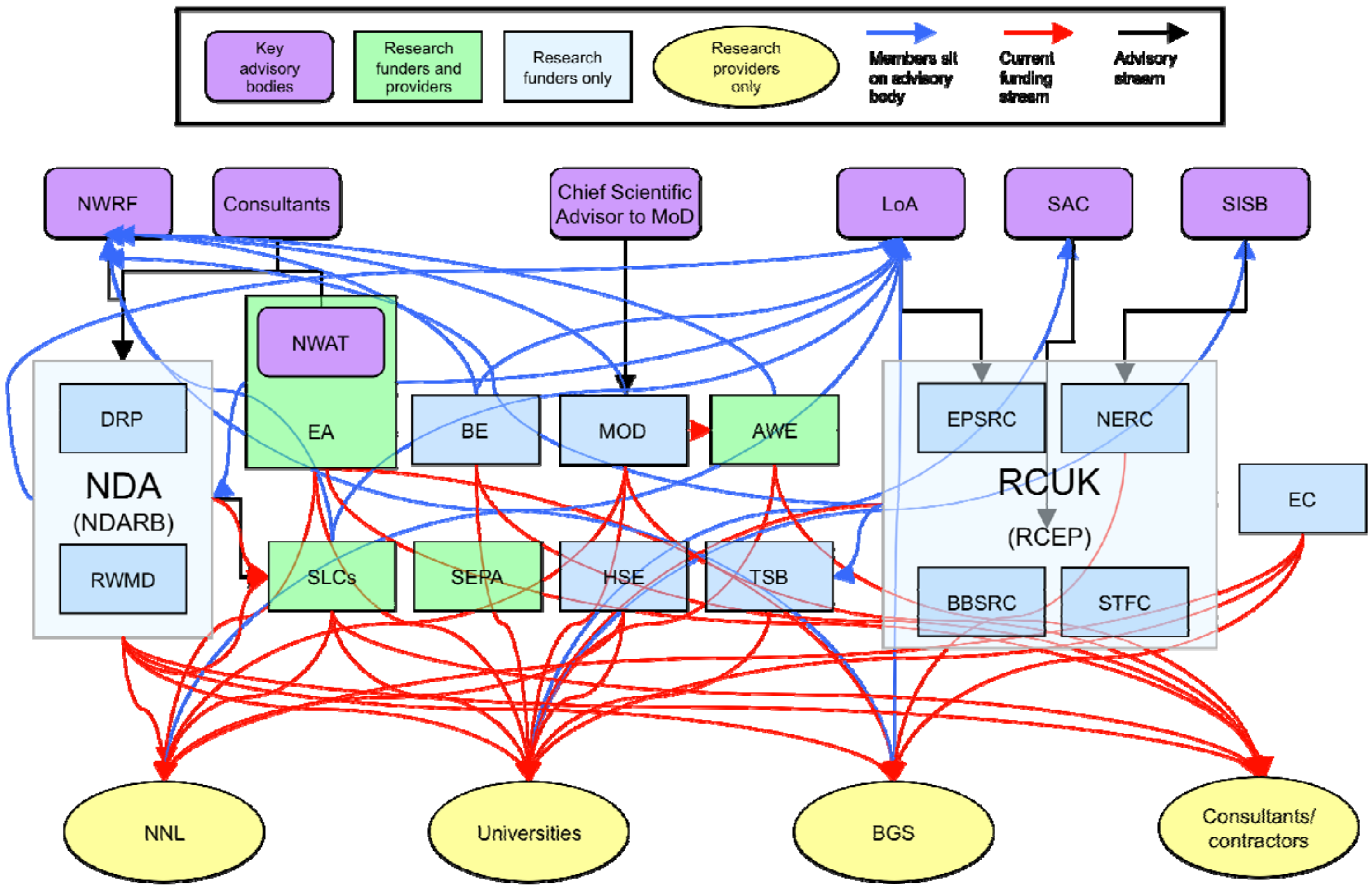
> *"promote a common understanding and collaboration between relevant bodies across the UK about respective R&D needs, risks and opportunities required to enable the delivery of the NDA mission. Where appropriate these activities will be linked to long term skills and capability requirements*.".

3.10 At the operational level, the Nuclear Waste Research Forum (NWRF) was set up to share information and create networks between SLCs. It reports to NDARB. NWRF includes representatives from NDA, its SLCs, RWMD, AWE and the regulators (NII, EA, SEPA and the Department for Transport (DfT)), the Ministry of Defence (MoD) and British Energy. It meets every three months. A number of NWRF sub-groups have been established to look at generic topics common across SLCs and other waste producers. These topics include waste packaging, wet wastes, sludges and heels characterisation, remote size reduction and dismantling, categorisation and re-categorisation of wastes, decontamination, high temperature processes, orphan wastes, and contaminated land and site end states. A new sub-group on interim storage held its first meeting in June 2009.

3.11 From feedback CoRWM has received at meetings with regulators and the SLCs involved, the NWRF is perceived to be generally working effectively. NWRF is recognised as a good meeting point to share ideas and identify areas of common interest. Progress has been made where it is possible to find simple pragmatic solutions to short-term operational problems, and to put in hand R&D which addresses specific problem areas and delivers solutions. However, CoRWM understands that there have been some difficulties caused by lack of technical personnel to do the work or by limited access to funding for longer-term R&D because of competition with short-term operational claims (CoRWM docs. 2386, 2519, 2464).

[2] *http://www.nda.gov.uk/*

Figure 1. Structure of UK R&D provision for management of higher activity wastes



Acronym Legend

AWE Atomic Weapons Establishment
BBSRC - Biotechnology and Biological Sciences Research Council
BE - British Energy
BGS - British Geological Survey
DRP - Direct Research Portfolio
EA - Environment Agency
EC - European Commission
EPSRC - Engineering and Physical Sciences Research Council
ESRC - Economic and Social Research Council
GDRF - Geological Disposal Research Forum
HSE - Health and Safety Executive
LoA - Letter of Arrangement group
MoD - Ministry of Defence
NDA - Nuclear Decommissioning Authority
NERC - Natural Environment Research Council
NNL - National Nuclear Laboratory
NWAT - Environment Agency's Nuclear Waste Assessment Team
NWRF - Nuclear Waste Research Forum
RCEP - Research Council Energy Programme
RCUK - Research Councils UK
RWMD - Radioactive Waste Management Directorate
SAC - RCEP's Scientific Advisory Committee
SEPA - Scottish Environment Protection Agency
SISB - Science and Innovation Strategy Board
SLCs - Site Licensing Companies
STFC - Science and Technology Facilities Council
TSB - Technology Strategy Board

3.12 NDA's DRP process was developed to support strategic and national R&D issues that are not funded directly by SLCs. It is a component of the broader R&D portfolio and has an annual budget of £6M. It started in 2005 as a single research contract with Nexia Solutions but has since been opened out and a tranche of DRP research was awarded to various organisations in 2008. The programme was determined from a review of the SLC TBuRDs. It is split into four lots covering support for University Interactions (Lot 1, awarded to NNL/Serco), Waste Processing (Lot 2 awarded to NNL/UKAEA/Hyder), Materials Characterisation (Lot 3, awarded to UKAEA/NNL/Serco) and Actinide/Strategic Material Investigation (Lot 4, awarded to NNL/UKAEA). NWRF contributed to a prioritisation of proposed DRP work areas. While this is intended to be a more open process than that used previously, where NDA staff reviewed the proposals of Nexia Solutions (now NNL), research providers have expressed concern about the complexity and opacity of the current DRP process (CoRWM doc. 2630).

R&D in the Letter of Compliance Process

3.13 Waste conditioning and packaging is overseen by NDA through the Letter of Compliance (LoC) process, which is described in CoRWM's Interim Storage report (CoRWM doc. 2500). LoC is a process designed to make sure that, as far as practicable, waste conditioning methods will produce waste packages that can be safely stored, transported and disposed of. The system was started by Nirex and was originally called the Letter of Comfort (because it was designed to give comfort to waste producers that Nirex would accept their packages for geological disposal). It is now operated by RWMD (para. 3.17).

3.14 To obtain an LoC, the waste owner has to provide evidence that the waste package will be compliant with the NDA specifications (Nirex, 2007). This often requires the owner to conduct R&D, the results of which are scrutinised to support the LoC application. For a typical cemented waste, factors such as the rate of setting, amount of free water, mechanical strength, heat production and fracturing are taken into account. For difficult wastes, the size of the R&D programmes required to develop and implement conditioning and packaging processes can be substantial in money and time (from hundreds of thousands to millions of pounds and over many years). NDA agreed to allow CoRWM to investigate the R&D underpinning some example LoC applications in order to explore this area more fully (CoRWM doc. 2688).

3.15 Nirex/NDA waste package specifications have changed with time and it is possible that they will change again. Thus by the time a GDF comes into operation, the UK will have several categories of ILW packages: older packages that were prepared to meet the earlier specifications, newer packages designed to meet the current specifications and possibly also packages designed to meet future, different specifications.

3.16 The NDA is undertaking a review of earlier LoCs and this will either provide reassurance that "old specification" waste packages will meet the more recent standards, or will identify the need for remedial action to ensure that packages will meet these standards. R&D will be necessary to determine the types of remedial actions required.

NDA R&D for Geological Disposal

3.17 RWMD was established in 2007 when Nirex was subsumed into NDA. It will be developed into a delivery organisation to implement geological disposal. The plan is for RWMD to become a wholly-owned subsidiary of NDA and then to become an SLC at a late stage in the process of GDF siting. RWMD has 70 employees and a total annual budget of £15-20M, of which the R&D components are 10 employees and about £3M. The RWMD Head of Research sits on NDARB. RWMD is also represented on NWRF. CoRWM understands that NDA is setting up an independent geological disposal advisory panel answering to NDARB and the RWMD Executive. The terms of reference and membership of the panel have not yet been made public. The panel will publish an annual report of its findings (CoRWM doc.2630).

3.18 In June 2008, RWMD put forward a Proposed R&D Strategy (NDA, 2008c) for consultation. Feedback from CoRWM (CoRWM doc. 2408), stakeholder meetings and other written responses led to a revised strategy, which is being produced as two separate documents. The first document, issued in March 2009, details the high level strategy and structures within the NDA for geological disposal R&D (NDA, 2009b). The second document will detail the planned R&D programme. It has not yet been published by RWMD, so scrutiny of it will form part of CoRWM's future work programme. In its response to the 2008 NDA R&D strategy document, CoRWM identified a number of areas where substantive research will be required (CoRWM doc. 2408) and some of these are described in Section 6 and Appendix A of this report.

3.19 RWMD's high level R&D strategy document defines its remit as (NDA, 2009b):

> *"to carry out R&D to support a national strategic need to support safe and secure geological disposal. We therefore commission applied research and development, targeted to fulfil specific needs in support of RWMD's objectives. We call this needs-driven R&D."*

3.20 RWMD will define an applied R&D programme that is needs-driven and focused on construction of the GDF and preparation of an accompanying safety case. RWMD expects to fund any applied research required to underpin implementation of its programme. Certain aspects of this may be supported through the DRP, where skills development is a primary driver. This is similar to the approach for other NDA R&D, which is split between the DRP and the SLCs.

3.21 RWMD recognises the importance of external review of its R&D and is developing a process to ensure this is carried out. CoRWM has had the opportunity to comment on RWMD's developing proposals, and understands RWMD is now augmenting its management system arrangements for review of deliverables to ensure the related guidance is sufficiently robust.

R&D in the NDA's Strategy Management System

3.22 The NDA's Strategy Management System (SMS) was set up in 2008. It will be used to build up the next NDA Strategy from a series of "topic strategies", and to ensure consistency with the strategies of each of the NDA's sites (CoRWM doc. 2418; NDA, 2009c). There will be several topic strategies for higher activity wastes, for nuclear materials management and for spent fuels management [3]. There is one topic strategy for R&D, which is described as a “critical enabler” for the other topics. CoRWM understands that R&D needs will be identified for radioactive waste management and for site restoration topics, while the R&D topic strategy will be a set of high level principles. However, the current SMS documents (NDA, 2009c) show little about how R&D will be treated and NDARB does not appear on the block diagram describing the SMS.

3.23 There is a Higher Activity Wastes Strategy (HAWS) Group, with representatives from the regulators, NDA, British Energy, MoD and SLCs, which oversees the development of the higher activity wastes topic strategies and which reports into the NDA SMS. There is also a UK Spent Fuels and Nuclear Materials Topic Overview Group, which includes representatives of Government, regulators and NDA, where R&D on the management of spent fuels, plutonium and uranium can be discussed at a strategic level. There will be no geological disposal topic strategy because the intention is that RWMD will become an SLC, with its own site strategy and TBuRD.

Other Nuclear Industry Organisations

3.24 Civil nuclear industry organisations such as British Energy and Urenco UK Ltd. (which enriches uranium) also fund R&D but, unlike the NDA, do not have major R&D programmes on radioactive waste management. Their approach is to carry out R&D as and when it is required to solve particular waste management problems. Typically, these organisations will do R&D as an input to “optioneering studies” (*i.e.* studies to identify and evaluate options for managing a particular type of waste). Their studies increasingly involve identifying techniques used in other countries, with the aim of buying “off the shelf” solutions, rather than carrying out any in-house R&D. An example of this is the R&D that British Energy carried out when evaluating options for conditioning and packaging the spent water treatment ion exchange resins from the Sizewell B PWR.

3.25 The situation is similar for MoD sites that are nuclear licensed sites and are run by contractors (*e.g.* Aldermaston, Devonport, Rosyth). None of these sites, nor MoD itself, has major R&D programmes on radioactive waste management. They carry out or commission R&D as and when it is needed. There is increasing co-operation between defence and civil sites through groups such as the NWRF (para. 3.10).

Role of the National Nuclear Laboratory

3.26 The NNL was launched in 2008. It is based on Nexia Solutions, a former subsidiary of BNFL. In April 2009 it became a government-owned, contractor operated organisation (GOCO). The management and operations contractor is a consortium of Battelle, Serco and the University of Manchester. The role of the contractor is to provide strategic vision and management to NNL and to develop it as a stand-alone business. The contract is for an initial three-year period with options to extend by up to two years.

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[3] *http://www.nda.gov.uk/strategy/overview.cfm*

3.27 The purpose of NNL can be summarised as being to:[4]

- identify and preserve key nuclear scientific and technical skills and facilities
- lead and integrate UK strategic technology programmes
- provide independent technical advice to the UK Government and its agencies
- operate world class facilities for research
- assist in the development of the market for the provision of nuclear research.

3.28 The areas of business of NNL include nuclear science, waste management, plant process support, modelling, materials and corrosion, specialist analytical services and environmental management. It operates at six locations in the UK: Sellafield, Workington, Preston, Risley, Harwell and Stonehouse. Its active facilities (Section 5) are owned by the NDA and leased by NNL, which operates them under the nuclear site licences of the relevant SLCs. They can be used for long-term, large-scale experiments with highly radioactive materials.

3.29 NNL has about 750 personnel, of whom about 400 are technical and a further 150 provide facilities support. Key personnel in the NNL structure are the seven Technical Authorities, each of which has overall responsibility for defining the technical strategy and maintaining quality within a defined technical area, and the eight Senior Research Fellows, who are NNL's leading technical experts with a responsibility for engaging with universities and other stakeholders and for quality publications within their area of expertise. NNL plays a key role in the maintenance and development of R&D skills (Section 4).

3.30 NNL delivers R&D using these facilities but currently for a fairly narrow "customer base". 75% of its business is from the NDA and SLCs with a further 20% from British Energy and MoD. Its customer base is expected to expand in the future. It receives no subsidy from Government but operates as a fully commercial organisation. If the NNL is to meet UK strategic needs for R&D then it will require customers that recognise those needs and fund projects accordingly.

Nuclear Safety Research and the Role of HSE

3.31 The management of the UK nuclear safety research programme was transferred from the Department for Trade and Industry to the Health and Safety Commission (now combined with HSE) in 1990. The Government set three primary objectives for the programme (HSE, 2009a):

- to ensure that adequate and balanced programmes of nuclear safety research continue to be carried out, based on a view of the issues likely to emerge in both the short and long term
- to ensure that, as far as reasonably practicable, the potential contribution which such research can make to securing higher standards of nuclear safety is maximised

[4] *http://www.nnl.co.uk/*

- to ensure that the results of any such research having implications for nuclear safety are disseminated as appropriate.

3.32 There were also supporting objectives, namely maintaining a sufficient range of independent capability and taking advantage of international collaboration (HSE, 2009a). The legal context for the programme is provided by the Health and Safety at Work … Act 1974, which places duties on HSE to make arrangements for carrying out research and to encourage research by others, and the Nuclear Installations Act 1965, which states that HSE may recover the costs of nuclear safety research from nuclear site licensees (and applicants for licences).

3.33 The latest edition of the HSE Nuclear Safety Research Strategy (HSE, 2009a) is published as part of the Nuclear Research Index (NRI). It covers the research that HSE will do and the research that it expects nuclear licensees to carry out. Within the NRI there is also an HSE Nuclear Directorate Research Strategy Statement for Waste and Decommissioning Research (HSE, 2009b). This statement is to ensure that nuclear sites consider HSE's needs and concerns in the waste and decommissioning technical area when they are establishing their research requirements (*e.g. via* TBuRDs in the case of NDA SLCs and *via* Nuclear Safety Research Schedules in the case of British Energy). The Statement applies to both operating and shutdown reactor plant. It is not prescriptive but is intended to list the topics on which, in HSE's view, R&D will be needed to support safety cases. It gives the regulatory and research goals as being:

> *"to ensure a sound technical basis for the safe and timely retrieval, passivation, immobilisation, containment and interim storage of radioactive wastes on both operating and shutdown reactor plant"*.

3.34 Much of the research by licensees will fit into a project programme and be funded by that project, rather than being part of an R&D programme as such.

3.35 NuSAC had the responsibility to inform HSE each year whether the nuclear safety research programmes of the industry and its regulators were adequate and balanced in supporting nuclear safety in the UK. Based on its sampling in 2007-08, NuSAC concluded that good progress had been made to define and develop topics requiring research. It judged the nuclear safety research situation to be satisfactory but, in the longer term, in need of continuing encouragement and scrutiny. The 2008 NuSAC review of the NDA SLCs' TBuRDs stated:

> "*We formed a favourable impression during our review of TBuRDs (2008). Standardisation of format has helped to ensure that all sites are addressing relevant issues, and some topics have yielded results that have been implemented. We did advise where further improvements might still be beneficial*.".

3.36 HSE's Nuclear Directorate (ND) reported in early 2009 that the 2008-09 nuclear safety research programme for radioactive waste management and decommissioning was being commissioned to plan by ND and the nuclear site licensees (HSE, 2009c). The programme focused on Magnox sites, Sellafield and Dounreay. ND identified the key areas and topics for research. The licensees identified the research required and told ND that it was being progressed (HSE, 2009c).

3.37 Since NuSAC was disbanded, its Research Review Group (RRG) has continued to advise HSE. In 2009, the RRG commented (CoRWM doc. 2630):

> *"(R&D) would benefit from a more transparent presentation of all the aims, in some detail, so that the adequacy of progress could be judged against a programme. Critically, there are many areas where solutions are still sought, and they must be provided on an acceptable timescale."*.

The Environment Agencies

3.38 EA and SEPA have relatively modest research programmes on topics of regulatory interest in the areas of radioactive waste management and related health and environmental protection issues (CoRWM doc. 2464). Both agencies aim primarily to influence others to carry out research and can require nuclear site licensees to do research *via* conditions in authorisations issued under the Radioactive Substances Act.

3.39 The research programme of EA's Nuclear Waste Assessment Team (NWAT), while small, is highly focused and makes good use of its resources. EA has a limited R&D budget, including around £1M over the next 5 years for in-house (2 scientists) and commissioned work, supplemented by industry charges levied by NWAT. This budget covers radioactive waste management and radioactive substances risk assessment, including new-build. It is partly used to "lever" EA into joint projects and programmes involving NII, industry and international bodies (such as the NEA Radioactive Waste Management Committee's Integrated Group for the Safety Case, para. 3.134). This approach gives the EA wider influence and greater access to knowledge to help it to underpin its regulatory decisions. Current EA projects include:

- HLW / spent fuel safety cases: how different elements including the waste form, container and disposal facility design contribute to the safety functions
- remediation of ILW packages, including non-intrusive techniques for monitoring the condition of packages in store, and guidance on choosing remediation options so as to minimise health and environmental impacts.

EA plans further projects in:

- chemical speciation of radionuclides and non-radioactive elements in the environment
- site issues such as appropriate characterisation techniques and managing graphite wastes.

3.40 SEPA commissions research mainly *via* the Scotland and Northern Ireland Forum for Environmental Research (SNIFFER). To date SEPA has funded little R&D on the management of higher activity waste.

The Research Councils

3.41 Support for research is available from the Research Councils, which are the UK Government agencies responsible for funding research and training. They disburse about £2.8B per annum to universities and research centres across the UK. The strategic partnership of the UK's seven Research Councils is Research Councils UK (RCUK), based in Swindon. Many activities are undertaken collectively and *via* cross-council initiatives. The research requirements for management of higher activity wastes encompass a wide range of disciplines (social science, ethics, radiochemistry, hydrogeology, engineering, microbiology, *inter alia*) and hence are relevant to several Research Councils. The Research Councils of most relevance to this report are the Engineering and Physical Sciences Research Council (EPSRC), the Natural Environment Research Council (NERC), the Biotechnology and Biological Sciences Research Council (BBSRC), the Economic and Social Research Council (ESRC) and the Science and Technology Facilities Council (STFC).

3.42 RCUK funds a wide range of fundamental research and training across the full spectrum of science, engineering and social sciences. Summarising RCUK's whole funding portfolio is well beyond the scope of this report but CoRWM recognises that some of this investment may, in future, lead to direct or indirect benefits to R&D relevant to higher activity wastes. The focus, here, is on describing funding programmes that are of direct relevance to R&D for interim storage and geological disposal of radioactive wastes, and management of nuclear materials.

3.43 The Research Councils work together in energy projects through the Research Councils' Energy Programme (RCEP), which brings together all facets of energy research, knowledge transfer, engagement and training across the Councils in a programme which includes nuclear fission and fusion. The EPSRC is the co-ordinating lead for the RCEP. Activities are developed through a Programme Co-ordination Group (PCG) comprising members of each of the Research Councils (budget holders and individuals responsible for research themes), with observers from the Department for Business, Innovation and Skills (BIS) [5] although not from the Department of Energy and Climate Change (DECC), which is responsible for nuclear and radioactive waste management policy. The PCG meets approximately once a month. A Scientific Advisory Committee (SAC), which does have DECC representation, is used to advise the RCEP on its balance of programmes and development of activities. It is an independent strategic committee which meets at least quarterly. In response to an RCEP paper, the SAC agreed that geological disposal is an area of interest and plans are underway to develop a managed activity with relevant stakeholders (CoRWM doc. 2524).

3.44 The majority of RCEP research funds are placed through 'managed calls'. Managed calls are generally in the form of a call for research proposals within a pre-specified topic (or topics). Industry is often involved in specifying the topics in such managed calls (para. 3.50). Each call has a pre-defined sum of funding available from the Research Councils, often with additional funds from industry. Research bids are invited from groupings typically comprising more than one university, together with allied organisations (each bidding team is termed a 'consortium'). Review of bids is usually a 2-stage process. Firstly, all proposals

[5] BIS was derived from two separate departments, the Department for Innovation, Universities and Skills (DIUS) and the Department for Business, Enterprise and Regulatory Reform (BERR).

submitted to RCEP are subjected to peer and merit review. Secondly, an awards panel comprising academics and industry members ranks the proposals.

3.45 In addition to the managed activities supported through the Energy Programme, the Councils also support research through their responsive mode schemes in which individuals or groups of researchers submit research proposals in any area of their choosing. The current level of funding directly related to the management of higher activity wastes *via* Research Council responsive mode schemes is discussed in the sections for individual Research Councils below.

3.46 The Research Councils also work closely with the Technology Strategy Board (TSB), an executive non-departmental public body established by Government in 2007 and sponsored by BIS, other Government Departments, the Devolved Administrations, Regional Development Authorities and other national and supranational bodies. The TSB funds applied research and development of products and processes that are near to market rather than fundamental research, which is the domain of RCUK. There are no currently funded TSB R&D programmes directly relevant to the management of higher activity wastes although it has highlighted nuclear energy as a possible area for future funding and is currently undergoing a review exercise.

EPSRC

3.47 EPSRC funds research and training in engineering and the physical sciences, investing about £740M per annum in a broad range of subjects from mathematics to materials science and from information technology to structural engineering. Almost all the EPSRC-funded R&D relevant to radioactive waste management is funded *via* managed calls in the form of consortia. These managed calls can either be solely EPSRC funded or funded through the joint RCEP led by EPSRC.

3.48 Current EPSRC-funded consortia relevant to waste conditioning, packaging, storage and geological disposal fall under the RCEP. EPSRC funds just over £26M of research under the 'Nuclear Energy' stream of RCEP. The majority of this is directed into research on power generation, and so is not relevant to the management of higher activity wastes. Existing EPSRC-funded consortia relevant to radioactive waste management are: Keeping the Nuclear Option Open (KNOO); Decommissioning, Immobilisation And Management Of Nuclear wastes for Disposal (DIAMOND) (EPSRC, 2009); and 'Biogeochemical Applications in Nuclear Decommissioning and Waste Disposal'. These consortia, all funded through the RCEP, are described briefly in Box 1. EPSRC held a scoping workshop on Future Activities in Nuclear Power Research and Training in June 2009 and it has up to £5M funds to support consortia in this area. A similar workshop is planned to consider geological disposal research.

3.49 The EPSRC also funds two research Chairs in the nuclear field at the Dalton Nuclear Institute, University of Manchester. One, in Radiation Chemistry, supports the development of generic knowledge in this field. The other, in Decommissioning Engineering, supports the development of generic knowledge in the field of decommissioning engineering that can be used to solve problems associated with nuclear decommissioning.

3.50 Existing EPSRC-funded research is principally supported through managed calls. The scope of each call is at the discretion of EPSRC, which has advisory input from a variety of sources, including the Letter of Arrangement (LoA) group. The EPSRC set up the LoA group in 2005 with members from nuclear companies and the regulators (EPSRC, HSE, BNFL, AWE, MoD, British Energy and NDA). The LoA group is a forum for research funders to share strategic priorities and potentially to identify areas for collaborative activities. The decision whether to proceed with proposed areas and the exact scope of an activity rests with EPSRC.

3.51 In April 2009, EPSRC held a workshop on "Nuclear Engineering" jointly with the USDOE and the National Science Foundation. The aim was to "identify opportunities in areas where UK-USA collaborations make sense and fill the needs for one or both countries", and nuclear engineering was defined very broadly. Topics discussed relevant to interim storage and geological disposal of higher activity wastes were largely within the *Spent Nuclear Fuel and Waste Management and/or Post Operation* theme, which encompassed:

a. reprocessing
b. waste forms
c. permanent storage
d. disposal
e. transmutation of waste (reduction of volumes and waste recycling)
f. environmental waste management and legacy waste
g. advanced fuel cycles.

3.52 In the context of the UK's MRWS programme, questions of interest were essentially restricted to four topics within this theme (wasteforms, permanent storage, disposal, and 'environmental waste management and legacy waste') out of a total of 34 topics identified across the six themes. Topics related to life extension, new build, future reactor systems and reprocessing dominated the workshop output. At the time the workshop was held, there was much uncertainty over the USA Yucca Mountain programme, so it was difficult to discuss geological disposal and interim storage did not appear to have attracted much USA research activity.

NERC

3.53 NERC funds research *via* universities and its own research centres with a remit to increase knowledge and understanding of the natural world and to tackle major environmental issues including climate change, biodiversity and natural hazards. It also provides independent research and training in the environmental sciences. NERC supports research totalling about £400M annually.

3.54 In 2007, NERC launched its new science strategy, following a 2-year consultation period with the UK's environmental research users, funders and providers. The strategy, Next Generation Science for Planet Earth, sets out an overview of how NERC, in partnership with others, will respond to the critical issue of the 21st century - the sustainability of life on Earth. The strategy defines the funding priorities for 2007-2012 and was developed with strong inputs from the Science and Innovation Strategy Board (SISB), NERC's principal advisory committee.

Box 1. Research Council Funded University Research Consortia

The KNOO consortium is a 4-year, ~£6M, RCUK initiative which started in 2005 and is funded through the multidisciplinary research consortia programme, Towards a Sustainable Energy Economy, to support nuclear-related research. KNOO is led by Imperial College and is a consortium of 7 universities; it comprises 4 work packages, only one of which is relevant to radioactive waste issues (WP-3: An Integrated Approach to Waste Immobilisation and Management). In developing KNOO, geological disposal was specifically excluded from the programme scope because it was not, at that time, Government policy. The KNOO programme ended in September 2009 and the Research Councils have announced a follow-up managed call in the nuclear area, predominantly aimed at reactor lifetime extension and new build.

The DIAMOND consortium (2008-2012, £4.28M) is led by the University of Leeds. It involves 6 universities and is divided into three areas - Environment, Migration and Risk; Decommissioning, the Historic Legacy and Site Termination; and Materials - Design, Development and Performance. Two areas focus on work relevant to waste management: Decommissioning, the Historic Legacy and Site Termination is centred on the improved and accurate characterisation of stored legacy wastes (particularly “Orphan wastes” for which no clear management route exists) and the development of novel technologies for retrieval and treatment; Materials - Design, Development and Performance aims to address key knowledge gaps in the conditioning, storage and disposal of wastes in order to underpin future decision-making in waste management.

The ‘Biogeochemical Applications in Nuclear Decommissioning and Waste Disposal’ consortium (2009-2013, £1.9M) involves 5 universities and the British Geological Survey. The consortium will explore the use of microbial technologies to reduce the risk of radionuclide migration from decommissioning and disposal sites by ‘microbially engineering’ precipitates to seal fractures in the surrounding rock/soil mass and by immobilising radionuclides within these precipitates.

Three other EPSRC research grants, awarded under RCEP over the period 2005-2012, are directly relevant to the MRWS programme. These awards, amounting to £2.16M, are focused either on the properties and behaviour of borosilicate glass or on the potential for micro-organisms in near-surface media to retard radionuclide migration.

In July 2009, the EPSRC, under its High End Computing programme, funded a further relevant research project, ‘Understanding the Chemistry of Ceramic Materials Under Irradiation’. This project, involving 3 universities and awarded a total of £756K over the period 2010-2014, will investigate the mechanisms by which radioactive elements are incorporated into possible host matrices, how radiation damage changes the host properties (in particular, dissolution), and how radioactive species may escape from such host matrices.

3.55 The NERC science strategy is delivered *via* seven science themes: climate system, biodiversity, earth science system, natural hazards, sustainable use of natural resources, environment pollution and human health (EPHH), and technologies. The themes most relevant to MRWS-related R&D are EPHH and Technologies.

3.56 EPHH examines the interactions of humans with the environment, how man-made changes may affect the health of humans and how adverse effects may be prevented. NERC is currently setting up an Expert Group, under the most recent EPHH theme action plan, to identify research gaps in the area of Radioactivity and the Environment, covering all aspects of radioactivity from atmospheric dispersion modelling to geological disposal. The group will be used to inform the development of the next round of NERC's Theme Action Plans during 2009, which will set out the actions to be taken to deliver the NERC science strategy.

3.57 The Technologies theme develops capabilities to detect hazardous species in the environment *via* novel instruments and sensors. The theme is mostly concerned with pathogens and toxins; radionuclides are not specifically mentioned.

3.58 NERC has four main avenues for the direct funding of radioactive waste management R&D:

- responsive mode funding of research that falls within its remit under the topic of 'environmental radioactivity'
- directed thematic grant programmes (managed calls)
- British Geological Survey (BGS) research centre funding
- Centre for Ecology and Hydrology (CEH) research centre funding.

3.59 The total direct and dedicated support *via* NERC responsive mode funding over the period from 1998-2012 for nuclear topics, including geological disposal, amounts to just over £1.4M. The research falls into three topic areas: 'abiotic' considerations on waste immobilisation and geosphere character; organic complexation of uranium and related elements; and biogeochemical interactions and radionuclide mobility in near-surface environments.

3.60 On behalf of MoD, NERC has managed a depleted uranium (DU) thematic research programme, which awarded £928K of funding over the period 2004-2008 in support of research aimed at characterising and understanding DU behaviour in the environment. The results are of relevance to the decommissioning and surface soil contamination aspects of NDA and nuclear site licensee work, but are of very limited applicability to the long-term management of radioactive wastes.

3.61 BGS provides NERC's main contribution to research that is relevant to the MRWS programme. Founded in 1835, BGS is the world's longest-established national geological survey and the UK's national centre for earth science information and expertise. It is a NERC Research Centre, deriving approximately half of its annual income (£40M) from NERC. The remainder comes from commissioned research from the public and private sectors. In line with this mixed-funding model, the BGS carries out research into geological disposal as part of its NERC-funded science programme and also in the context of commissioned research funded by third parties. Three BGS staff who work on radioactive waste disposal issues, full time, form the core of its Radioactive Waste Team. These are complemented by a further 37 BGS scientists who currently work on projects relating to radioactive waste disposal on a part-time basis, leading to a total BGS commitment of 13 man years of effort per year. This compares with an estimate of 25 man years of radioactive-waste-related research in 1995, with about 20 man years at that time on the service and advice component of work.

3.62 BGS is conducting three projects relevant to geological disposal within its NERC Science Programme remit. These are: *Bio-Tran*, investigating microbial transport and microbial indicators of mass transport through geological media; *Geosphere Containment*, developing fundamental understanding of the mass transport properties and hydromechanical behaviour of low permeability media (anthropogenic and natural) with application to radioactive waste disposal, carbon dioxide sequestration, gas storage and contaminant transport; and *Paleohydrogeology,* developing paleohydrogeology techniques to support geological disposal. Direct support from NERC for these programmes was about £470K over a seven-year period from 2003-2010.

3.63 BGS is involved in, and in some instances leads, research programmes directed at understanding the behaviour of the engineered components of a GDF in the sub-surface and characterising host rock masses and their fracture systems. The areas include projects on bentonite, the engineering disturbed zone (EDZ) fracture transmissivity and near-field chemical containment. A series of geological disposal-related research studies have been carried out by BGS for Japanese contractors. These focused on the characterisation of fluid pathways and fluid-rock interactions in the Mizunami URL site, Honshu, Japan.

3.64 NERC also has the ability to fund research through CEH, which is a NERC-funded institute for integrated research in terrestrial and freshwater ecosystems and their interaction with the atmosphere. In recent years, no research of direct relevance to the management of higher activity wastes has been funded by NERC *via* the CEH.

Other Research Councils

3.65 BBSRC funds research relating to the understanding and exploitation of biological systems. Its remit includes research at all levels of biological systems, from molecules and cells through tissues to whole populations and their interactions; it covers plants, animals and microbes. It also supports a number of important industrial stakeholders, including the agriculture, food, chemical, healthcare and pharmaceutical sectors. Its current budget is about £420M per annum. Its current strategic priorities include global security, living with environmental change and bionanotechnology. BBSRC does not have any current grants in the area of radioactive waste management or remediation of radioactively contaminated land. This contrasts markedly with the USA programme, where biological effects on radioactive contamination, and bioremediation, have been strongly supported over many years, initially through the dedicated Natural and Accelerated Bioremediation Program (NABIR) and subsequently within the wider Environmental Remediation Sciences Program (ERSP). [6] Similarly, the Swedish Deep Biosphere Laboratory [7] has existed for over 20 years, conducting a biological research programme in support of geological disposal.

3.66 ESRC is the UK's leading agency for research funding and training in economic and social sciences. It receives most of its funding (about £203M per annum) from BIS. It has recently reviewed its strategic plan which now includes a

[6] *http://esd.lbl.gov/research/projects/ersp/generalinfo/intro.html*
[7] *http://www.gmm.gu.se/groups/pedersen/index.php*

strategic challenge on Environment, Energy and Resilience, one of only seven. CoRWM asked RCEP representatives, specifically, whether or not ESRC was funding work into the public understanding of the scientific, social and ethical issues surrounding long-term radioactive waste management and, in particular, issues relating to management in the face of considerable scientific uncertainty and issues of intergenerational equity. In addition, since public and stakeholder engagement (PSE) is regarded as a given in many radioactive waste programmes today, CoRWM asked ESRC whether or not it was funding research into the impact of PSE on the decision-making process and/or on the most appropriate ways to undertake PSE in this area. In its response, made prior to the revision of its strategic plan, ESRC noted (CoRWM doc. 2524) that “current investment in this area is limited, but there may be greater opportunities to explore new agenda in the near future”.

3.67 STFC was formed in 2007 by merging the Particle Physics & Astronomy Research Council and the Council for the Central Laboratory of the Research Councils. With an annual budget of around £500M, STFC funds research in astronomy and nuclear and particle physics. It also provides the research community with access to large facilities at two principal UK sites, the Daresbury and Harwell Science and Innovation Campuses, as well as at the Institute Laue Langevin (ILL) and the European Synchrotron Radiation Facility (ESRF) in Grenoble. Harwell is home to ISIS, the world's most powerful pulsed neutron and muon source, which is used to study the atomic structure of materials; Vulcan, the world's highest intensity focused laser; and the Diamond synchrotron, in which STFC has an 86% share. The Cockcroft Institute at Daresbury focuses on designing the next generation of particle accelerators.

3.68 There is a long history of experiments using small quantities of transuranic materials at ISIS and ILL. ISIS is currently working with EPSRC grant holders to support their experimental programme in radioactive waste management. Diamond currently permits experimental work with samples with low levels of radioactivity. It is reviewing what needs to be done to respond to future demands of the scientific community, whether this be with transuranic materials or higher activity levels (Section 5).

EU Research Funding

3.69 All aspects of nuclear fission R&D, including work on wasteforms and geological disposal, have been supported over many years at the European Union (EU) level. There have been eight European Atomic Energy Community programmes since 1975, and since 1984 these have been integrated into the broader EU Framework Programmes (FPs), of which there have been seven. Historically, the UK was an active participant in EU programmes, particularly through BGS and the United Kingdom Atomic Energy Authority (UKAEA). Following the shift in UK focus to ILW, including the formation of Nirex, and organisational changes in UKAEA in the 1980s, then the hiatus in UK work on disposal of higher activity wastes after 1997, UK involvement in FPs declined significantly. Reports from the FPs, especially FP4 to FP6, contain research results and overviews that could now be useful to the UK.

3.70 In the current FP7 programme (2007-2011) fusion is dominant, but a budget of €287M has been allocated to fission research. The stated priority for fission is establishment of a sound scientific and technical basis for better management (safer and more resource-efficient, competitive and environment-friendly) of energy and waste and the impact thereof. A further €517M has been allocated for the EU's Joint Research Centre (JRC) activities in the nuclear sphere, which are intended to support co-operative international activities in nuclear waste management, environmental impact, nuclear security and nuclear safety.[8] European research activities are co-ordinated through the Sustainable Nuclear Energy Technology Platform.[9] An EU Implementing Geological Disposal Technology Platform (IGD-TP) is also being set up to provide a framework led by industry to define R&D priorities, timeframes and action plans in this area. CoRWM members made informal comments on the draft "vision document" for the platform.

3.71 Only one FP7 Euratom project is led by a UK institution: BGS was recently awarded the ~£2M Fate of Repository Gases (FORGE) project on gas migration (para. A.59). The FORGE project is designed to characterise and quantify the conditions during geological disposal under which gas formation will occur with sufficient pressure increase to result in radionuclide migration from the GDF into the surrounding host rock. The project will include model development to underpin GDF designs that lie within a safe gas generation envelope.

3.72 A number of other FP7 Euratom research projects relevant to the management of higher activity wastes include one or more UK partners. These include:

- Actinide Recycling by Separation and Transmutation (ACSEPT) - 34 European partners including the Universities of Reading and Edinburgh, and the NNL with a technical focus on separation and transmutation of actinide elements. The total budget for this programme is €24M, of which €9M will be funded by the EU. Approximately €4.5M will be spent in the UK (€3.9M by NNL and €600K by universities), of which €1.6M will be funded by the EU.
- Treatment and Disposal of Irradiated Graphite and other Carbonaceous Wastes (Carbowaste) - 27 partners including Amec, Bradtec, Doosan Babcock, NDA, NNL and University of Manchester in the UK. This project aims to develop an integrated waste management approach for existing stocks of irradiated graphite and carbonaceous waste and for future ones such as graphite-based Generation IV reactor systems (€3.4M to be spent by UK organisations with EU contribution of €1.9M).
- Redox Phenomena Controlling Systems (RECOSY) - 32 partners, with Loughborough and Manchester Universities and BGS in the UK as associate partners. The objectives of RECOSY are the development of a sound understanding of redox phenomena controlling the long-term release/retention of radionuclides in nuclear waste disposal and the provision of tools to apply the results to performance assessment and safety cases.

3.73 Other EU projects include Fundamental Processes of Radionuclide Migration (FUNMIG) and Near Field Processes (NF-Pro) (both run in FP6 and recently

[8] *http://www.europa.eu/*
[9] *http://www.snetp.eu/*

completed). NDA has current commitments in support of UK elements of EU projects (which are typically of 3-5 years duration) in excess of £1M.

The Learned Societies

3.74 The Learned Societies provide invaluable communication resources to their membership *via* journals, websites and meetings, workshops and conferences. Several (in particular, the Geological Society of London, the Institute of Physics (IoP) and the Institute of Materials, Minerals and Mining (IOMMM)) have been particularly helpful to CoRWM during the preparation of this report (*e.g.* CoRWM docs. 2455, 2519) by hosting meetings and surveying their membership. Radioactive waste management is a topic in which the Royal Society (RS) has a long-standing interest. The Royal Society funds Policy Reviews which influence research, such as the report on Strategy Options for the UK's Separated Plutonium (Royal Society, 2007). Representatives of the British Nuclear Energy Society (BNES), the Geological Society of London, IoP, IOMMM and the Royal Society of Chemistry (RSC) contributed to the planning and format of the NDA RWMD's R&D Strategy Workshop to support geological disposal, held in Loughborough in November 2008. In addition, there have been joint learned society meetings involving, for example, IoP, RS, RSC, the Mineralogical Society, the Geological Society of London and the British Geophysical Society. A group of the Learned Societies has agreed, in principle, to set up a joint website to provide independent scientific information to the public on higher activity waste issues, although they are still discussing a funding route.

3.75 The Royal Academy of Engineering, like the Royal Society, has encouraged debate on radioactive waste issues. It held a meeting in December 2006 to discuss Future Developments in the Management of Nuclear Waste: Building on CoRWM. It also held a workshop in December 2008 on skills for the nuclear industries and defence, which brought together stakeholders from civil and defence nuclear engineering, representatives of the engineering educational providers and others interested in the provision of engineering skills across the nuclear industries. This meeting agreed that there is a requirement for a truly planned and co-ordinated approach to the identification, quantification, development and delivery of the engineering skills base at every level. Further work to take this forward is being scoped.

Past UK Co-ordination of Provision of R&D

1970s

3.76 UK R&D on the long-term management of higher activity wastes expanded in the late 1970s following the publication of the sixth report of the Royal Commission on Environmental Pollution (the "Flowers report") (RCEP, 1976). This report recommended that there should be no commitment to a large nuclear power programme until:

> *"it has been demonstrated beyond reasonable doubt that a method exists to ensure the safe containment of long-lived highly radioactive waste for the indefinite future."*.

3.77 RCEP noted that there was a lack of clarity about who had the responsibility for determining the best waste management strategy. It recommended that the Department of the Environment (DoE) be given this responsibility. RCEP also saw a need for a national disposal facility, developed and managed by a Nuclear Waste Disposal Corporation, and for a Nuclear Waste Management Advisory Committee to sponsor research (RCEP, 1976).

3.78 In its response to the Flowers report, Government gave DoE the responsibility for radioactive waste management policy, increased research on HLW disposal and recognised the need for a national disposal facility for ILW (UK Government, 1977). Also, in 1978, Government established the Radioactive Waste Management Advisory Committee (RWMAC). The terms of reference for RWMAC were:

> *"To advise the Secretaries of State for the Environment, Scotland and Wales on major issues relating to the development and implementation of an overall policy for the management of civil radioactive waste, including the waste management implications of nuclear policy, of the design of nuclear systems and of research and development, and the environmental aspects of the handling and treatment of wastes."*.

3.79 RWMAC defined its role in relation to R&D as:

> *"assessing the overall scale, balance and priorities of the Government's radioactive waste management research programme, and the adequacy of the total resources devoted to research activities, whether by Government or by the industry"* (RWMAC, 1982).

3.80 In 1979, drilling started at Altnabreac as part of research on geological disposal of HLW. UK expenditure on R&D for radioactive waste management in 1978-9 was £13.3M and in 1979-80 it was £19.8M. About 50% of the expenditure was by BNFL and about 25% by DoE (RWMAC, 1982).

1980s

3.81 The main players in radioactive waste management R&D in the 1980s were:

- DoE, which included the environmental regulator for England and Wales, Her Majesty's Inspectorate of Pollution (HMIP), so had both policy and regulatory responsibilities
- the Ministry of Agriculture, Fisheries and Food (MAFF), which had regulatory responsibilities under the Radioactive Substances Act; for land, the relevant part of MAFF was the Food Science Division (FSD) and for sea, the Directorate of Fisheries Research (DFR)
- the Nuclear Installations Inspectorate, for nuclear safety aspects
- UK Nirex Ltd, which was formed in 1983 for disposal of low and intermediate level wastes and was funded by the nuclear industry
- UKAEA, which was funded by the Department of Energy
- BNFL, which recovered most of its R&D costs from its customers in the UK and overseas
- CEGB and SSEB, the generating companies

- MoD
- the National Radiological Protection Board (NRPB), which carried out work under contract to other UK organisations and to the European Commission, but which received funding for research related to its statutory role from the Department of Health and Social Security.

3.82 DoE, MAFF and others funded work at the NERC institutes, *i.e.* BGS, the Institute of Oceanographic Sciences (mainly for research related to sub-seabed disposal of HLW) and the Institute for Terrestrial Ecology (ITE). The Building Research Establishment (BRE) was funded by DoE and Nirex for design work on land disposal facilities (near-surface and deep).

3.83 The research programmes covered all types of radioactive wastes: gaseous effluents, liquid effluents, and solid LLW, ILW and HLW. In 1981, there was a major change of direction in R&D when the Government decided that the research drilling programme for geological disposal of HLW should cease. R&D on ocean disposal of HLW continued until about 1987, by which time the Government policy was to store HLW for a minimum of 50 years. R&D on ILW disposal increased after the establishment of Nirex.

3.84 RWMAC scrutinised the R&D programmes of the various organisations throughout the 1980s. It published a major review of HLW disposal research in 1983 and considered the options for long-term management of spent fuel in 1985 (RWMAC, 1983, 1985). In 1987 RWMAC noted in its 8th Report that:

> *"Research and development is needed in the field of radioactive waste management to provide a suitable information base for proper development of general policies and specific strategies. We consider that it is important to have a co-ordinated and balanced programme making the best use of resources to meet the waste management objectives of the various Departments. Suitable arrangements are also required for peer review of results and for competent assessments of the quality of work."*.

3.85 There was a DoE symposium on research objectives in 1986, to review research management procedures and strategic objectives. Participants included those responsible for sponsoring and undertaking research, Government Departments and advisory bodies such as RWMAC. The symposium identified several issues that required clarification or strengthening of procedures. These included programme co-ordination, programme review and peer review of results. It was also considered that more attention should be given to presentation of research results to the general public (RWMAC, 1987).

3.86 After the symposium, DoE reviewed the inter-departmental committee structure for liaison on monitoring and allocation of research resources. There were two overall liaison committees, each with a sub-committee, one for the interests of the regulators and one for industry and regulators together (RWMAC, 1987).

3.87 In 1987-88, DoE employed consultants to carry out a review of national research requirements for radioactive waste management. This identified gaps and overlaps and enabled the liaison committees to consider the balance of R&D programmes and the use of resources. RWMAC continued to review R&D in five sectors: land disposal, ocean disposal, environmental studies, waste conditioning and strategy and systems studies (RWMAC, 1988, 1989).

3.88 Throughout the 1980s, RWMAC collected information on planned expenditure on radioactive waste management R&D and included it in its annual reports. Data were presented by sector and by funding organisation (RWMAC, 1987, 1988, 1989). Total expenditure rose from £28.6M in 1980-81 to £46.66M in 1989-90. Table 2 summarises the expenditure breakdown for 1989-90 (RWMAC, 1989).

Table 2. UK Radioactive Waste Management R&D Expenditure in 1989-90

Sector	*Planned UK R&D expenditure (£M)*	*Major funders*
Land disposal	13.92	Nirex (£6M), DoE (£4.9M)
Ocean disposal	0.47	MAFF DFR (£0.45M)
Environmental studies	7.1	DoE (£1.9M), BNFL (£1.7M), MAFF DFR (£1.6M), MAFF FSD (£1.2M),
Waste conditioning	23.92	BNFL (£16M), DoE (£3.5M), UKAEA (£2.42M), CEGB (£2M)
Strategy and system studies	1.25	DoE (£0.5M), BNFL (£0.3M), CEGB (£0.2M)
Total	46.66	

1990s

3.89 At the time of the reconstitution of the committee in 1991, the relevant Minister asked RWMAC to review the DoE radioactive substances research programme. By this time, HMIP (Her Majesty's Inspectorate of Pollution) had its own research programme, which was focused on its regulatory role, and the DoE research programme for radioactive waste management focused on policy issues. RWMAC completed and published its review in 1993 (RWMAC, 1993).

3.90 In its review, RWMAC expressed concern about the scope for overlap of the research programmes of DoE, other Government Departments, Research Councils and non-Government organisations. It recommended that DoE create a unit to track research overlaps. DoE responded that its Radioactivity Research and Environment Monitoring committee (RADREM), which had members from Government Departments and industry, provided an effective liaison mechanism. The committee met bi-annually and had four sub-committees, each for a specific area, to identify and report developments, gaps and overlaps (RWMAC, 1994).

3.91 RWMAC also recommended that DoE develop expertise so that it could manage its research programme in-house. DoE responded that it secured technical support for management of its research programme by means of a consultancy.

It considered this to be both an effective and a flexible arrangement (RWMAC, 1994).

3.92 Although RWMAC continued to review the DoE (subsequently the Department for Environment, Transport and the Regions (DETR)) radioactive substances research programme during the 1990s, the committee no longer reviewed UK radioactive waste management R&D as a whole. RWMAC reviewed the results of the DETR HLW and Spent Fuel Research Strategy Project. It also considered the Nirex-proposed work programme following the 1997 RCF decision (RWMAC, 1998). RADREM operated until 1995 but produced no published reports on co-ordination of R&D.

3.93 After the RCF decision, the need for strategic co-ordination was recognised by the House of Lords Science and Technology Committee (Lords, 1998) who concluded:

> *"When there is agreement on the national strategy (for long-lived waste management) a comprehensive research programme should be set out, linked to milestones in the development of the facilities. The Commission should be responsible for co-ordinating all UK research on the long-term management of nuclear waste…."*.

Public and Stakeholder Engagement for R&D Programmes

3.94 In the past, there was little opportunity for stakeholders outside the R&D funding and providing organisations to influence UK R&D programmes on radioactive waste management. For example, NGOs were not invited to sit on the various committees or to take part in reviews of research requirements. While some organisations published all the results of their research (*e.g.* Nirex, Her Majesty's Inspectorate of Pollution), others published very little. On the whole, little attention was paid to providing information about R&D to the public in an easily accessible form.

3.95 CoRWM has found that the situation is much the same today. Most of the fora at which R&D requirements are discussed are closed and do not issue publicly available documents. TBuRDs are not publicly available, in full, for most SLCs and are, in any case, only suitable for use by those with considerable expertise. Considerable amounts of R&D are viewed as "commercial" and the results are not published. This is particularly the case for waste conditioning and packaging research.

3.96 There are signs that the situation will be better for geological disposal research. For example, there was stakeholder consultation about the proposed RWMD R&D Strategy (para. 3.18) and RWMD plans to consult about the R&D programme to implement the strategy (CoRWM doc. 2677). However, none of the organisations involved in radioactive waste management R&D routinely produce documents that explain in accessible language what they think the key uncertainties are and what R&D is in hand or planned to address those uncertainties. This is despite the importance that the public and stakeholders attach to R&D (CoRWM doc. 2488). There is a specific need for an accessible summary of what is known about geological disposal and of R&D requirements beyond those that RWMD intends to tackle in the near future (CoRWM doc. 2677).

International Experience in Defining R&D Programmes

3.97 A number of countries are conducting R&D programmes to support long-term management of higher activity wastes. It is not the intention to review or summarise all of these here. Instead, this section contains examples of how R&D programmes are organised, drawn from six countries that CoRWM has visited or has good knowledge of, to provide comparison with the UK situation. It also considers the role of international organisations in assisting countries to define their research programmes and in international co-ordination of R&D.

USA – Yucca Mountain

3.98 USDOE has been investigating Yucca Mountain as a site for geological disposal of spent nuclear reactor fuel and other radioactive waste in the USA since 1987. The site is located within unsaturated ignimbrites (pyroclastic volcanic rocks) above the contemporary water table on federal land adjacent to the Nevada Test Site in Nye County, Nevada. USDOE submitted a licence application to the Nuclear Regulatory Commission (NRC) for construction at Yucca Mountain in June 2008; the preliminary process of checking over and 'docketing' the application was completed in September 2008. In early 2009, the new USA Secretary of Energy stated that the Yucca Mountain project would be terminated and a "blue ribbon panel" would be convened to study alternatives, including new potential GDF locations and management options for spent fuel other than geological disposal.[10] USDOE work related to the Yucca Mountain licence application continues but all other work on the project has stopped.

3.99 To date, all relevant R&D to support the Yucca Mountain disposal site has been controlled and commissioned by USDOE. The DOE does not have in-house expertise across all the required subject areas; consequently, it hires project Management and Operations (M&O) contractors. The organisations conducting the R&D, until recently, were termed the 'Participants'. These are the National Laboratories and the US Geological Survey (USGS). Each year, all participants submit plans to DOE on the research they believe to be required. Universities can only become actively involved in conducting research for DOE *via* collaboration with the national laboratories. Academics are, however, supported by independent funding provided by the State of Nevada and Nye County, who are currently contesting the DOE licence application for Yucca Mountain.

3.100 This "Program Plan (PP)" is DOE's overarching planning document. The PP describes the work to be carried out over the following five years. It is updated every year, so the plans for the "out years" (*i.e.* years beyond the upcoming years) change regularly. Input for the PP is provided by "assistant program managers", who are responsible for particular topics, with the help of the M&O contractors and participants. The plans for each topic area are compiled into one document, the PP, which then goes through an internal DOE approval procedure. Much of what is contained in the PP is for the purposes of budgeting, so that the DOE can see what the technical implications are of reducing research plans to

[10] http://www.nrc.gov/

match a given budget. None of the PP is available for public comment (*i.e.* there is no consultation process), although it is a public document and copies are sent to other branches of government. The PP is primarily an internal DOE document rather than a mechanism for obtaining feedback on the planning and research prioritisation strategy.

3.101 All research reports are subject to internal review but this process is more geared towards quality assurance than a review of research quality. Most fundamental research is published in the academic literature and hence subject to independent peer review. Some of the published research, including a book (Ewing & Macfarlane, 2006), has identified technical problems with the Yucca Mountain GDF design.

3.102 Independent review of the research programme, as a whole, is provided by the Nuclear Waste Technical Review Board (NWTRB). The NWTRB is an independent agency of the USA Federal Government whose purpose is to provide independent scientific and technical oversight of the DOE's programme for managing and disposing of high-level radioactive waste and spent nuclear fuel. It reports to Congress and the Secretary of Energy at least twice a year. The Government appoints well-respected experts to act as independent members of the Board, based on recommendations from the National Academy of Sciences.[11] Meetings of the Board are convened once or twice a year. For the past 20 years, NWTRB has focused on the DOE's Yucca Mountain programme. Now that this programme has effectively ended, NWTRB is developing and compiling technical information to inform the USA evaluation of waste management alternatives, while monitoring any new DOE work related to the management of HLW and spent fuel.

3.103 The United States Nuclear Regulatory Commission provides independent guidance on regulation and licensing for development of the GDF.

3.104 In 2001, the Office of Basic Energy Sciences (BES) in USDOE's Office of Science commissioned a "Basic Research Needs" series of workshops to identify the fundamental research needed to assure a secure energy future. These workshops have engaged academic researchers in defining fundamental research priorities toward a sustainable USA energy policy. In 2006, a 4-day workshop was held entitled 'Basic Research Needs for Advanced Nuclear Energy Systems'. A major component of this workshop was to identify fundamental research issues for geological disposal (USDOE, 2006). Research challenges and priorities identified in the workshop included those in Box 2.

3.105 The workshop involved a total of 235 invited experts from 31 universities, 11 national laboratories, 6 industries, 3 government agencies, and 11 foreign countries and exemplifies the USA practice of engaging the wider R&D community in the major research programmes such as for geological disposal.

[11] *http://www.nwtrb.gov/*

Box 2. USDOE 2006 Workshop R&D Issues

Grand Challenges

- computational thermodynamics of complex fluids and solids
- integrated characterisation, modelling and monitoring of geological systems
- simulation of multiscale systems for ultra-long times

Priority Research Directions

- mineral-water interface complexity and dynamics
- nanoparticle and colloid physics and chemistry
- dynamic imaging of flow and transport
- transport properties and *in-situ* characterisation of fluid trapping, isolation and immobilisation
- fluid-induced rock deformation
- biogeochemistry in extreme subsurface environments

Cross-Cutting Issues

- the microscopic basis of macroscopic complexity
- highly reactive subsurface materials and environments
- thermodynamics of the solute-to-solid continuum

Japan

3.106 Geological disposal of Japanese HLW was set out as the end point of a process embodied in the 2000 Act, "Specified Radioactive Waste Final Disposal Act", which also set up the Nuclear Waste Management Organisation, NUMO. The 2002 report, "Requirements of Geological Environment to select Preliminary Investigation Areas (PIAs) of HLW Disposal", set out the basis for site exclusion following a voluntarism approach, and led to the Open Solicitation in December 2002. NUMO was set up as the organisation responsible for delivery of a repository system, and as implementer it was made responsible for site selection and characterisation, the licensing of applications and organisation of the programme of repository development, and overseeing the construction, operation and closure of any repository. NUMO is supervised by the Ministry of Economy, Trade and Industry (METI) and funded by owners of the nuclear power reactors. The fund is managed by the Radioactive Waste Management funding and research Centre (RWMC – see below).

3.107 In the Japanese nuclear waste disposal programme, the term '*Research and Development*' is used to include all work aimed at building fundamental scientific understanding and establishing necessary technology. '*Demonstration and Validation*' (D&V) refers to work which confirms that the resultant tools, models and engineering concepts are practical, and builds the confidence needed for implementation, licensing and public acceptance.

3.108 There are several organisations in Japan involved in carrying out or sponsoring R&D aimed directly at supporting the nuclear waste disposal programme. These R&D organizations include, amongst others the Japan Atomic Energy Agency (JAEA), RWMC, the Central Research Institute of Electric Power Industry (CRIEPI), National Institute of Advanced Industrial Science and Technology (AIST), National Institute of Radiological Sciences (NIRS), and NUMO itself. The sponsoring organisations include the Agency for Natural Resources and Energy (ANRE) of METI and the Ministry of Education, Culture, Sports, Science and Technology (MEXT).

3.109 Co-ordination of this research infrastructure is provided through a Geological Disposal R&D Co-ordination Council, which was established in July 2005 under supervision of ANRE and involves NUMO and the other R&D providers. This co-ordination resulted in production, by March 2007, of a framework for database integration and 'roadmap' for research into the implementation of geological disposal that is being followed today. This co-ordination is regarded as an essential feature of the R&D programmes, and has been put in place to optimise the research efforts and strategies in Japan. JAEA is the main technical support organisation which has been promoting R&D activities such as two URLs, and development of an advanced Knowledge Management System.

Sweden

3.110 Figure 2 shows how geological disposal work is co-ordinated in Sweden. Disposal of wastes is the responsibility of the nuclear power utilities and a fee, supporting the Swedish Nuclear Waste Fund (SNWF), is levied by Government on each power generating company. The nuclear power utilities have formed a jointly owned company, SKB, the Swedish nuclear fuel and waste management company[12] which is responsible for management, storage and geological disposal of Swedish nuclear and radioactive waste. The SNWF is used to fund SKB, but is also open to bids from other agencies such as Authorities, Municipalities and Non Governmental Organisations (NGOs). Investigations toward deep geological disposal in Sweden have been ongoing for almost 30 years and are at an advanced stage. Site investigations focused on two prospective sites in fractured hard rock: Forsmark (municipality of Östhammar) and Laxemar (municipality of Oskarshamn), both of which were volunteer communities. SKB selected Forsmark as the site in May 2009. Spent fuel intended for the geological facility is held at an SKB interim storage facility in Oskarshamn.

Figure 2. Co-ordination of Geological Disposal Issues in Sweden

[12] http://www.skb.se

3.111 Fundamental and applied research in support of geological disposal is principally conducted within SKB; a small amount of additional independent R&D is conducted *via* the Swedish Radiation Safety Authority (SSM)[13], university PhD students and outside consultants. Every 3 years, SKB submits a research, development and demonstration programme (the FUD programme) to SSM which describes SKB's planned scientific and sociological research. The programme is reviewed by SSM, the National Council for Nuclear Waste (the Swedish equivalent to CoRWM) and independent overseas experts. It is also posted on the web for public consultation. SSM takes all the comments made into account before making a recommendation to Government about the programme. The Council's review of the 2007 SKB programme is available.[14] The Swedish NGO Office for Nuclear Waste Review (MKG) has formally requested the Government to scrutinise carefully SKB's proposed FUD-07 programme on the grounds that new research on copper corrosion calls into question aspects of the KBS-3 concept (MKG 2008).

3.112 Much of the R&D into final storage of spent nuclear fuel has taken place underground in the Äspö Hard Rock Laboratory, north of Oskarshamn. The Äspö research facility has been the focus of much fundamental geosphere research activity as well as supporting the development and testing of technological disposal solutions. Experiments are carried out at a depth of about 500 metres in collaboration with Swedish and international experts; Äspö has played a central role in a large number of EU nuclear-related research programmes.

3.113 Results of Swedish R&D are published in a series of reports, all of which are independently peer reviewed, often by international experts including some from the UK, freely available and downloadable from SKB's website. Some research is also published in academic journals.

Finland

3.114 In 1994, the Nuclear Energy Act came into force in Finland, according to which all nuclear waste must be treated, stored and disposed of in Finland. Detailed site investigations began at four sites in 1993, resulting in the recommendation and selection of a single site, in the bedrock of Eurajoki's Olkiluoto island, in December 2000.

3.115 Since 1994, research, development and planning work for geological disposal in Finland has been carried out by Posiva Oy, a company jointly formed by the nuclear power companies Teollisuuden Voima Oy (TVO) and Imatran Voima Oy (IVO). R&D is principally supported by the excavation of the underground rock characterisation facility, ONKALO, as part of the site investigations carried out in Olkiluoto. At depth investigations in the Olkiluoto rock characterisation facility are underway. The R&D programme reports in 3-year periods and is reviewed by the regulator (STUK).

3.116 Finland also has a Public Sector Research Programme aimed at supporting the regulatory activities and maintaining expertise in national research institutes;

[13] The Swedish Radiation Safety Authority (SSM) was formed in July 2008 by merging the Swedish Radiation Protection Institute (SSI) and the Swedish Nuclear Power Inspectorate (SKI).
[14] *http://www.karnavfallsradet.se/Uploads/Files/337.pdf*

funded at €1.5m per annum collected from licence holders. Several national research institutes participate in the programme which is focused on disposal of spent nuclear fuel.

Canada

3.117 Canada has been investigating geological disposal since the 1970s. Until 2002, Atomic Energy of Canada Ltd (AECL) was responsible for the programme, which focused on the rocks of the Canadian shield. Much of the research was undertaken at Whiteshell Laboratories, near Winnipeg. A URL was built in the 1980s at a site that would not be used for a GDF. There was an extensive review of policy for the long-term management of highly active wastes in the late 1990s, which concluded that the technical feasibility of geological disposal had been demonstrated but its public acceptability had not.

3.118 Canada's Nuclear Waste Management Organization (NWMO) was established in 2002 to investigate approaches for managing Canada's spent nuclear fuel. NWMO made recommendations to Government in 2005. In June 2007, the Canadian Government selected Adaptive Phased Management (APM) as the approach for long-term management of spent fuel, which has at its end-point, geological disposal. NWMO is currently consulting on a siting process that is based on communities volunteering to host a GDF. The geological disposal project will involve the creation of a "centre of expertise" for technical, environmental and community studies related to the design and operation of GDFs. This centre will "become the hub for national and international scientific collaboration for many decades".[15]

3.119 NWMO's technical R&D programme is currently focused on developing and evaluating conceptual designs for a deep geological repository, improving the readiness for site evaluations, used fuel transportation, and preliminary safety assessments of potential candidate host sites for long-term management of spent fuel.

3.120 To ensure independent review of Canadian R&D for APM, the Independent Technical Review Group (ITRG) has been established. ITRG annually assesses the appropriateness of NWMO's scientific and technical approaches and methodologies, and compares them with international best practice. The group is also required to assess the resources NWMO has to address technical issues which may arise during the siting process. Current ITRG members are from Canada, Sweden, Switzerland and the UK and members are either academics or have significant experience in international work on radioactive waste disposal.

3.121 In early 2009, NWMO became responsible for the development and construction of the GDF for ILW and LLW that is to be established beneath the Bruce nuclear power station. Another recent development is that AECL is constructing a new dry storage facility for legacy wastes and spent fuels at its Chalk River site, to be used until a GDF is available.[16]

[15] *http://www.nwmo.ca/*
[16] *http://www.aecl.ca/Development/SD-WMD/FPSP.htm*

France

3.122 There are six major groups that contribute to nuclear R&D in France. These are the utilities, Electricité de France (EDF), Areva and GdF-Suez; the Atomic Energy Commission (CEA); the national waste management organisation (ANDRA); the National Research Agency (CNRS); the regulatory body, the Nuclear Safety Authority (ASN); the Government *via* its Ministry for Economy and Industry; and Parliament, through its commissioning of the National Evaluation Commission (CNE) to provide independent assessment of R&D.

3.123 France has investigated the geological disposal of higher activity radioactive waste since the 1970s. Throughout the 1970s and 1980s, disposal R&D was carried out by ANDRA, which was then a division of the CEA. There was a major step-change in organisation and co-ordination in 1991 when Law 91-1381 was passed. This specified that there was to be R&D on three major topics:

- partitioning and transmutation (P&T)
- waste packaging and the effects of long-term surface storage
- geological disposal.

3.124 The geological disposal programme was to include the development of at least two URLs in different types of rock. The law made ANDRA a public service company, separate from the CEA. ANDRA was given responsibility for co-ordination of R&D related to interim storage and geological disposal. CEA was given responsibility for co-ordination of R&D into P&T, mostly performed by the CEA and CNRS (Niel, 1996). The law stipulated that by 2006 the government had to submit to Parliament an overall assessment of the research concerning high level, long-lived waste, with a draft law authorising, if appropriate, the creation of a disposal facility for these wastes.

3.125 The 1991 law also established the CNE to monitor the R&D work carried out by, or on behalf of, ANDRA and CEA, and report to parliament on progress. The annual reports produced by the CNE on ANDRA and CEA activities are reviewed by the Parliamentary Office on the Assessment of Scientific and Technological Options (OPECST). In 2006, OPECST produced a report on the state of radioactive waste management in France, following a major review of ANDRA and CEA progress by the CNE in 2005. On the basis of this review and report, in June 2006 a parliamentary Act was passed in which phased deep geological disposal was selected as the preferred option for HLW, at a site to be selected by 2015, following conditioning and interim surface storage. This Act also required that R&D would continue in the URL in the claystone / mudrocks at Bure, in north-eastern France, and that any facility should incorporate 'reversibility' at every stage.

3.126 Recent and on-going R&D programmes in France continue to be divided into three thematic areas consistent with the 1991 Law and 2006 Act (CNE, 2006; Flocard, 2006). CEA deals with P&T, packaging and interim storage. ANDRA deals with geological disposal and longer term storage (including underground storage).

3.127 The radioactive waste management research being conducted by ANDRA principally takes the form of joint programmes at a national, European or international level (Landais, 2008). ANDRA is strongly involved in FP6 and FP7 European research initiatives, and acts as both a contributor (*e.g.* FORGE) and co-ordinator in these. It also acts as the co-ordinating body for French contributions to wider international programmes, such as the 'development of coupled THCM models and their validation against experiments' (DECOVALEX). At national level, the public sector research partners are the government-funded CNRS (National Centre for Scientific Research), which supports a number of national centres and institutes in various technical areas, and the universities, which have co-ordinated their actions in this area through the PACE programme (*Programme sur l'aval du cycle électronucléaire*) organised around research consortia on important research themes. Organisations from within the nuclear industry (*e.g.* EDF, Areva), and also the CEA, participate in many of the research consortia. Some examples of recent consortia include:

Forpro (*FORmation géologique PROfonde*) [Deep Geological Formation], which covers research into and within underground laboratories and involves ANDRA and CEA;
Gedeon (*GEstion des DEchets par des Options Nouvelles*) [Waste Management through New Options], which has focused on sub-critical accelerator driven systems and thorium-based fuel, and has involved CEA, CNRS, EDF and Areva;
Nomade (*NOuvelles MAtrices DEchets*) [New Waste Matrices], which is focused on the study of new conditioning matrices, and involves CEA and CNRS;
MoMaS (*MOdélisation MAthématique et Simulations numériques*) [Mathematical Modeling and Digital Simulations], which aims to develop advanced models to simulate radioactive waste management problems and involves CEA, CNRS, ANDRA, BRGM, and EDF;
Practis (*Physico-chimie de Radioéléments, des ACTinides, aux Interfaces et en Solutions*) [Physical-chemistry of Radioelements, Actinides, Interfaces and Solutions], which involves CEA, CNRS, EDF and ANDRA.

3.128 The CNRS maintains research institutes, for example the National Institute for Earth Sciences and Astronomy (INSU) and the Institute National de Physique Nucléaire et de Physique des Particules (IN2P3), which contribute to R&D programmes on radioactive waste or are likely to in the future. The current CNRS interdisciplinary theme, 'Energy', appears to be geared, to some extent, towards facilitating R&D in radioactive waste disposal through co-operative programmes linked into the ANDRA and CEA research themes.

3.129 The CNRS follow-on programme after PACE covering 2006-2011 is PACEN (*Programme pour l'Aval du Cycle Electro-Nucleaire*). The theme areas in PACEN cover the following subjects.

- Transmutation, which is largely related to energy development.
- Partitioning, including both pyrochemical and hydrometallurgical technologies.
- Geological characterisation *via* ongoing research under Forpro and PARIS. The latter research consortium is focused on deep drilling of the Paris Basin

and in concert with Forpro is designed to advance understanding of water and gas reactions, monitoring, underground chemistry, and the importance of interactions and feedbacks on scales from microns to metres. The MoMaS consortium continues to 2011 to develop modelling simulations that incorporate multiphase flows and coupled behaviour, quantification of uncertainties and establishment of benchmark models and modelling tools.

- Near-field issues including waste matrices, container-clay interactions and interfaces.

3.130 R&D in nuclear safety, transport and security is co-ordinated separately from that relating to radioactive waste disposal. A combined independent agency, known as the '*Institut de Radioprotection et de Sûreté Nucléaire*' (IRSN), was established in 2002 with the role of advising and briefing the regulators on issues relating to radiological risk and nuclear safety. IRSN was given responsibility for research in:

- nuclear safety
- safe transport of radioactive materials
- health and environment radiation protection
- physical protection and control of nuclear materials
- protection of nuclear facilities and nuclear materials transport against possible attacks or sabotage.

3.131 IRSN has also been placed in charge of preparing reviews of ANDRA documentation (*e.g.* the Dossier Argile, 2005) for the French regulator, ASN.

Role of International Organisations

3.132 The three international organisations that have a role in helping countries to define and co-ordinate their R&D programmes on radioactive waste management are the EU, the NEA of OECD and the IAEA. These organisations are discussed in turn below.

3.133 While the financial contribution from the EU (paras. 3.69-3.73) is useful, much of the value of EU research projects is in bringing participants together to exchange ideas and information. This helps EU member countries to make the best use of their resources, for example by each concentrating its R&D on a particular aspect of a common problem and then pooling their results.

3.134 The NEA's general objective in its radioactive waste management work is to contribute to the adoption of safe and efficient policies and practices in its member countries. It focuses on geological disposal of HLW and spent fuel. Its work is supervised by its Radioactive Waste Management Committee (RWMC), which is assisted by three working parties:[17]

- Forum on Stakeholder Confidence
- Integration Group for the Safety Case (IGSC)
- Working Party on Management of Materials from Decommissioning and Dismantling.

[17] *http://www.nea.fr/html/rwm/*

3.135 RWMC and its working parties provide the overall forum for exchange of information, which is achieved through meetings and the production of reports. Detailed technical work is carried out by means of working groups, topical sessions, workshops, symposia and technical reviews. NEA also organises international peer reviews of national studies and projects. For example, it organised a peer review of the Dossier Argile 2005 (para. 3.131) by a team of independent specialists from various countries. The review covered research and safety assessment. Two of the aims of the review were to determine whether the future research needs identified in the Dossier were consistent with the existing knowledge base and whether the stated research priorities were appropriate.

3.136 RWMC is currently carrying out a project on reversibility and retrievability in geological disposal. Current IGSC activities include:

- a working group on the characterisation, understanding and performance of argillaceous rocks for geological disposal (the "Clay Club")
- a project on approaches and methods for integrating geological information in GDF safety cases
- a project on sorption of radionuclides on geological media
- a project on engineered barrier systems
- maintaining a database of features, events and processes (FEPs) that need to be considered in GDF post-closure safety cases
- a thermodynamic database project.

3.137 IAEA's work on radioactive waste management is carried out by its Department of Nuclear Safety and Security. It includes establishing safety standards, producing guidance on the application of safety standards and sending teams of experts to developing countries to assist them in policy, regulatory and practical aspects of waste management.

3.138 IAEA also organises Co-ordinated Research Projects (CRPs) that are designed to encourage the acquisition and dissemination of new knowledge.[18] CRPs involve developed countries, which pay for their own research and participation, and developing countries, which are funded by IAEA. The results of CRPs are published by IAEA. A CRP on the use of numerical models in support of site characterisation and performance assessment studies for GDFs has been running since 2005 and is due to end in 2010.

3.139 In addition, IAEA runs knowledge transfer networks. There is a "Network of Centres of Excellence" in training and demonstration of radioactive waste underground research facilities, the "URF Network".[19] This has been running since 2001. Its "members" are countries that have URFs and associated laboratories that they offer for training, demonstration and research activities by "participants", that is countries that do not have such facilities. The URF Network has 9 members and 21 participants. The UK is a member and the Geoenvironmental Research Centre, Cardiff University, is its centre of excellence. The objectives of the URF Network are to:

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[18] *http://www-crp.iaea.org/*
[19] *http://www.iaea.org/OurWork/ST/NE/NEFW/wts_URF_homepage.html*

- encourage the transfer and preservation of knowledge and technologies
- work on solutions for countries that at present do not have URFs
- supplement national efforts and promote public confidence in radioactive waste disposal schemes
- contribute to the resolution of key technical issues.

Conclusions on UK R&D Programme

3.140 Many organisations in the UK are involved in funding and carrying out R&D relevant to the management of higher activity wastes. These include NDA and its SLCs, other nuclear industry organisations (civil and defence), the NNL, the regulators, the Research Councils, universities, and consultants and contractors. CoRWM's conclusions on UK R&D programmes relate mainly to co-ordination within and between these organisations.

NDA and Other Nuclear Industry Organisations

3.141 NDA has made a good start in some respects. The TBuRD system is designed to ensure SLCs identify R&D requirements and the NWRF aims to ensure R&D needs are discussed between SLCs, British Energy and regulators at a technical level. RWMD has developed its R&D Strategy for geological disposal and will produce a more detailed document setting out its forward programme of R&D. CoRWM understands that RWMD is in the process of setting up an advisory panel to assist it in developing its programme. NDA also funds R&D relevant to its mission directly, for example, through its DRP.

3.142 However, there seems to be little strategic co-ordination of SLC, RWMD and DRP R&D within NDA. In particular, it is not clear how RWMD R&D on geological disposal will be co-ordinated with the R&D by NDA and its SLCs on waste conditioning, packaging and storage, or on the management of spent fuels, plutonium and uranium. NDA seems to see R&D only as an adjunct to its strategy work, not something to which it should also have a strategic approach.

3.143 Various groups set up by NDA, for example the NWRF, involve other nuclear industry organisations and the regulators. As far as CoRWM has been able to determine, these groups are useful for identifying gaps and overlaps in R&D. However, they are not set up to provide strategic co-ordination of R&D nor to agree nuclear industry R&D priorities at a national level. As a result, they cannot ensure that key issues are addressed in a timely way or that the best use is made of resources.

Regulators

3.144 HSE has a responsibility to ensure that appropriate nuclear safety research programmes are carried out and that the results are disseminated. This includes nuclear safety research related to the management of higher activity wastes. HSE publishes a Nuclear Safety Research Strategy that covers both research that it will commission and research that it expects nuclear site licensees to undertake. The mechanism for deriving national nuclear safety research requirements is well-established and has input from an independent expert group. HSE can recover the costs of its own research from licensees.

3.145 EA and SEPA commission research in support of their regulatory roles and influence nuclear industry organisations to carry out research on the management of radioactive wastes. They recover some of their costs from the industry. The EA research budget is small compared to the expenditure of the corresponding regulator in the 1980s and 1990s. In CoRWM's view, the EA will need to commission more research in the later stages of the MRWS programme to support it in its role as a regulator of geological disposal. CoRWM also thinks that, as Scottish Government policy is developed and implemented, SEPA will need to commission research related to its regulation of the management of higher activity wastes.

Research Councils

3.146 The UK has seven Research Councils. Five of these are relevant to R&D on the management of higher activity wastes. These Research Councils support research in their own institutes and provide research grants to universities. They are the main funders of fundamental research, while the nuclear industry focuses on applied research and on development.

3.147 At present there is no process for identifying where fundamental research is needed to underpin and complement applied research on the management of higher activity wastes. Only the EPSRC has a clear mechanism for obtaining input from the nuclear industry to its programmes. This mechanism is not focused on fundamental research, nor does it involve contact between the prospective researchers, who should be providing the ideas, and the industry, who will use the results. CoRWM believes that, in general, there is an over-emphasis on applied research within the Research Councils, to the detriment of the MRWS programme.

3.148 CoRWM has found that there is insufficient co-ordination between the various Research Councils at a strategic level on radioactive waste-management-related issues. There is also insufficient co-ordination between the Research Councils, the nuclear industry and the regulators.

3.149 In addition, CoRWM has some concerns about specific Research Councils. These can be summarised as follows.

- EPSRC makes too little use of funding strategies other than managed calls; these calls are perceived to be heavily influenced by the nuclear industry.
- NERC has been slow to respond to the needs of the MRWS programme.
- BBSRC is not currently funding any research specific to radioactive waste management, unlike its counterparts in other countries.
- As far as CoRWM is aware, STFC is not taking any steps to ensure that independent research can be carried out in the active facilities operated by the NNL.

EU Research Funding

3.150 The UK does participate in EU Framework Programmes but to a lesser extent than in the past. Several EU colleagues have commented to CoRWM members about the limited participation of UK universities in Framework Programmes in comparison to other countries with similar sized nuclear industries. One reason for this may be that UK participants have difficulty in obtaining funding to match the EU contribution and to cover the full economic costs of participation.

3.151 In CoRWM's view, the UK should make increased efforts not only to participate in but also to influence Framework Programmes on R&D for the management of higher activity wastes. It is also important that effective use is made of knowledge gained in past Framework Programmes.

Learned Societies

3.152 There is good co-ordination emerging among the Learned Societies and good communication with their members on radioactive waste management issues, including geological disposal. As well-respected and independent institutions they should prove very useful in helping to inform a technical and wider public audience about the MRWS programme, as well as developing the skills base through their members. However, CoRWM does not believe the Learned Societies are in a position to provide strategic co-ordination of R&D.

Past UK Co-ordination of R&D

3.153 In the past, there were mechanisms for strategic co-ordination of UK waste management R&D. These were Government-led because at that time Government departments funded a considerable amount of R&D to support policy development. The co-ordination mechanisms ceased to exist in the 1990s, after Government departments had scaled back their R&D on HLW disposal. After the RCF decision in 1997, there was further scaling back by Nirex and by the regulators. Nuclear industry R&D increasingly focused on immediate needs, rather than long-term waste management issues and the Research Councils and academic communities reduced their programmes as Government and industry funding diminished.

3.154 CoRWM considered whether the co-ordination mechanisms used in the past could be applied today. It concluded that they could not. Although the number of key players now is similar to what it was, the players' roles and responsibilities are very different. In particular, Government neither directly funds nor leads R&D programmes. Further, past co-ordination mechanisms relied largely on discussions behind closed doors and standards of openness and transparency are much higher today.

Public and Stakeholder Engagement

3.155 There is little opportunity for stakeholders outside the R&D funding and providing organisations to influence UK R&D programmes on radioactive waste management. Most fora at which R&D requirements are discussed are closed and much R&D is regarded as "commercial" so the results are not published.

3.156 CoRWM believes that this situation must change if a wide range of stakeholders and the public are to have confidence that higher activity wastes will be managed safely in the long term. More stakeholders should be involved in establishing R&D requirements. Accessible information should be made available to the public about R&D needs, plans and progress.

International Experience

3.157 Countries such as Sweden and Finland have good mechanisms for co-ordinating R&D but the waste inventories they have to deal with are orders of magnitude smaller and simpler than in the UK, and their Government, regulatory and nuclear industry structures are less complex. The Swedish scheme of submission of the forward R&D programme to the regulators every 3 years, wide consultation, and subsequent recommendation to the Government by the regulator (SSM) is commendable. The French system with a national commission evaluating the R&D and producing annual reports that are reviewed by a parliamentary commission also has much merit. The USA has mechanisms for co-ordinating geological disposal research but does not appear to have good mechanisms for co-ordinating other radioactive waste management research. The workshops organised by DOE in the USA are very good for discussing R&D requirements. CoRWM believes that similar workshops should be held in the UK, with participants from the European Union and other countries.

4. R&D SKILLS TO SUPPORT THE MRWS PROGRAMME

4.1 In keeping with its terms of reference and as part of its scrutiny of the R&D undertaken, CoRWM is seeking to reassure itself that an appropriate skills base is, or will be, available to the UK to undertake R&D and that R&D is integrated into skills development activities as an essential component in developing high-level skills (Section 1). R&D skills to support the MRWS programme have to be viewed as part of a wider nuclear industry skills issue although some 'new' skills, particularly those associated with geological disposal, will be required. As with many existing skills, some of these new skills are available, and should be transferable, from non-nuclear areas such as the hydrocarbon and civil engineering industries. This section focuses on R&D skills relevant to MRWS but against the wider nuclear industry background.

4.2 R&D skills cannot be considered in isolation from the basic training of personnel and the two are considered in this report as integral components of the same issue. Although an attempt is made in this section to separate basic skills training from research training, the boundaries are inevitably diffuse.

4.3 Any attempt to review a continuously changing situation must inevitably date quite quickly. The information below has been updated to the end of summer 2009 as far as possible, except for those data lists where a partial update would destroy the comparative basis.

Skills Requirements

4.4 A wide range of skills will be required for the long-term management of higher activity wastes, spread across many disciplines. Among the more obvious in the contexts of interim storage and geological disposal are nuclear science (including nuclear physics and radiochemistry), the geosciences (including geochemistry, geophysics and hydrogeology), materials science and civil and mechanical engineering (including geotechnics and underground construction). Many specialised skills will be required for the different phases of implementation of geological disposal such as site characterisation, construction, operation and closure of the GDF and significant R&D will be required to remove, reduce, or quantify the underlying uncertainties so as to produce a satisfactory site-specific safety case.

4.5 While the emphasis in this section is on the skills required for R&D, the wider skills and training issues are also considered and it is CoRWM's intention to deal more fully with the specialist skills required for site characterisation and other aspects of geological disposal in its future work programme. In discussing the skills issue across the range of disciplines, it is appropriate to focus on those aspects that are primarily nuclear related. However, there are many non-nuclear aspects of, for example, the geological, materials and engineering sciences, that are particularly relevant and these are dealt with in paragraph 4.35 *et seq.*.

Nuclear Skills – Current UK Situation

4.6 Since 2000, a succession of reports on nuclear skills and training (*e.g.* OECD/NEA, 2000; HSE-NII, 2002; NSG, 2002; Cogent, 2008) has identified a number of concerns including:

- a shortage of skilled manpower in the UK that could affect the defence, nuclear power and health sectors and have serious implications for the long-term management of radioactive wastes;
- a projected requirement for 15,000 to 19,000 trained personnel to be recruited to the nuclear sector by around 2017;
- a nuclear industry that has become heavily dependent on generic provision, *i.e.* recruitment of good quality graduates from non-nuclear specific degree courses;
- a fragile specialised post-graduate training sector in the nuclear area;
- a top priority of increasing vocational and technical skills, with a recommendation to quadruple the number of apprentices by 2013.

4.7 The most recent report, a more detailed analysis by Cogent (Cogent, 2009), forecasts a skills gap of up to 14,000 by 2025, which equates to a need for 1,000 new recruits a year, with the main drivers being:

- an ageing workforce that retires earlier than the UK workforce in general
- a shift in skills from electricity generation to decommissioning
- a demand for skills to operate a new batch of nuclear power stations.

4.8 It is clear from all of these reports that the situation had declined to the point of grave concern and, although this has been recognised and measures begun to address it, arrangements are not yet adequately rebuilt for the future. This is especially the case for the decommissioning and radioactive waste management programmes and there will be competition between these areas and the expected new build programme.

Nuclear Skills - Training

4.9 Many bodies and organisations are involved in the provision of nuclear skills in the UK and the relationships between them are complex (Figure 3).

4.10 The current approach to training is based on a "skills pyramid" (Figure 4) in which the sizes of the sections approximate to the relative numbers required. In keeping with the main conclusions of a Cogent report (Cogent, 2008), most of the initial efforts were concentrated on the lower part of the skills pyramid. This emphasised the skills needed at these levels and demanded by employers but, with this being addressed, attention is now turning also to the upper areas of the pyramid.

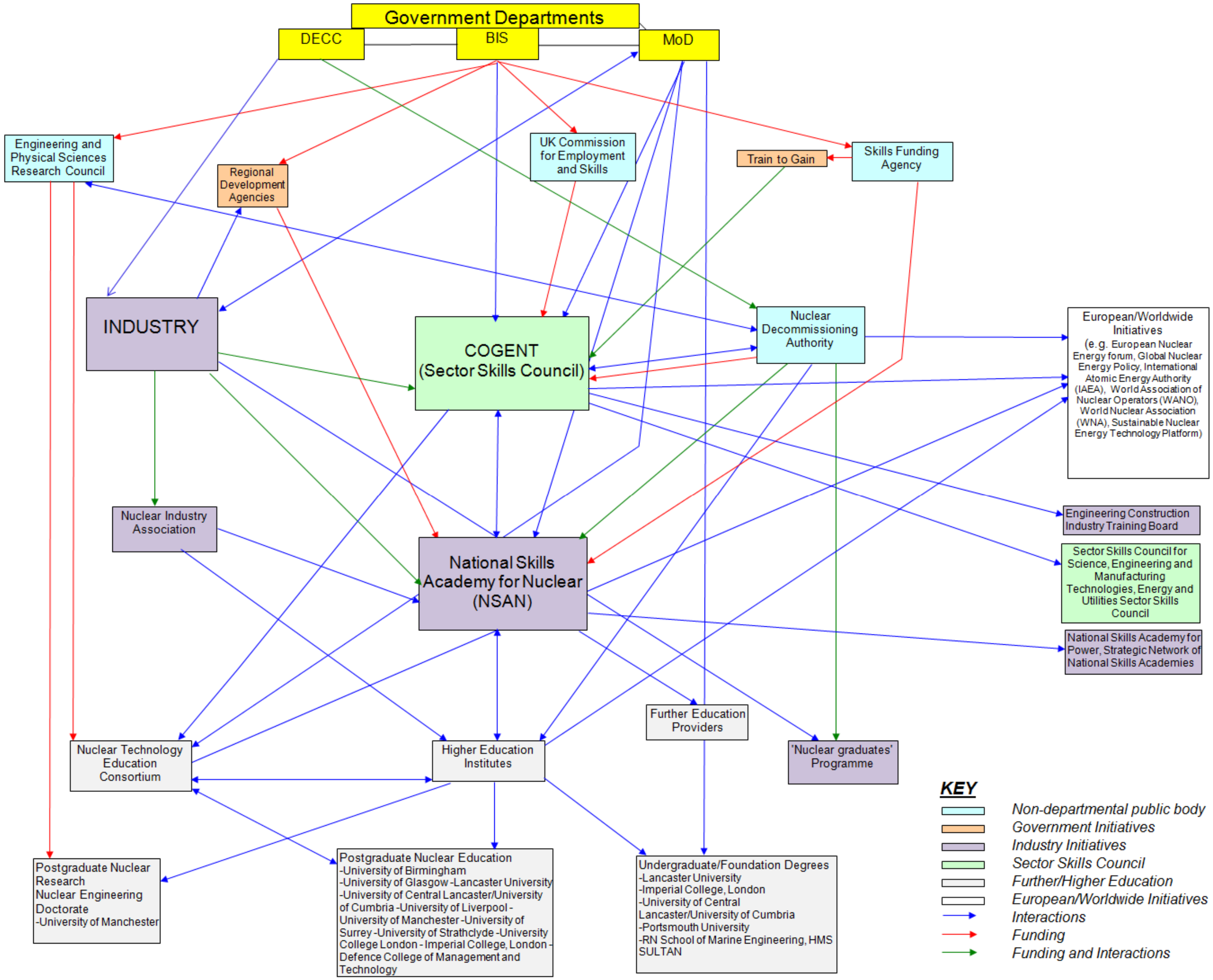


Figure 3. UK Nuclear Skills Map
Source: DECC

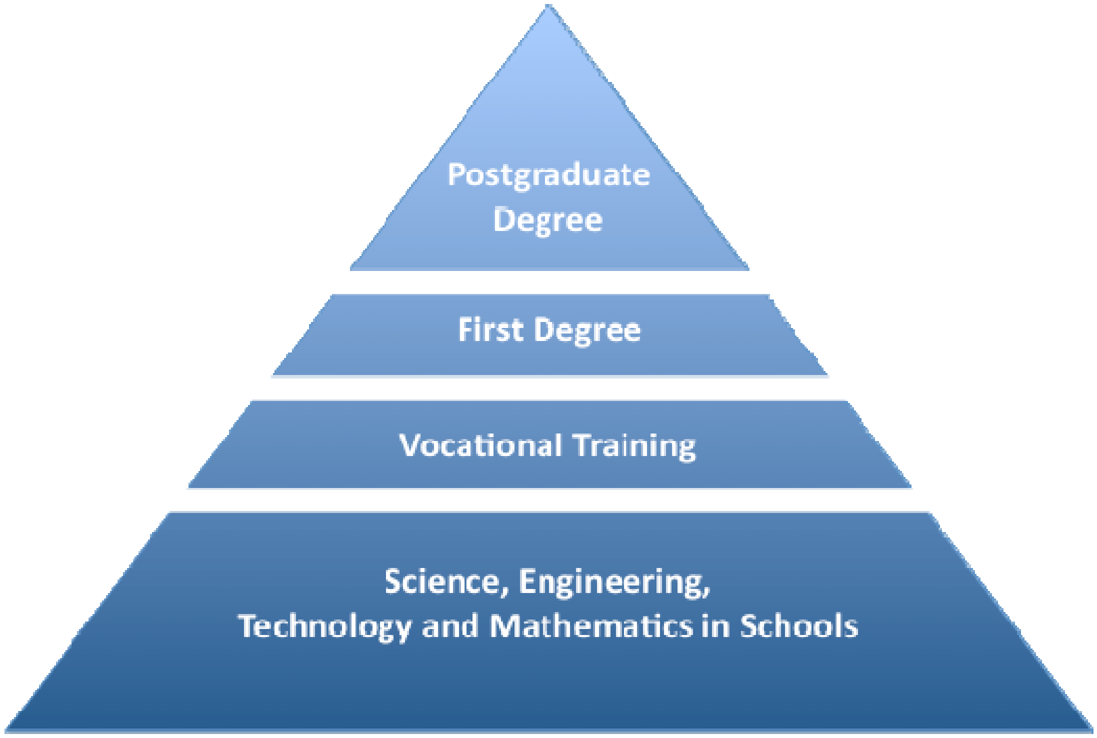


Figure 4. Skills Pyramid

4.11 The principal 'players' in the provision of nuclear skills in the UK are the Cogent Sector Skills Council, the National Skills Academy for Nuclear (NSAN), NDA, NNL and the universities. However, the significant contribution made by the industry through 'on the job' training (*e.g.* the Nuclear Power Academy run by British Energy at Barnwood) should not be underestimated. It is encouraging that all of these bodies are now taking steps to redress the situation. The roles and contributions of some of the key providers are outlined below. Training in the specialised skills required for R&D is at the top of the pyramid and the current situation is described in paragraph 4.21 *et seq.*.

Cogent

4.12 The Cogent Sector Skills Council has recently been relicensed by Government, through the UK Commission on Employment and Skills, to take an overview of a wide range of science-based industries. It is an employer-led organisation that produces education and training standards and qualifications for industries such as oil and gas, petrochemical and nuclear. For the nuclear industry, it works to deliver these through NSAN. Cogent is required to conduct Labour Market Intelligence (LMI) research across its industrial remit and is currently undertaking this for the civil and defence nuclear programmes, including waste management and new build (Cogent, 2009).

National Skills Academy for Nuclear

4.13 NSAN began operating in January 2008 as a wholly owned subsidiary of Cogent and is led and directed by its nuclear industry employer boards. Its remit is to address the key skills and training challenges facing the nuclear industry and ensure the availability of a skilled workforce to meet future demands. These include defence and new build in addition to decommissioning and the MRWS programme.

4.14 NSAN is not a direct provider of training. It is an enabling organisation which sets up and funds training schemes and initiatives through partnerships with training providers (schools, universities and employer organisations). It is funded half by employers and half by BIS but after its first three years it is expected to be self-sustaining. It is still developing its work programme and training infrastructure. Its current approach is mainly focused on the lower levels of the skills pyramid (Figure 4), particularly vocational training and foundation degrees but it is now also turning its attention to higher level skills. For example, it is currently developing a post-graduate Certificate of Nuclear Professionalism. NSAN is also trying to encourage mobility within the industry with initiatives like its Nuclear Skills Passport, a basic skills qualification that would be accepted by all employers. HSE has stated that NSAN is "a lynchpin in providing the nuclear industry with a sustainable approach to meeting the nuclear skills shortage" (HSE, 2009c).

4.15 NSAN is a small, flexible organisation that can respond quickly to identified needs but its remit requires it to focus on employer requirements. Many employers, such as SLCs, have Lifetime Plans that run well into the next century but questions of prioritisation necessitate concentration of limited resources on short-term issues. For NSAN to focus exclusively on employer requirements, therefore, runs the risk of skills needs not becoming evident in a timely manner owing to the relatively short time horizon of most employers (CoRWM doc. 2444). For example, developing the skills related to geological disposal, which require long lead times, may not yet be 'on the radar' of many nuclear industry employers. Exercises, such as Cogent's LMI, which looks ahead to 2025 will help but, since this too is led by employer-identified needs, it is by no means certain to do so.

Nuclear Decommissioning Authority

4.16 The NDA's "Skills and Capability Strategy" (NDA, 2008d) reports progress on its initiatives in this area since 2005. Its approach to skills and training covers all four levels of the skills pyramid, namely, the science, engineering, mathematics and technical curriculum in schools; vocational training; first degrees and higher degrees. The latter are more appropriate to skills for research and are covered in paragraph 4.21 *et seq.*.

4.17 At the schools level, NDA supports the Energy Foresight programme, led by NSAN, which aims to improve understanding of nuclear power and nuclear technology. NDA provides instructional and other material in support of the national curriculum to over 400 schools. Vocational training initiatives are supported through NVQs in nuclear technology and decommissioning, and the funding of apprenticeships, both within NDA and its supply chain. Around 100 apprentices a year are recruited, mainly within NDA and its SLCs (CoRWM doc. 2373). The Energus facility in Cumbria opened in June 2009. It is funded by NDA, NSAN and industry employers among others and will train up to 150 apprentices, mainly in support of the operational skills requirements for Sellafield. It also hosts higher education students in nuclear-related subjects through a link with the University of Cumbria. The supply chain tends to find recruitment of apprentices more difficult, largely because of the short-term nature of most of its contracts.

4.18 At the next level of the pyramid, there is support for foundation degrees offering a mix of academic learning and on-the-job training. Working through its SLCs and the supply chain, NDA attempts to identify the skills that will be required and looks to NSAN as a key enabler of these up to the foundation degree level. For training and skills beyond the foundation degree, NDA sponsors first degrees at various universities.

Universities

4.19 The UK situation with regard to the provision of nuclear skills through first degrees has improved only marginally since the HSE-NII report (HSE-NII 2002). Two universities (Imperial College and Lancaster) now offer a total of four courses with significant nuclear content leading to an MEng degree. Details of university provision are given in Box 3.

Box 3. Nuclear-related Undergraduate Courses

Any attempt to outline the provision of courses (and research activities) in higher education can only be a snapshot at the time of writing. The data on first degree courses given below (and on higher degree courses in Box 4) are based largely on information in the Cogent gap analysis ("A gap analysis for the nuclear industry. An investigation into gaps in provision based on current and predicted future skill needs" - www.cogent-ssc.com), on the Nuclear Liaison website (www.nuclearliaison.com) and from a presentation to a Geological Society of London meeting by JW Roberts of the University of Sheffield's Immobilisation Science Laboratory ("The storage and disposal of radioactive waste", Geological Society of London, 21 May 2008).

For almost 20 years prior to 2006, there were no first degree courses in nuclear engineering or waste management in the UK but there are now two institutions offering nuclear degrees, namely:

- Imperial College, London
  - MEng in Mechanical and Nuclear Engineering
  - MEng in Chemical and Nuclear Engineering
  - MEng in Materials and Nuclear Engineering
- Lancaster University
- MEng in Nuclear Engineering.

In addition to these, the University of Central Lancashire (John Tyndall Institute for Nuclear Research) runs a variety of nuclear-related Foundation Degrees as part of the NSAN portfolio.

4.20 Against this, much of the nuclear industry currently does not seek to recruit specifically nuclear-trained graduates, opting instead for good quality graduates in the physical and engineering sciences. This appears to be a preference, rather than an enforced situation, although we understand that AWE is currently trying to increase its recruitment of nuclear-trained graduates. In recent years, the annual recruitment to the industry has been around 500 science, engineering and technology graduates but this is likely to rise as decommissioning and new build proceed. Industry is keen to strengthen links with universities on skills development but notes that the timescales for achieving this are 5-10 years, which is longer than the competition-based contract arrangements that tend to be used for many projects.

Nuclear Skills – Higher Level Skills for R&D

4.21 Figure 5 illustrates the decline in numbers employed in UK nuclear fission-related R&D from nearly 9,000 in 1980 to around 1,000 in 2004. Over the last 5 years, the number has remained at about this level, of which, around 750 are employed by the NNL. The closure of many R&D facilities and the associated decline in personnel has left the UK's capability for nuclear R&D significantly depleted.

4.22 The principal organisations providing training in the nuclear-related research skills needed for the R&D to underpin the MRWS programme are the universities, NDA (and some of its SLCs) and NNL. Other nuclear industry organisations and the industry's supply chain also provide training, but the latter often have difficulties planning and supporting high-level training over 3 years or more owing to the short-term nature of their contracts. Although not providers of training, Cogent and NSAN are working to develop "products" to help to sustain this important resource and NSAN has recently announced a round of bursaries to support training all the way up the pyramid. There is clear evidence that the situation is improving gradually but there is still some way to go.

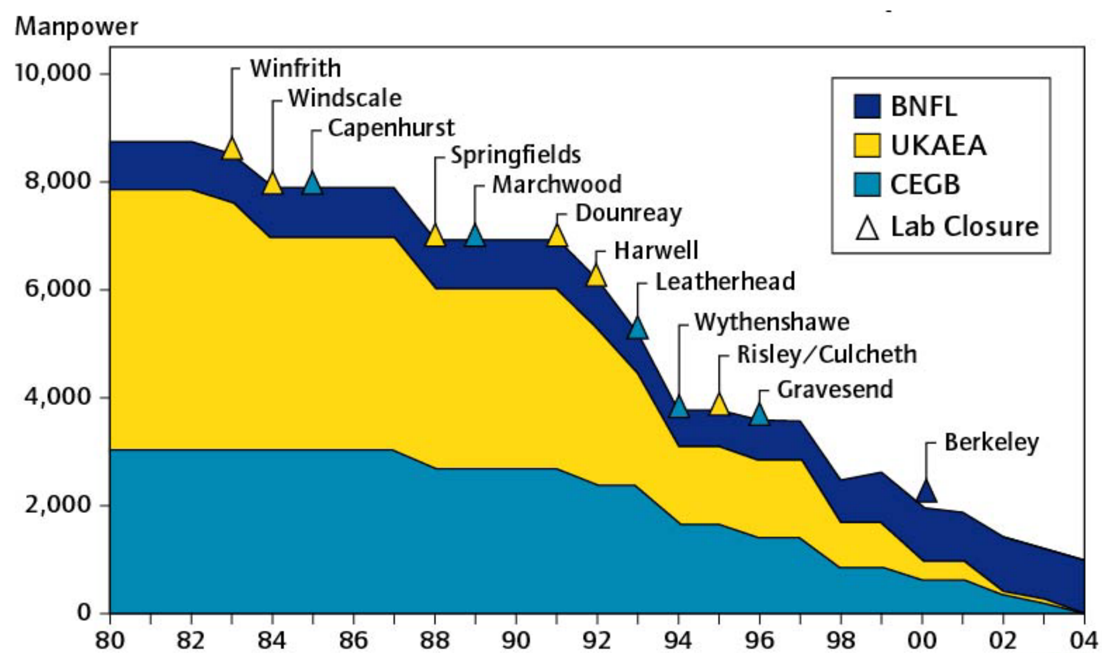


Figure 5. Illustrative decline in manpower employed in nuclear fission related R&D
Source: NNL

Universities

4.23 Research skills appropriate to nuclear R&D activities are provided in the higher education sector over a range of levels and disciplines. Starting with taught Master degrees, most of which involve research projects, these opportunities advance through research-based Master degrees to Doctorates (PhDs) and post-doctoral research.

4.24 There are fourteen taught Master courses in the nuclear-related technical and scientific disciplines currently available in the UK. These are listed in Box 4. Decommissioning and clean-up are reasonably well represented but there are few of direct relevance to interim storage or geological disposal. The principal exceptions are the MSc degree offered by the NTEC consortium and the MSc in Nuclear Environmental Science and Technology offered by the University of Sheffield (Box 4).

4.25 A range of PhD research training is available in universities, with PhD provision particularly relevant to the MRWS programme concentrated in: the University Research Alliances (URAs); the nuclear research consortia; and a number of other smaller university research groups undertaking research and providing training in nuclear-related areas (see Box 4).

4.26 The four BNFL URAs were established in 1999-2001 as a response to the decline in the UK research skills base as described in Box 4. Following their initial 5 years of funding from BNFL these have become largely self-sustaining (with partial funding from NDA) and have proved very effective sources of skilled people. They have produced over 100 PhDs and trained more than 80 post-doctoral research associates (PDRAs) and, although not all are in the nuclear area (a consequence of the need for self-funding), many are now employed in the nuclear industry.

4.27 The Research Councils, principally EPSRC, have funded a small number of large research and training consortia (Box 4), among the functions of which is to provide PhD training in areas pertinent to their research brief.

4.28 There are at least a dozen other university groups providing research training in relevant areas spread across eight English and Welsh universities. Details of the URAs, nuclear research and training consortia and other nuclear-related research groups are given in Box 4. Scrutiny of the published details of research activities in the URAs, groups and consortia reveals that, while many relate to waste conditioning and other pre-disposal aspects of waste management, very few are orientated towards geological disposal.

NDA High Level Skills Training for R&D

4.29 Although the NDA's Skills and Capability Strategy is focused mainly on the lower parts of the skills pyramid, NDA does sponsor PhD studentships in universities, through its PhD Bursaries Scheme, recently incorporated into its DRP, which typically supports 5 students per year, and through SLCs *via* CASE (Co-operative Awards in Science and Engineering) studentships. There is, however, concern in some quarters (CoRWM doc. 2630) that the DRP is not conducive to graduate-level skills development, which is best achieved through PhD research training in universities. Typical DRP projects are on a much shorter timescale than a PhD project, which can require a commitment of up to 4 years.

Box 4. Postgraduate University Provision

There are several nuclear-related post-graduate taught courses in UK universities, of which, those in italics below are most likely to be potentially relevant to the decommissioning, clean up and waste management programmes.

- University of Birmingham
  - MSc in Physics and Technology of Nuclear Reactors
  - *Certificate & Diploma in Radioactive Waste Management & Decommissioning*
- Imperial College
  - MEng in Chemical and Nuclear Engineering
  - *MEng in Materials and Nuclear Engineering*
  - MEng in Mechanical and Nuclear Engineering
- Lancaster University
  - MEng in Nuclear Engineering
  - *MSc in Decommissioning & Clean-Up*
  - MSc in Safety Engineering
- University of Central Lancashire
  - *MSc, Diploma, Certificate in Energy and Environmental Engineering (Nuclear Decommissioning)*
  - *Certificate in English for Nuclear Decommissioning*
- University of Liverpool
  - MSc in Radiometrics: Instrumentation & Modelling
  - *Certificate in Radioactive Waste Monitoring & Decommissioning*
- University of Sheffield
  - *MSc in Nuclear Environmental Science & Technology*
  - *MSc in Nuclear Science and Technology*
- University of Surrey
  - MSc in Radiation & Environmental Protection
  - MSc in Radiation Detection & Measurement

The Nuclear Technology Education Consortium (NTEC), collaboration between 11 universities and research institutes, offers programmes leading to MSc, Diploma, Certificate or Continuing Professional Development (CPD) qualifications. The MSc combines the best elements from each of the institutions by allowing selection of 8 modules from a total of 31 available across the partnership, combined with a project. Four of the core modules relate specifically to decommissioning and the management, processing, storage and disposal of wastes.

Undoubtedly the major sources of high-level research skills from the university sector are PhD graduates and post-doctoral research assistants/fellows. Increasing numbers of these are becoming available across a wide range of scientific and engineering disciplines and among the most appropriate for the R&D needed to underpin the MRWS programme will be those from the nuclear-related University Research Alliances (URAs), research & training consortia and specialised research groups described below.

A drop in public funding of nuclear R&D from over £450M in the 1970s to less than £10M in the mid-1990s combined with a rapid decline in the UK skills base created grave concerns about the future of nuclear-related research. In response to this, BNFL established four URAs with initial core funding of £2M each. These were set up from 1999-2001 as follows, with staff (as of January 2009) in square brackets.

- Centre for Radiochemistry Research (CRR) – University of Manchester [4 academic staff]
- Institute for Particle Science & Engineering (IPSE) – University of Leeds [3 academic staff and a technology manager]
- Immobilisation Science Laboratory (ISL) – University of Sheffield [11 academic staff and a technical manager]
- Materials Performance Centre (MPC) – UMIST/University of Manchester [10 academic staff]

These have proved very effective in terms of the numbers of PhD students attracted and degrees awarded; post-doctoral research assistants (PDRAs) employed and trained; research projects undertaken and papers published (data in table below as of October 2008).

Box 4. (*continued*)

URA	PhDs	PDRAs	Papers
CRR	49	29	104
IPSE	14	17	78
ISL	11	13	75
MPC	35	24	60

Each of the URAs has generated several million pounds of research funding in addition to their initial core funding and they are clearly an invaluable component of the research and high-level skills bases. After their 5-year, start-up period, BNFL intended the URAs to be self-sufficient and all have achieved this. However, they have all had to diversify their funding sources and as a result, a substantial part of their activities are directed to areas other than storage and disposal. In some cases, their research portfolios now include significant non-nuclear activities.

There are a number of other university groups undertaking nuclear-related research and providing PhD training in areas relevant to the management of higher activity wastes. These are:

- <u>University of Birmingham</u>
  - Nuclear Power Technology Group, Department of Physics
  - Radiation Biophysics Group, Department of Physics
- <u>University of Cardiff</u>
  - Geotechnical Research Centre, School of Engineering
- <u>University of Cambridge</u>
  - Various groups, Department of Earth Sciences
- <u>Hull University</u>
  - Design, Materials & Process Performance, Department of Engineering
- <u>Imperial College</u>
  - Centre for Nuclear Engineering
- <u>Lancaster University</u>
  - Control & Instrumentation Research Group, Department of Engineering
- <u>Loughborough University</u>
  - Environmental Radiochemistry Research Group, Department of Chemistry
  - Radiation Damage Prediction Group, Department of Mathematics
- <u>University of Manchester</u>
  - School of Earth, Atmospheric and Environmental Science
  - School of Mechanical, Aeronautical and Civil Engineering
  - School of Chemistry.

A number of consortia have been funded by the research councils (notably EPSRC) to undertake research and provide doctoral-level research training in the nuclear area. These include:

- The Nuclear Engineering Doctorate (EngD) programme. This is a collaboration between six universities: Manchester, Imperial College, Sheffield, Leeds, Strathclyde and Bristol. It provides a 4-year PhD programme that includes taught modules and research projects on the management, immobilisation, storage and disposal of radioactive wastes.
- Keeping the Nuclear Option Open (KNOO - see Box 1) has been established to maintain and develop PhD level skills relevant to nuclear power generation.
- DIAMOND (Box 1) funded mainly by EPSRC, is a 4-year programme which also seeks to address a growing EU-wide skills gap in the decommissioning and waste field and offers PhD and post-doctoral training.
- The Biogeochemical Applications in Nuclear Decommissioning and Waste Disposal Consortium (Box 1), A 4-year programme involving 5 universities and BGS.

4.30 The NDA also operates a graduate recruitment scheme, which covers a wide range of disciplines and involves over 20 companies. The scheme currently attracts over 1,000 applicants a year, of which, about 10 are recruited annually (CoRWM doc. 2373). During the three-year scheme, the recruits receive two years of post-graduate training and are placed with SLCs and supply chain companies on a rotational basis to gain practical and industrial experience. This is an excellent scheme and, although relatively new, appears to be working well (CoRWM doc. 2373). There is, however, some concern that without any guarantee of, or commitment to, employment upon completion (as was the case with the first cohort recruited) these people could subsequently be lost to non-nuclear careers (CoRWM doc. 2630).

4.31 NDA is a partner with the University of Manchester in the Dalton Cumbria Facility. Although small (3 academic posts), this aims to undertake nuclear-related research and provide research training and post-graduate level education in radiation sciences and in decommissioning engineering.

The National Nuclear Laboratory

4.32 NNL has a specific responsibility to maintain the critical skills required to support civil nuclear R&D. Arising from a skills review in which 72 essential areas were identified, it now maintains an R&D skills risk register. A key function of this register is to suggest actions to mitigate the risks, such as initiating recruitment before a skills gap appears. The NNL governance process will enable it to raise skills issues and this should ensure that skills are not lost by chance.

4.33 One of NNL's concerns is that NDA's tendering process has led to the need for nuclear skills to become spread across a much larger number of organisations than previously, with potential problems in maintaining appropriate technical standards.

4.34 In the view of NNL (CoRWM doc. 2630), in order to deliver its commitment on training, NNL needs to ensure that it has access to a wide range of R&D skills. It plans to pursue a growth strategy that increases staff numbers.

Relevant Non-Nuclear Skills

4.35 A substantial range of non-nuclear skills will be required for the successful implementation of the MRWS programme, particularly in the geological, materials and engineering sciences. It is beyond the scope of this report to assess the level of skills provision in these areas, as each is a substantial sector in its own right. Consequently, text here is limited to comment on the geosciences sector where serious concerns have been directly expressed to CoRWM through bilateral meetings (CoRWM docs. 2455, 2456). It is noted, however, that it has also been drawn to CoRWM's attention that fewer than ten UK universities have "full capability" first degree courses in materials science, despite the demand for graduates (CoRWM doc. 2630).

4.36 At present, there are 25 university departments teaching first degrees in geological sciences or environmental geosciences in the UK. The universities listed in Box 5 produce about 1,000 graduates a year, with around half staying in earth-sciences-related employment. Of these, many are recruited by overseas employers (especially in the mining, hydrocarbon, water and civil engineering industries in which geosciences skills shortages are worldwide).

4.37 Undergraduate geophysics courses are offered by 13 universities. Owing to the high standards required from school leavers in maths and physics, these courses traditionally have far lower student numbers than geological sciences degrees.

4.38 The geological disposal R&D programme will also require specialist sub-disciplines like engineering geology and hydrogeology (Box 5). Taught MSc degrees in engineering geology are available at 22 UK universities but the levels of recruitment are such that many of them do not run. Only six universities offer a taught MSc in hydrogeology and again, the number of students taking these is small.

4.39 Nationally and internationally, graduates in geophysics, engineering geology and hydrogeology are currently all in short supply; the nuclear industry will need to compete strongly with the mining, hydrocarbon, water and civil engineering industries to attract highly-qualified researchers to work in the nuclear sector. Concerns about this were raised during meetings between CoRWM and the Learned Societies (including the Geological Society of London and the International Association of Hydrogeologists) (CoRWM docs. 2484, 2455). These discussed the availability of geosciences graduates and postgraduates to enter the nuclear industry and to proceed to PhDs in key sub-disciplines of particular relevance to R&D for the geological disposal programme, *e.g.* hydrogeology: NDA estimates that the maximum number of hydrogeologists required at the peak of site characterisation activity will be around 100 and it hopes to exploit the experience gained by hydrogeologists who have been involved in delivering geological disposal overseas rather than relying on UK-based experts.

4.40 A specific concern was also raised by BGS (CoRWM doc. 2456) about the increasing shortage of geosciences graduates who are also highly numerate. This arises because A-level mathematics is not a prerequisite for most geosciences degree courses and so graduates from these programmes have limited mathematical and modelling ability. Numerate geoscientists are essential for numerical modelling of radionuclide migration through the geosphere that surrounds a GDF. Numerate geoscientists are also highly sought after by the oil and gas industry, and for the development of potential carbon capture and storage capability and a national shortage will inevitably impact on R&D related to geological disposal.

4.41 Bilateral meetings between CoRWM and a range of learned societies, industry organisations and Research Councils have not identified any other particular concerns regarding skills provision in the materials and engineering (other than engineering geology) disciplines beyond the more general national concern regarding shortages of well-qualified recruits with suitable backgrounds in mathematics and the physical sciences.

NDA Skills Requirements for Implementation of Geological Disposal

4.42 NDA's Skills and Capability strategy was written before Nirex was fully incorporated into NDA (NDA, 2008d) and does not identify any substantive need for NDA to acquire additional or specialised skills to implement geological disposal. When CoRWM met with NDA in April 2008 (CoRWM doc. 2373), it was informed that NDA's skills development was being extended to the geological disposal programme with input to the NDA Skills and Capability Strategy from RWMD.

4.43 CoRWM questioned (CoRWM doc. 2456) whether NDA has the necessary level of in-house geosciences expertise to enable external work (*e.g.*, in site characterisation and geosphere studies) to be integrated effectively into its overall programme. It was assured that NDA recognises this issue and is actively recruiting to match programme needs. CoRWM understands two senior staff members have recently been recruited in this area (CoRWM doc. 2630).

4.44 Of particular importance to the geological disposal programme is the need to understand the interactions that will occur over very long periods between emplaced wastes, containers and buffer materials and the geosphere. The geosphere components include not only the rocks within which a GDF is constructed, but also the fracture systems in these rocks, the groundwater fluids percolating through the rocks and GDF, and any introduced micro-organisms. Understanding and predicting these interactions in enough detail to develop a safety case requires a combination of sophisticated mathematical modelling and high quality experimental data that, for geological systems, are often extremely difficult to obtain.

4.45 There is evidence that the UK needs more skills capability in the area of 'coupled thermal-hydraulic-chemical-mechanical' (THCM) processes. Study of these processes is a major feature of the leading international R&D programmes (CoRWM docs 2455, 2484).

4.46 There is also the issue of experience in underground R&D. Many countries that are implementing geological disposal have had URLs for many years and have built up considerable experience (Section 5). Some UK researchers have worked in URLs in other countries but the numbers of people involved are small and some of the experience was gained many years ago by people who are now close to retirement. It is important that UK-based personnel are trained in underground R&D skills and working practices through active participation in overseas URL programmes to ensure the UK has a suitably experienced workforce when required (Section 5).

Consultant and Contractor based R&D Skills

4.47 An important pool of UK geoscience experience relevant to the geological disposal of radioactive waste currently resides in consulting organisations and among independent consultants. A large amount of commissioned work has been (and is still being) done by UK-based consultants for overseas WMOs, most notably in Sweden, Finland, the USA, France and Japan. Many of these scientists have 20-30 years of experience but, as with much of the nuclear industry, they are approaching retirement, and in many cases are working beyond retirement.

Box 5. Skills to Support the Geological Disposal Programme

In terms of the skills required to support the geological disposal programme, the three areas most likely to be called upon for provision are the geological and materials sciences, and civil engineering. At a meeting with the learned societies and NERC (CoRWM doc. 2455), concern was expressed about the supply of geosciences graduates both for entry to radioactive waste management in the nuclear industry and to go on to higher degree programmes in key sub-disciplines relevant to R&D for geological disposal such as geochemistry, hydrogeology, engineering geology and mining.

At present there are 25 university departments teaching first degrees in geological sciences or environmental geosciences in the UK. These are at the following universities:

Aberdeen	Cardiff	Leeds	Oxford	University College
Aberystwyth	Durham	Leicester	Plymouth	
Birmingham	Edinburgh	Liverpool	Portsmouth	
Bristol	Imperial	Manchester	Royal Holloway	
Camborne	Keele	Newcastle	Southampton	
Cambridge	Lancaster	Open	St Andrews	

The universities listed produce about 1,000 graduates a year, of which, around half stay in earth sciences related employment. Of these many are recruited by overseas employers (especially the mining, hydrocarbon, water and civil engineering industries in which geosciences skills shortages are worldwide).

BGS has told CoRWM (CoRWM doc. 2456) that, while it can still recruit satisfactory numbers of good geosciences graduates, it is becoming increasingly concerned about the shortage of highly numerate recruits who will be needed in ever greater numbers for modelling and other work. This is probably part of a wider problem in the numbers of students doing mathematics and physical sciences in the secondary and tertiary education systems. It could impact on the implementation of geological disposal in the UK, including the ability to learn from, and contribute to, international programmes.

There is also concern from the geological disposal perspective about the situation regarding taught Master degrees in the relevant specialist sub-disciplines like engineering geology and hydrogeology.

Within the broader definition of engineering geology (*i.e.*, including soil/rock mechanics and mining) 22 institutions offer a taught MSc, namely the following universities –

Bangor	Durham	Leeds	Reading
Birmingham	Glasgow	Manchester	Sheffield
Camborne	Greenwich	Newcastle	South Bank
Cambridge	Herriot-Watt	Nottingham	Southampton
Cardiff	Imperial	Nottingham Trent	
Dundee	Kingston	Portsmouth	

while only six universities have a taught MSc in hydrogeology, namely –

Birmingham	Imperial	Newcastle
Cardiff	Leeds	Sheffield

Given the relatively small numbers of students involved, the latter is of particular concern in view of the likely requirements for expertise in hydrogeology throughout the geological disposal programme.

Worthy of mention in this context is the Empower programme. This is a scheme whereby students taking a Master's course in earth sciences or environmental geology (at any university) are given exposure to the nuclear sector through research project placements or other activities. A pilot scheme ran in 2008 and the full programme, funded by the NDA, EA, AWE and British Energy, commenced in 2009. It is hoped this will lead to greater recruitment of geoscientists to the industry at a critical time.

Retention of Skills

4.48 It has been brought to CoRWM's attention that the radioactive waste management side of the industry will face severe competition for its skilled staff (CoRWM doc. 2677), not only from existing industries like hydrocarbons, water and civil engineering but also from emerging activities such as nuclear new build and carbon capture and sequestration. Also, a proportion of the R&D skilled staff would be expected to move into other roles in the nuclear industry and its regulators, rather than remaining in R&D roles (CoRWM doc. 2630).

Conclusions on Skills

4.49 For nuclear skills in general, but R&D in particular, the picture in the UK has been one of decline since the 1980s, largely a result of research laboratory closures but not helped by the "unfashionable" perception of careers in the nuclear industry. By 2000, this was giving grounds for serious concern. It is therefore encouraging that recently there have been significant improvements in the skills and training area. These are partly a consequence of the setting up of NDA and the "skills alliance" formed between Cogent and NSAN. They should be further helped by the improving image of the industry, due partly to the media association of the new build, energy gap and climate change issues. Nevertheless, arrangements for providing R&D skills are not yet adequately rebuilt for the future. The large number of organisations involved and the complexity of the relations between them means the provision of R&D skills and training in the UK is fragmented. Simplification of the responsibilities for ensuring the UK has the requisite skills should therefore be seriously considered.

4.50 NDA appears to be making good progress within the area of its own remit but nationally the wider scenario lacks strategic control. The inter-relationships between the responsible organisations are extremely complex and it is far from clear which take overall responsibility for providing leadership and co-ordination. This applies both to the identification of skills requirements and the provision of training. NSAN is an important initiative but has tended to focus on industry's more immediate needs. With Cogent, NSAN is now looking towards skills shortages to 2025 but these are still defined by current industry profiles. CoRWM encourages NSAN to develop some pro-active initiatives rather than relying entirely on employers' perceived needs and to do so over a timescale of decades.

4.51 In parallel with the depletion in R&D skills in the UK nuclear industry, the provision of research skills *via* higher degrees was seen as very "fragile" until recently. The establishment of the URAs by BNFL marked the beginning of a considerable improvement in the nuclear area which has continued with the funding by the Research Councils (mainly EPSRC) of nuclear-related research and training consortia and other university-based programmes. However, there appears to be an assumption in the industry that now the URAs are established the higher level skills problem is solved (CoRWM doc. 2630). These research centres require continued support to go on delivering skilled researchers in the relevant areas and without it may be forced to further reduce their nuclear-related activities. The commitment of the NDA to supporting research through its DRP, SLCs and other avenues has also contributed to the improving situation, although questions have been raised about the effectiveness of this support.

4.52 It is to be hoped that the establishment of the NNL will provide further impetus to skills improvement but CoRWM has concerns about how training and provision of research skills will be reconciled with the need for commercial operation. While NNL will be a customer-funded organisation and it is appropriate that it operates as “just another supplier” in most circumstances, it is important to identify and agree those areas in which a strategic role needs to be played. In these areas it will be necessary to ensure that arrangements are in place to facilitate delivery of such strategic support. Skills provision is a strategic area and it is unclear to CoRWM how NNL funding for this will be assured.

4.53 There is still a shortage of Master-level courses with a significant nuclear component. In addition, EPSRC has now terminated its funding for the NTEC Masters’ programme so, although NDA has provided interim funding for 2009, its future is unclear. The supply of relevant, non-nuclear, research skills in other disciplines is perceived as better but in some areas, like geoscience, not as healthy as it should be. Particular deficiencies remain in the numbers of MSc and PhD graduates in key sub-disciplines for implementing geological disposal, such as hydrogeology and numerical modelling. Since other countries’ geological disposal programmes are likely to overlap with that of the UK, as will other challenging and attractive international projects, such as carbon capture and sequestration, CoRWM believes there is significant risk in over-reliance on attracting this expertise from overseas.

4.54 Despite some positive developments, research with its integral skills training in areas relevant to the R&D needed to underpin the implementation of geological disposal, remains fragmented overall. Responsibility for the provision of R&D skills is split between many organisations and there appears to be little effective national leadership and insufficient strategic direction.

4.55 Although not focused specifically on the nuclear industry, Cogent is well placed to provide guidance on the basic skills and training requirements of the industry through its employer-driven approach and alliance with NSAN. However, it is not directly involved in the provision of higher level research training of the sort required to underpin the MRWS programme nor is it in a position to make strategic judgements on the research programmes of which such training is part, especially those towards the fundamental end of the research spectrum. Consequently, CoRWM considers that additional expertise would be required within Cogent to enable it to provide effective national leadership and strategic direction for the provision of R&D skills pertinent to the management of higher activity wastes.

5. INFRASTRUCTURE REQUIRED FOR R&D

5.1 In this context, infrastructure means laboratories and other research facilities and the equipment within them.

5.2 R&D to support the MRWS programme may be viewed as falling into two groups: that which is specific to the nuclear industry (for example development of plutonium wasteforms), and other broadly applicable R&D which is relevant to the management of higher activity wastes as well as other industries (for example, remote subsurface investigation in support of structural geological characterisation and mapping). The former usually requires work with radioactive materials and has very specific and complex infrastructure requirements. By contrast, the latter relies mainly on the UK's broader national R&D capability. CoRWM hopes to examine the broader group in more detail in future. This report focuses on infrastructure to support nuclear specific R&D.

5.3 This section begins with consideration of "active facilities", that is research facilities where work with radioactive materials can be carried out, in the UK and other countries. There is then a discussion of underground facilities for geological disposal R&D.

UK Active Facilities

Universities

5.4 Within UK universities there is very little capacity to work with radioactive materials relevant to the nuclear fuel cycle. Several groups (*e.g.* Sussex, Edinburgh, Oxford, Imperial College) work on fundamental aspects of the chemistry and materials science of uranium and thorium but have no infrastructure to support experiments with transuranium elements. The majority of this research is based around one or two academic staff in each institution. Loughborough University has dedicated radiochemistry laboratories, but limited capacity to work with high hazard radioisotopes.

5.5 Starting in 1999, BNFL created a series of university partnerships (University Research Alliances, para 4.26 and Box 4). The MPC and ISL have the capacity to work with uranium-active materials (and irradiated graphite in the case of MPC), while the CRR has some capacity for work with neptunium and plutonium, including the UK's remaining supply of plutonium-242, whose long half-life allows work with milligram quantities in a limited range of conditions. All four URAs have access to a wide range of instruments although their use, even with uranium, can be quite restricted.

5.6 BNFL's start-up funding was provided to each URA for 5 years, with the expectation that they would become self-sufficient after that time. This is the case for all four URAs, which have diversified and now have major programmes in areas such as propulsion, new build, national security and non-nuclear topics.

National Nuclear Laboratory Facilities

5.7 NNL runs facilities at Springfields (relatively new uranium-active laboratories) and Sellafield, specifically the B13 and recently built BTC (BNFL Technology Centre) facilities. The BTC has been renamed the Central Laboratory. NNL does not own these B13 and Central Laboratory facilities but leases them from NDA and operates them under the Sellafield SLC site licence (para 3.28). The contractual arrangements are not currently the same in all its facilities although this is set to change with the informal arrangements currently in place being progressively replaced by more formal contracts. The time frame for this is not yet established, although NNL considers that in the meantime the various interfaces could all be managed.

5.8 B13 contains shielded caves and a range of instruments and is undergoing refurbishment and improvements with the aim of ensuring it can continue to play a role through to 2025. The availability of equivalent facilities after this date is unclear though they will still be needed. The Central Laboratory is not yet fully commissioned. Phase 1 (gloveboxes, fumehoods and a graphite laboratory) has been commissioned. Phases 2 and 3, the MOX laboratories and hot cells respectively, have been in care and maintenance for 1-2 years. NNL is currently preparing a business case for the commissioning of Phases 2 and 3, based on HM Treasury Green Book guidance, and is hopeful the case will be accepted. Emphasis is being put on demonstrating there is a demand for the facilities proposed for Phases 2 and 3. NNL can provide, at least in outline, several programmes which would require these facilities and its customers, particularly Sellafield Ltd., are starting to develop longer term projects, which would justify commissioning. Even if fully commissioned, the Central Laboratory will require significant changes to, or further development of, its infrastructure (*e.g.* installation of specialised controlled atmosphere gloveboxes; instruments for characterisation of active samples) to carry out a research programme in geological disposal comparable to those undertaken overseas.

5.9 Further commissioning and expansion of capability in NNL facilities will be dependent on customer demand and successful preparation of business cases to support this demand (*e.g.* from NDA, SLCs and Research Councils).

5.10 While STFC and NNL have held discussions, CoRWM understands that there are currently no plans to include any major facilities at the NNL under the auspices of the STFC in order to ensure access for industry-independent R&D (CoRWM doc. 2443).

5.11 In general NNL has a limited equipment base for characterisation of radioactive materials, funded either by customers through specific projects or, in some cases, through self-investment. The Central Laboratory has only a limited range of equipment and has few routes to expanding this. As a result, this facility is significantly less well equipped than its overseas equivalents. This situation arises because NNL makes an annual profit of £5-6M which is insufficient to allow investment in high capital cost items, especially in a nuclear environment.

5.12 CoRWM understands that the management contractor for the NNL is required to increase access to facilities for universities and other organisations that carry out R&D. Although it is intended to provide access to allow fundamental research funded by the Research Councils to be carried out, and discussions are in progress, at present there is no mechanism by which the Research Councils can fund university research in NNL facilities, particularly when it involves the purchase of equipment. In addition, the potential user community is confused about the process and terms of access to NNL active facilities (CoRWM doc. 2630).

Other Facilities

5.13 There are a number of supply chain organisations that have some capacity to work with radioactive materials. These include AMEC, which operates the NIRAS facility, Serco and Waste Management Technology. Most of these facilities can only handle low levels of activity. For example, most of the NIRAS facility is geared towards environmental radioactivity and it can only accommodate experiments with the less active ILW. The MoD also has some facilities, for example on the Aldermaston site.

International Examples of Active Facilities

5.14 Several countries, particularly the major nuclear nations, have R&D facilities to support civil and/or military programmes. However, direct comparisons of UK facilities with those overseas are not straightforward. There are substantial differences in national requirements, depending largely on whether or not fuel has been reprocessed on an industrial scale, while some laboratories incorporate nuclear research into a more general energy programme, and some support both civil and military programmes. Nevertheless, it is possible and instructive to identify a few illustrative examples for comparison.

France

5.15 France operates a nuclear fuel cycle that includes reprocessing of irradiated fuel and recycling of plutonium in mixed oxide fuel (MOX), and has done so for some decades. In France, much R&D is conducted by CEA, which has responsibilities in both civil and military nuclear energy. This includes decommissioning and some aspects of waste disposal, together with new reactors, nuclear fusion and novel waste management technologies such as partitioning and transmutation (para. 3.14).

5.16 The focus of R&D on radioactive waste in CEA is Marcoule, and particularly the recently (2003) completed Atalante facility.[20] In many ways, this is a close parallel to the Central Laboratory of the UK NNL (para 5.7). Marcoule is a long-established site, with both old and current facilities, and Atalante is a purpose-built R&D facility on that site. Atalante has 19,000 m^2 of laboratories, including 17 glovebox-equipped laboratories and seven sets of shielded hot cells and remote manipulators. Some other specialist facilities have also been developed by, or with the involvement of, the CEA, for example, the Soleil synchrotron built at Saclay, and the dedicated radioactive materials beamline (MARS) on Soleil. Recent and planned CEA active facilities include the Phénix fast neutron radiation source, which was taken off-line in March 2009, the prototype sodium fast reactor ASTRID (which can be used to produce plutonium, americium and other actinides) that is planned to be operational by 2020, and the Jules Horowitz reactor that will provide irradiated materials by 2015.

[20] http://www-marcoule.cea.fr

Germany

5.17 Although Germany has operated civil nuclear reactors for many years, fuel has never been reprocessed on a large scale in that country. A significant quantity of German fuel has been shipped to France and the UK for reprocessing and, under the terms of these contracts, vitrified HLW has been returned to Germany for disposal. Germany also proposes geological disposal of spent fuel and its early power reactors are now being decommissioned. In the former East Germany, large scale uranium mining has led to extensive contamination both on the surface and underground.

5.18 R&D into cleanup and waste disposal is concentrated in two federally-supported research centres, Institut fur Nukleare Entsorgung (INE) at Karlsruhe and Forschungszentrum Dresden (FZD). Both have links to universities, and academic institutions such as the Technical University, Munich, or the University of Mainz which have significant infrastructure, including a research reactor at Mainz.

5.19 INE is co-located with the ANKA synchrotron on the Forschungszentrum Karlsruhe site, and has a dedicated beamline on ANKA which can be used with radioactive materials. FZD operates the ROBL radioactive materials beamline at the European Synchrotron Radiation Facility, Grenoble. Both INE and FZD have extensive glovebox facilities optimised for geological disposal research.

5.20 Germany also hosts the European Institute for Transuranium Elements (ITU) on the Forschungszentrum Karlsruhe site. This is one of the EU Joint Research Centres and has extensive glovebox and hot cell facilities in which it conducts experiments on wasteform development and performance, and the behaviour of fuel in disposal conditions. Its EU-funded institutional budget is €37.9m per year.

USA

5.21 The USA has exploited nuclear fission on a large scale since the 1940s. Most reprocessing was focused on production of plutonium for weapons, while the West Valley reprocessing plant, built to support civil nuclear power, never entered full operation. Spent fuel from USA nuclear power stations is currently stored awaiting disposal but there is a policy review and there is increasing interest in reprocessing this material to reduce the volumes of waste for disposal. Decommissioning and cleanup of the weapons plants, in particular the Hanford and Savannah River sites, present many challenges comparable to those faced in the UK. Transuranic waste from the USA military programme (in many respects similar to UK plutonium contaminated material (PCM)) is disposed of underground in the Waste Isolation Pilot Plant (WIPP) in New Mexico.

5.22 The majority of relevant R&D in the USA is conducted in the “DOE complex”. Within this, seven National Laboratories have active facilities which are, or could be, used to support radioactive waste management and disposal R&D. The DOE programme also includes collaboration with numerous universities, including Washington State, Florida State, University of Nevada at Las Vegas, and University of California, Berkeley. Several of these universities have glovebox facilities.

5.23 The Pacific Northwest National Laboratory (PNNL) is close to the Hanford site, which was a major USA plutonium production facility for many decades and is now decommissioning. Two of PNNL's flagship facilities are the Radiochemical Processing Laboratory,[21] which is equipped with gloveboxes and hot cells, together with a wide range of instrumentation for use with radioactive samples, and the Environmental Molecular Science Laboratory, which has a major programme in subsurface science.

5.24 The USA has several synchrotron radiation sources which can be used with radioactive materials, including SSRL (Stanford Synchrotron Radiation Laboratory) at Stanford, APS (Advanced Photon Source) at Argonne and ALS (Advanced Light Source) at Berkeley.

5.25 USDOE recently commissioned from the National Academy of Sciences (NAS) an independent evaluation of its nuclear energy research programme (USDOE, 2008b). A common theme among the NAS recommendations was the need to invest in research facilities that enable the Office of Nuclear Energy (ONE) to meet its research priorities and to develop a process for prioritising, evaluating and obtaining those capabilities. Battelle Memorial Institute and Idaho National Laboratory were then asked to report on the type of facilities needed for the next twenty years as summarised by NAS (USDOE, 2008b). The facilities that ONE plans to invest in include hot cells, materials test reactors including fast reactors and demonstration reprocessing technologies.

Accessibility to the UK of Active Facilities in Other Countries

5.26 Access to USA National Laboratories is difficult because they are generally not open to collaborations, beyond USDOE-funded research, in which overseas institutions rarely participate. In addition, for the nuclear weapons laboratories, there are major issues with security clearance (a US Q-clearance, rarely allowed for non-US nationals, is generally required).

5.27 European facilities can be accessed to a limited degree through, for example, the FP6 Actinet-6 Network of Excellence and its proposed successor, Actinet I3. However, access through this route is very competitive, relatively limited in scale, short term (project duration less than a year) and lacking in continuity (the last call for Actinet-6 was in November 2007 and the first call under Actinet I3 is still awaited). Most significantly, users accessing the facilities through Actinet have no say in specifying the capability of the facilities or the instrumentation available. Given these constraints, the UK could not rely on these access routes to sustain major strategic R&D programmes.

5.28 The logistics of transporting radioactive materials make working overseas complex and expensive. For example, it is prohibited to move fissile material by air in the USA, so samples have to be transported by sea and road. UK groups have moved small transuranic samples to both European and USA facilities as Excepted Packages. The lead time is up to 4 weeks, which is an issue for unstable materials, while the cost for a single movement is normally £1K and can be up to £4K, depending on the material moved. Further, real time analyses of

[21] *http://rpl.pnl.gov/documents/pdf/rpl2008.pdf*

reactions and atmosphere sensitive materials cannot be performed at these facilities.

5.29 Larger samples of transuranic materials or samples with high external dose rates require large, often heavily-shielded containers, sometimes specially designed, for shipping and again, this is logistically complex and very expensive.

5.30 International nuclear materials safeguards agreements require detailed accountancy and record-keeping. This is complex within the EU (the Euratom system) and even more so if material is exported from the EU.

Underground Facilities

5.31 Many countries have radioactive waste management policies that involve geological disposal. Waste management organisations (WMOs) in these countries face broadly similar challenges in demonstrating, not only to regulators but also to the broader scientific/technical communities, politicians and the general public, that any proposed GDF is technically feasible, that it can be operated and maintained safely and that it will remain safe over very long periods of time after it has been closed and sealed. The scientific and engineering arguments that have to be developed to satisfy this level of scrutiny must be extremely robust.

5.32 WMOs in many countries have developed underground research facilities (URFs) to assist in this process by filling knowledge gaps and providing evidence to support the technical case for GDF development. This is the situation in Belgium, Canada, Finland, France, Germany, Japan, Sweden, Switzerland and the USA. In each case the WMO has made a decision that the level of knowledge in certain areas can only be brought to that required by performing R&D underground in an environment that approaches real conditions for a GDF.

5.33 Underground facilities fall into three categories:

1. facilities constructed as part of, or in conjunction with, other underground developments (*e.g.* mines or civil engineering projects)
2. generic URFs developed at sites that are not scheduled for geological disposal
3. site-specific facilities developed at sites at which geological disposal is planned.

5.34 Facilities in the first category were used in the early years of geological disposal R&D and have now largely been superseded by facilities in the other two categories (examples were the Stripa mine in Sweden and the Climax mine in the USA). Generic facilities have been developed in Japan, Canada, Belgium, Switzerland and Sweden. The current policy in France, Finland, USA and Germany has been to develop site-specific facilities. However, the technical cases for both the operational WIPP GDF in the USA and the licensed GDF at Konrad in Germany were developed without the aid of site-specific underground facilities.

5.35 The range of possible functions of underground facilities can be summarised as follows:

1. Comparison and calibration of geosphere data collected from surface-based investigations with that from underground investigations.
2. Comparison and calibration of data collection methods and equipment for geosphere characterisation purposes.
3. To develop and enhance understanding of the impacts of rock excavation on both the rock mass and existing underground openings.
4. To develop and enhance understanding, through simulating the effects of the placement of waste in actual conditions that replicate those in a GDF.
5. To develop and enhance conceptual and numerical models for the transport of radionuclides through a rock mass.
6. To develop an improved understanding of, and test how, a proposed engineered barrier system (EBS) will perform under conditions that replicate those in a GDF.
7. To design and undertake experiments that will give an understanding of the long-term performance of the disposal facility as a whole to ensure the robustness of the safety case for a GDF.
8. Build and maintain public confidence that all practical steps are being undertaken to establish the technical feasibility and safety performance of a GDF.

5.36 Some of the activities carried out in underground facilities come under the heading of site characterisation (*e.g.* items 1 and 2 above); others are R&D. Some of the R&D activities are required as input to GDF design or safety case development. Others will be needed during much of the period that a GDF is open in order to maintain the safety case and to allow improvements to be made to, for example, backfilling and sealing materials and methods. Examples of R&D topics are shown in Box 6.

5.37 The UK has never had a URF. However, UK scientists have participated in R&D programmes in facilities in several other countries.

5.38 By only mentioning site-specific underground investigations, the White Paper (Defra *et al*., 2008) implicitly rules out the construction of a generic URF in the UK. It states that the NDA shall undertake long-term underground investigations to confirm that the site selected to host a GDF is suitable and that a facility can be constructed that can meet all safety and environmental regulatory requirements. The process of site characterisation will commence with non-intrusive surface based investigations followed by intrusive borehole investigations from ground surface (Stage 5 in the MRWS site selection process). The White Paper makes it clear that characterisation work will continue into Stage 6, during which tunnels at depths of hundreds of metres will be constructed for the purpose of underground investigation. The investigations in this underground environment are planned to be long-term and are intended to draw on a range of scientific and technical disciplines such as geology, geophysics, hydrogeology, chemistry and others. In the context of Stage 6 of the MRWS process, underground investigations will in effect be the first stage of the construction of a GDF.

Box 6. Examples of Topics on which Underground R&D is needed for GDF Design and Safety Case Development

- The responses of the rock mass and existing underground openings to excavation, this could include:
  - excavation techniques and excavation support techniques for the long term
  - deep drilling techniques
  - research into the response of rock masses to excavation technique, and opening size and orientation;
  - the development of EDZs
  - the possible effect of excavation on existing underground openings in given *in situ* stress conditions and the influence of excavation on stress fields.
- Engineered barrier performance:
  - full scale barrier tests
  - container tests
  - buffer and overpack tests
  - tunnel and shaft seals and ultimately facility seals
  - borehole sealing
- Radionuclide movement through the geosphere:
  - solute advection and diffusion
  - colloidal transport
  - radionuclide sorption
  - gas threshold pressure relationships
- Waste handling under realistic conditions:
  - effects of heat and radiation on the host rock
  - heat effect on structures
  - thermal-hydraulic-chemical-mechanical testing
- The long-term performance of the GDF and the efficacy of the EBS under realistic conditions:
  - demonstration and testing of disposal concept
  - materials interfaces, for example surrounding the co-location concept
  - backfill behaviour and efficacy
  - corrosion of waste containers
  - degradation of waste forms
  - long-term performance of multiple underground openings.

5.39 The RWMD R&D Strategy explains how its R&D will evolve during the MRWS process (NDA, 2009b). It states that during Stage 5 (surface-based investigations) its R&D will focus on the site-specific processes that will determine the performance of engineered barriers or control the movement of fluids and radionuclides. For Stage 6 it states that:

> "*A key aspect of this phase will be underground investigations. There will be some site-specific information at a large spatial scale, which can only be obtained by investigation underground in the specific geology to be considered for hosting the facility. We will carry out these investigations as part of the construction of the facility and therefore our planning does not include a separate phase for R&D in an underground research laboratory.*"

5.40 Early in 2009 the emphasis in RWMD planning seemed to be on site characterisation and on confirming that R&D results obtained in the laboratory or in URFs in other countries would be applicable to the specific site at which it is proposed to construct a GDF in the UK (NDA, 2009b). This would be similar to the approach in Finland, where the ONKALO facility at the Olkiluoto GDF site is to be used for characterisation and confirmation but not for extensive R&D. However, scientists from Finland have for many years participated in R&D programmes in URFs in Sweden, which are in geological environments that are relevant to Olkiluoto. RWMD has recently indicated that its underground investigations will include R&D to address uncertainties and support safety case development (CoRWM doc. 2630; NDA, 2009k).

Conclusions on Infrastructure for R&D

Active Facilities

5.41 The UK has a limited number of facilities that are able to support research with radioactive materials. In particular, the country has very few research facilities in which it is possible to handle materials with levels of radioactivity above the very low concentrations found in the environment. The key facilities are those run by the NNL, which as a result of rationalisation operates the majority of the UK's active civil research infrastructure.

5.42 In CoRWM's view, the NNL's currently planned facilities, even when fully commissioned, will be inadequate to support the full range of research required to manage higher activity wastes. Significant improvements and additional facilities are needed to provide the UK with the capability to do research for its wide range of higher activity wastes.

5.43 It is unclear to CoRWM how the NNL facilities will be made available for the full spectrum of research that is needed to underpin the MRWS programme. The only R&D that can be performed in NNL facilities is that funded by NNL customers, namely NDA and other nuclear industry organisations, who are unlikely to support much fundamental research. There is currently no mechanism for the Research Councils to fund university research carried out in NNL active facilities, particularly that for which equipment must be bought.

5.44 CoRWM believes that further development of NNL facilities for research with highly radioactive materials, and greater access to them, are the only realistic route to the provision of the national research infrastructure needed for the management of higher activity wastes.

Underground Research Facilities

5.45 It is clear to CoRWM that both underground site characterisation and underground R&D are needed at any prospective GDF site in the UK. Surface-based investigations will not be sufficient for site characterisation. Even with the latest investigative techniques, significant underground site characterisation will be required in relation to rock mass characteristics, hydrogeology, geochemistry and stress conditions. Underground R&D will be needed to inform GDF design and support safety case development, including by finding out whether R&D results obtained elsewhere are applicable to a UK site. In practice, there is unlikely to be a clear distinction between site characterisation and R&D; rather there will be a continuum of activities, all supporting GDF design and safety case development.

5.46 In CoRWM's view, the most effective way to carry out the necessary underground R&D would be in a URF at any site where it is proposed to construct a GDF. The URF could share access with the GDF but should be constructed so as to avoid interaction with it. The URF would be used prior to the start of waste emplacement and for as long as necessary while the GDF is open. It could, for example, hold dummy waste packages that could be retrieved for detailed inspection, or be used to develop and test post-closure monitoring techniques.

5.47 The R&D to be carried out in a URF before waste emplacement begins must be clearly specified, discussed with a wide range of stakeholders, including the host community and researchers independent of the NDA, and agreed with regulators. It is important to allow sufficient time to carry out the R&D, and to process and assimilate the results, before a decision is taken to construct the GDF. All those involved in the geological disposal programme need to be aware that the R&D may take decades.

5.48 Until a site-specific URF is available in the UK, there will need to be increased participation in generic R&D programmes in underground facilities in other countries. This would enable UK researchers to gain experience and to develop techniques for use in this country, as well as providing additional knowledge for the UK's geological disposal programme.

5.49 Other countries that are investigating the feasibility of geological disposal have carried out underground R&D, either at prospective disposal sites or in separate facilities in similar geologies to such sites. The international consensus is that underground R&D helps to increase public confidence. Carrying it out at a prospective disposal site will be more cost effective than establishing a separate URF in a similar geological environment.

5.50 RCUK (Section 3) has the ability to fund, or part-fund directly, large scale research facilities. Examples of generic large-scale facilities are aircraft, ships and large data sets. It is possible that RCUK could contribute to the funding of a URF, particularly supporting provision of infrastructure or equipment, or access to underground facilities, for fundamental research.

6. SOME R&D ISSUES

6.1 R&D carried out over the last few decades in the UK and other countries has produced a substantial body of knowledge about the conditioning, packaging, storage and geological disposal of higher activity wastes. This knowledge base is sufficient to support the choice of long-term management methods for these wastes. In particular, CoRWM is convinced that enough is currently known about geological disposal to engender confidence that it is the right way forward. However, there are still uncertainties that need to be addressed and knowledge gaps that need to be filled before it can be implemented at a specific site in the UK. Further information is also required as input to detailed decisions on the conditioning, packaging and storage of the UK's higher activity wastes. R&D over the next few decades must focus on these uncertainties and gaps in knowledge.

6.2 During the course of its work in 2008 and 2009, CoRWM became aware of a number of specific topics which it believes may require significant R&D. Details of these topics are given in Appendix A. In this section CoRWM highlights key points arising from its examination of these topics. The Committee's consideration of specific topics was by no means exhaustive but serves to illustrate the nature and extent of some of the key issues. It is not in CoRWM's remit, nor does it have the resources, to cover all issues in detail.

Key Points on Waste Conditioning, Packaging and Storage R&D

ILW Product Lifetimes

6.3 CoRWM is concerned about the level of R&D effort being devoted to determining the lifetimes of ILW wasteforms. Given the number and diversity of ILW packages that will be produced over the rest of the lifetime of the UK's nuclear sites, and the potential significance of wasteform performance for transportability and disposability, the effort being devoted to resolving uncertainties over product lifetimes does not seem to be sufficient. NDA's UK storage review (NDA, 2009d) identifies the existence and nature of this problem but gives no indication that there will be substantial further R&D.

Graphite

6.4 If immobilised and packaged in similar ways to other ILW, bulk graphite would occupy a great deal of space in a GDF. It is therefore important to explore treatment options that would reduce the volume of graphite for geological disposal. Current graphite R&D is being carried out under the 4-year EC Carbowaste programme. NDA is taking the lead on UK strategy development for graphite, with support from its Magnox SLCs and involvement of British Energy. CoRWM understands that the IAEA is also establishing a Co-ordinated Research Project on graphite. This is to be welcomed because it will enable a wider range of countries to share expertise and ideas. There may also be a need for bilateral co-operative approaches.

Management of Spent Fuels

6.5 There are several topics on which R&D is likely to be needed in order to develop reference and contingent strategies for the management of spent fuels. These include:

- drying Magnox fuel, prior to dry storage
- encapsulation of Magnox fuel for geological disposal
- drying AGR fuel, prior to dry storage
- conditioning and packaging of AGR fuel for geological disposal
- conditioning and packaging Sizewell B PWR fuel for geological disposal.

6.6 R&D on some of these topics is in hand but some have yet to be addressed. It is anticipated that work on management strategies for "exotic fuels" and for submarine fuel will lead to the identification of a number of R&D needs.

Key Points on Geological Disposal R&D

Radionuclide Migration with Groundwater from a Closed GDF

6.7 If predictions of radionuclide migration with groundwater are to be reliable they need to be based on a good understanding of the mechanisms involved. This requires, for the key radionuclides, advances in knowledge of:

- the physico-chemical forms of the radionuclides
- the spatial variability, temporal evolution and reactivity of mineral surfaces
- upscaling molecular level models to estimate bulk chemical properties and predict transport over hundreds of metres.

Gas Generation and Migration in a Closed GDF

6.8 Gas generation and migration are of particular importance to geological disposal in the UK because of the high volumes and diverse nature of higher activity wastes, and the volumes of groundwater that could be present in a closed GDF after resaturation. The bulk gases of concern are hydrogen and methane. BGS is the lead researcher in the EU FORGE project and is supported in this by the NDA. This is a good example of working with the international community on an issue of particular relevance to the UK.

Criticality in a Closed GDF

6.9 Previous UK work on criticality in a closed GDF has focused on ILW, for which the criticality hazard appears to be low. The hazard for spent fuel and/or plutonium is higher and requires rigorous assessment for the purposes of safety case development and optimisation of GDF design. The assessment of criticality hazard is demanding, requiring knowledge of wasteform performance, nuclear physics data, fissile material migration in the GDF environment, and neutron transport modelling. In the absence of specific information on the GDF, wasteforms and inventory, the primary need for research into criticality is to preserve and develop UK capability and make the most use of work carried out in countries that have been working on geological disposal of spent fuel for many years.

Co-Location of Various Types of Waste in a GDF

6.10 There are several issues on which research is likely to be required to inform a decision on whether it is preferable to have one GDF in which all higher activity waste is co-located or two (or more) GDFs for different types of higher activity wastes. These issues include: the potential for and extent of cement-bentonite interactions, the impact of highly alkaline waters on HLW, the effects of thermally-driven circulation on performance of the ILW disposal system, and the impact of gas generation in the ILW/LLW part of a GDF on groundwater movement in the HLW/spent fuel part.

GDF Design

6.11 CoRWM recommended (CoRWM doc. 2550) that there should be an integrated process for GDF design, site assessment and safety case development. Such a process is likely to highlight areas of uncertainty in relation to design development, detailed design and assessment of design performance throughout the operational life of a GDF. For example, R&D may be required at the concept development stage to understand the impact that co-location will have on GDF design. At the detailed design stage the site specific response of the rock mass to construction activity will need to be understood and the long-term stability of all underground openings will need to be established.

Geosphere Characterisation

6.12 Surface-based characterisation will be undertaken during Stage 5 of the MRWS site selection process and underground characterisation during Stage 6. The NDA is carrying out a Geosphere Characterisation project that aims to develop and maintain an understanding of the approaches to the design and implementation of the investigations (both surface and sub-surface) that will be required and to prepare for such work.

6.13 The project has not yet concluded but areas have been identified that, CoRWM considers, would benefit from R&D. For example, R&D may be required to define the chemical descriptions and models for the near field, geosphere and biosphere and in the definition of models of site-scale hydrology, hydrogeology and paleohydrogeology. As the project progresses other topics for R&D will be identified. It is unclear, to CoRWM, whether R&D needs identified from this project are progressing or are being planned, or whether the skills and resources have been identified to undertake the work.

Microbiology

6.14 Microbial processes are poorly understood and may impact on the performance of a GDF. Whilst many aspects of a GDF's microbial ecology will be site specific, there is a need to build capability to conduct site specific R&D and it is desirable to carry out generic research in advance of site specific studies. It is necessary to develop UK capability in techniques for the sampling and characterisation of subsurface microbial communities, which are technically difficult. Generic research areas could include the ecology of high pH, anaerobes and thermophiles and the ecology of radioactive, hydrogen-rich systems.

Geosphere Evolution

6.15 Over the lifespan of a GDF there will potentially be significant changes in groundwater chemistry, regional groundwater gradients, rock hydraulic properties, geochemical properties (including mineralogical surfaces for adsorption), mechanical loading, microbial ecology and sea level. To reduce uncertainty in model predictions of physical, chemical and microbiological geosphere evolution there is a need for further research to develop fundamental process-based models. Further, to validate such models, new field analogues should be sought that illuminate the role of individual processes in geosphere evolution and are applicable to the timescales appropriate for geological disposal of higher activity wastes.

7. CONCLUSIONS AND RECOMMENDATIONS

Strategic Co-ordination of UK Radioactive Waste Management R&D

7.1 CoRWM considers that there is a need for more strategic co-ordination of R&D for the management of higher activity wastes throughout the UK. This strategic co-ordination is required within NDA (including its SLCs), between NDA and other parts of the nuclear industry (including MoD), amongst the Research Councils, and between the nuclear industry, its regulators and the Research Councils.

7.2 Within NDA the need is for more strategic co-ordination of R&D carried out by its SLCs, RWMD and within its DRP. It is particularly important to co-ordinate RWMD's R&D for implementation of geological disposal with SLC and DRP R&D for waste conditioning, packaging and storage and on the management of spent fuels, plutonium and uranium that may be declared to be wastes. The lack of such co-ordination would lead to a poor use of the NDA's resources (effort, time and money).

7.3 Between NDA and the nuclear industry there is a need for strategic co-ordination of R&D and agreement on national priorities. As well as enabling better use to be made of resources, this would ensure that key issues are tackled in a timely way.

7.4 Of the five Research Councils that could potentially fund research relevant to the management of higher activity radioactive wastes, only two are doing so at present and only one at a substantial level. The Research Councils do not seem to have recognised the need to come together to identify the fundamental research required to underpin the MRWS programme. They should work together in an open and transparent way and involve prospective researchers in all the relevant fields, as well as the nuclear industry and its regulators. All these stakeholders should agree national priorities for the research to be funded by the Councils. This will maximise the benefits of the Research Councils' resources to the MRWS programme.

7.5 CoRWM does not wish to be prescriptive about the co-ordination mechanisms to be used in any of these cases. However, it has identified a number of attributes it thinks the mechanisms should have in all cases. These are that the mechanisms should:

- cover the R&D needs of all the relevant UK organisations
- be open and transparent
- involve researchers, the nuclear industry, its regulators and other stakeholders
- agree national priorities for R&D
- encourage innovation
- foster collaboration with other countries
- ensure R&D is carried out in a timely manner
- involve independent national and international review
- ensure R&D results are disseminated and acted upon.

7.6 In CoRWM's view no single existing body, as presently constituted, is capable of overseeing the necessary strategic co-ordination mechanisms. Either several bodies would need to work together or an existing body would need to be augmented in order to fulfil the oversight role.

7.7 It is essential that future UK R&D programmes for the management of higher activity wastes contain sufficient fundamental research, as well as applied research and development. In deciding which R&D to fund and when, account should be taken of the needs of the overall programme for the management of higher activity wastes, the needs for safety case development and the lead times and durations of R&D projects.

Recommendation 1

CoRWM recommends to Government that it ensures that there is strategic co-ordination of UK R&D for the management of higher activity wastes. Such co-ordination is required within the NDA, between the NDA and the rest of the nuclear industry, amongst the Research Councils and between the whole of the nuclear industry, its regulators and the Research Councils.

Regulatory Research

7.8 HSE has a responsibility to ensure that appropriate nuclear safety research programmes are carried out, including nuclear safety research related to the management of higher activity waste. It has a well-established mechanism for fulfilling this responsibility. HSE commissions its own research and sets out the research topics that nuclear site licensees should address.

7.9 EA and SEPA have relatively modest research programmes on topics of regulatory interest in the areas of radioactive waste management and related health and environmental protection issues. CoRWM believes that EA will need to commission more independent research as the MRWS programme proceeds in order to carry out its role as a regulator of geological disposal of higher activity wastes. CoRWM also expects that SEPA will need to commission research to assist it in the regulation of the management of higher activity wastes in Scotland.

Recommendation 2

CoRWM recommends to Government that it ensures that the Environment Agency and the Scottish Environment Protection Agency obtain the resources that they need to access and commission the additional independent research required to support them fully in their regulation of the management of higher activity wastes.

R&D Skills to Support the MRWS Programme

7.10 The importance of maintaining nuclear skills in the UK was recognised some years ago and steps have been taken to reverse the decline that was occurring. In recent years there has been a significant improvement but there is some way to go, particularly for R&D skills.

7.11 CoRWM has found that responsibility for the provision of R&D skills is split between many organisations. Although each organisation is playing its part, there seems to be a lack of national leadership and strategic direction. CoRWM thinks that this would be best rectified by assigning to a single organisation the responsibility for providing this leadership and direction. This organisation should be capable of taking a clear overview of the R&D skills needs of the whole of the nuclear industry, existing and new, civil and defence. CoRWM believes that the Cogent Sector Skills Council, with additional expertise, could fulfil this role.

Recommendation 3

CoRWM recommends to Government that it assigns to a single organisation the responsibility for providing national leadership and strategic direction for provision of R&D skills relevant to the long-term management of radioactive wastes.

Infrastructure Required for R&D – Facilities for Research with Highly Radioactive Materials

7.12 CoRWM considers that the UK's existing facilities for research with highly radioactive materials are inadequate and in need of improvement. In addition, new facilities need to be established in order to support the full spectrum of research relevant to the management of higher activity wastes, including geological disposal.

7.13 Almost all of the existing facilities for research with highly radioactive materials are operated by NNL. There are plans to widen access, but at present the only R&D that can be performed in these facilities is that funded by NNL customers, primarily the NDA and other nuclear industry organisations. It is essential that funders and providers of fundamental research can access the facilities they need in order to contribute to R&D for the management of higher activity wastes, both now and in the future.

Recommendation 4

CoRWM recommends to Government that it ensures that facilities for research with highly radioactive materials are improved and their capability enhanced so that they can be used for the full spectrum of research relevant to the long-term management of higher activity wastes. These facilities should be accessible to all researchers who need them.

Infrastructure Required for R&D – Underground Research Facility

7.14 Underground investigations will be needed at the site of any proposed GDF in the UK. These investigations need to include both underground site characterisation work and underground R&D if they are to provide sufficient input to GDF design and safety case development. CoRWM is of the view that this R&D should be carried out in a URF at any site where it is proposed to construct a GDF.

7.15 An R&D programme should be carried out in the URF prior to the decision as to whether to proceed with GDF construction. This programme should be discussed with a range of stakeholders, including the community local to the site and independent scientists, and agreed with regulators. The geological disposal programme should allow time to carry out the required R&D and to disseminate and assimilate its results. It should be recognised that this underground R&D may take decades. The URF should continue to be used for as long as is necessary while the GDF is open.

7.16 Until a URF is available in the UK, generic R&D should be carried out in underground facilities in other countries. This would allow UK researchers to gain the necessary experience, as well as providing information and techniques to be used in the UK geological disposal programme.

> ***Recommendation 5***
>
> *CoRWM recommends to Government that an underground research facility be constructed at any site where it is proposed to construct a geological disposal facility.*

Public and Stakeholder Engagement for R&D

7.17 At present, as in the past, stakeholders who are outside the organisations that fund and carry out R&D have little opportunity to influence UK R&D programmes on radioactive waste management. There is a general lack of transparency in establishing R&D requirements and commercial reasons are often cited as a reason for not publishing results.

7.18 CoRWM believes that this situation must change. As implied in Recommendation 1, a wider range of stakeholders should be involved in establishing R&D requirements. It is also necessary to make accessible information available to the public about R&D needs, progress and plans.

> ***Recommendation 6***
>
> *CoRWM recommends to Government that mechanisms are put in place to ensure that a wider range of stakeholders than to date will be involved in establishing R&D requirements for the long-term management of higher activity wastes and that accessible information will be made available to the public about R&D needs, plans and progress.*

Specific R&D Issues

7.19 In addition to arrangements for providing R&D and the skills and infrastructure needed for it, CoRWM also considered some of the topics on which further R&D is likely to be required for the long-term management of the UK's higher activity wastes. In doing so it recognised that future R&D programmes will need to build on the substantial body of knowledge that already exists as a result of past R&D in the UK and other countries. This current knowledge base is sufficient to be confident that geological disposal is the right way forward. In future R&D it will be necessary to focus on knowledge gaps and uncertainties that are important for UK wastes and, in the case of geological disposal, for the types of rocks in which a GDF may be located. The results of CoRWM's consideration of specific topics are in Section 6 and Appendix A. CoRWM did not attempt to identify, consider or prioritise every topic on which R&D may be needed. The material in Section 6 and Appendix A is only intended to illustrate the range of R&D that could be required over the next few decades.

APPENDIX A EXAMPLES OF R&D ISSUES

A.1 As highlighted in paragraphs 6.1 and 6.2, a substantial body of knowledge exists about the conditioning, packaging, storage and geological disposal of higher activity wastes. This knowledge base is sufficient for CoRWM to be confident that geological disposal is the right way forward. During its work CoRWM became aware of a number of topics, given in this Appendix, which it believes may require significant R&D. This list of topics, while extensive, should not be taken as a reason for not proceeding with geological disposal. It simply highlights that there are still uncertainties and knowledge gaps, inevitable in such a large undertaking, which will need to be addressed by further R&D.

Waste Package Specifications, Post-Closure Safety and Retrievability

A.2 The waste package specifications used by the NDA were developed by Nirex and are closely linked to its concepts for geological disposal of ILW (Nirex, 2007). The post-closure safety cases for these concepts did not take any credit for the waste container or the physical durability of the waste form. However, they assumed cementitious waste forms and took into account a contribution of these to the alkaline environment which would exist within a disposal facility, largely as a result of the cementitious backfill. The package specifications now include a target container life (500 years) and target time for the waste form to retain its integrity (200 years) based on storage, emplacement in a GDF and the potential for the GDF to remain open for a few hundred years with waste packages readily retrievable (NDA, 2008a). Post-closure safety is dealt with in the LoC process by assessing whether the proposed waste form will be compatible with the assumed cementitious backfill, rather than by explicit specifications. This lack of a clear link between the safety case and the waste package specifications causes confusion and makes it difficult to specify R&D requirements on the behaviour of waste packages after disposal.

A.3 In the IoP Storage meeting (CoRWM doc. 2519) the issue of the impact of the need for retrievability on R&D programmes was emphasised. However, like the issue of store lifetime, the lack of clarity on retrievability makes defining R&D programmes difficult for those in the industry. In its 2006 recommendations CoRWM made it clear that it did not see retrievability as a necessary prerequisite of any geological disposal concept for the UK's higher activity wastes. However, Government decided (Defra *et al.,* 2008) that host communities should have a role in deciding on the time for which a GDF is designed to remain open, with waste packages retrievable.

A.4 NDA waste package specifications are currently based on an assumption that retrievability may be needed for up to 300 years. This leads to a target container life of 500 years. Demonstrating this target could be met would require considerable R&D. It is thus important to clarify the status of the target. This in turn requires an examination of the technical implications of retrievability. In addition, earlier waste packages have been prepared to different, less stringent specifications, and it is uncertain whether these will comply with the newer, more demanding specifications.

Current and Planned R&D for ILW

A.5 In CoRWM's meetings with NDA, NNL, SLCs, other waste producers, regulators and others it has been made aware of some topics that are, or it believes should be, the focus of R&D programmes for ILW. CoRWM has some concerns that the 2006 NDA Needs, Risks and Opportunities in R&D document (NDA, 2006a) does not address conditioning, packaging and storage of ILW to the extent that is now appropriate. It hopes the version currently in preparation will cover these issues in this section of Appendix A in more detail. Documents that proved useful in preparing this section include the NDA's Review of UK Storage Related R&D (draft seen by CoRWM) and Nexia Solutions (now NNL) Review of the Current Status of Underpinning R&D Relating to ILW Package Longevity (Nexia, 2007). The latter report is based on a meeting of interested groups including EA, SEPA, Nirex, UKAEA, BNGSL, Magnox SLC and Nexia Solutions which was chaired by the NDA and is an example of good practice in terms of bringing all relevant stakeholders together.

ILW Containing Reactive Metals

A.6 After about 15 years of storage localised surface bulges have been observed on Magnox Encapsulation Plant (MEP) drums containing reactive metals (EA, 2008). Since these anomalies were discovered the regulators have required Sellafield Ltd to investigate what caused them to appear, as input to determining whether remedial action is required. The original LoC for the MEP drums took full account of the likely corrosion of Magnox metal in the drums during storage and contained a caveat about the uranium content of the drums. The bulges are thought to be a result of the presence of large (kilogramme-sized) pieces of uranium in the drums and operational procedures have been changed to prevent this in future. Work is continuing to confirm the causes of the bulges and assess their significance (CoRWM doc. 2464; NDA, 2008a).

A.7 Questions of wasteform durability are described within SLC TBuRDs, for example 35185 Encapsulated ILW Drum Storage and 35125 Magnox Waste Encapsulation in the Sellafield TBuRD. It is stated explicitly in the Sellafield TBuRD "This strategy covers encapsulation and safe storage of ILW products produced by consignor plants on the Sellafield site up to the point at which a disposal route becomes available".

A.8 In the context of a 500-year target lifetime for the waste container (CoRWM doc. 2389), both measurement of "store corrosivity" and quantitative assessment of "waste package degradation" are very challenging, not least because there is no current consensus on those parameters which need to be measured, and there will be a need to measure non-linear processes which give rise to very small changes and operate at very slow rates. A required element of the safety cases for storage and disposal will be a well-founded predictive model for waste package behaviour. Due to the long timescales, CoRWM believes that any such model will need to be derived from a process-based, mechanistic understanding; extrapolation from empirical data is unlikely to be sufficient. Currently, this required level of mechanistic understanding does not exist for UK waste packages.

Graphite

A.9 The UK has a large volume (about 86,300 tonnes of ILW equivalent to a raw volume of about 73,000m^3) of graphite that is activated or contaminated. This has implications for the geological disposal programme due to the large space the graphite would potentially occupy in any GDF unless waste volume minimisation technology is applied. Options for graphite treatment, reuse and disposal have been discussed at several recent workshops (Norris *et al*., 2007; NDA, 2006b). Apart from its volume, a key concern with this waste is that it contains significant quantities of the potentially mobile and relatively long-lived radionuclides carbon-14 and chlorine-36. Since geological disposal of the current volume of graphite may not be the optimal route, R&D is being undertaken to identify the better solutions. The options being considered for bulk reactor graphite are:

- Treat all graphite waste as ILW and ensure the GDF caters for the large volumes of material. This is the baseline option.
- Condition graphite waste to remove the long-lived radioisotopes and dispose of the residual graphite at LLWR or an alternative near-surface disposal facility.
- Condition LLW and/or ILW graphite waste to remove most of the contamination and free release or reuse the graphite where possible.
- Separate disposal facility (or facilities) for graphitic wastes, including a near-surface disposal option.
- Interim store ILW graphitic wastes and condition for either LLW disposal or free release.

A.10 Current graphite R&D is being carried out under the 4-year EC Carbowaste programme. The NDA is taking the lead in UK strategy development for graphite, with support from its Magnox SLCs who are optioneering potential treatment and disposal options for irradiated graphite for NDA. Currently, the reference position in the UK for the disposal of graphite is geological disposal. The reference position in France is underground disposal at depths of between 15 and 200 metres, though preliminary investigations by CEA that indicated potential for migration of chlorine-36 have led to a recommendation for disposal at depths of greater than 100 metres in thick mudrock. Russia also has a major interest in the disposal of graphite and Spain and Italy have graphite reactors. CoRWM understands that the forthcoming IAEA Co-ordinated Research Project on graphite will bring all these countries together to share expertise and ideas. There may also be a need for bilateral co-operative approaches, for example between the UK and France.

Other Planned ILW R&D

A.11 The NDA’s 2006 Needs, Risks and Opportunities document (NDA, 2006b) identified some key issues for R&D. For ILW these included increasing the ratio of waste to cement, improving grout percolation through waste and reducing the difficulties of reactive metals. Other needs highlighted included alternative (but cheap and room temperature) matrices for ILW wastes that currently are reacting with cement, an understanding of the long-term behaviour of stored wastes so minimising degradation, and remedial action on stored sea dump drums. In addition the Review of the Current Status of Underpinning R&D Relating to ILW Package Longevity (Nexia, 2007) identified issues including: failure criteria, wasteform integrity at end of storage period, overpack strategy and reworking, reactive metals, alternative options to encapsulation and alternative containers (materials/design).

A.12 CoRWM believes that R&D into remedial action on failed or out of specification packages should be addressed as a priority. Options have been examined in a review by EA (EA, 2005). NDA has also carried out some work on overpacking (NDA, 2008a), as have Magnox sites (McHugh, 2008).

Steel Corrosion

A.13 A recent review of the long-term behaviour of the steels used for ILW storage containers (Lyon, 2008) supports the general assertion that the current container materials (typically 316L and some 304 austenitic stainless steels although some early drums were mild steel) will last suitable (500 year) timescales if manufactured appropriately and stored in controlled atmospheric conditions. However, there were concerns that limited overall confidence including container material specifications, manufacture and failure criteria; aspects of internal and external corrosion; and the nature of the desired storage atmosphere. A specific concern is the ability of current steels to resist atmosphere assisted stress corrosion cracking (ASCC) which is exacerbated by the saline atmospheres prevalent at many UK storage locations.

A.14 Current research is focused on using high performance duplex alloy (mixed austenite and ferrite) stainless steels which are more resistant to ASCC. Currently, there is no national programme of developing a single best (in terms of corrosion resistance, cost and ease of fabrication) container material and different nuclear site licensees use different steels. Other key drivers in container development (CoRWM doc. 2386) are to match the container to the wasteform it contains (so high risk wastes can be packaged in a more robust container), matching containers to the store and eventual GDF environment and standardising and simplifying container design. In addition failure criteria for the containers are not well established making it difficult to develop a safety case since, in principle, any microscopic pinhole constitutes failure.

High Temperature Conditioning Processes

A.15 To date, high temperature conditioning processes have not been used in the UK for ILW. They are used in Europe and have the advantage of producing durable waste forms with low volumes. Interest in such processes has increased recently. For example, British Energy is considering hot pressing for the Sizewell B ion exchange resins (CoRWM docs. 2419, 2489), and Sellafield is considering thermal treatment for SIXEP sand, clinoptilolite and sludge (NDA, 2008a). These investigations of alternatives to encapsulation in cement are timely.

Storage Systems

A.16 An issue in storage systems is the balance between the contribution of the store building and that of the container. Some stores (*e.g.* the EPS1 store at Sellafield) are massive and provide the radiation shielding for the packages they hold but are expensive. Alternatives are simpler weatherproof store buildings with self-shielded containers, such as mini store systems, inside. The mini store concept in which ILW waste is stored in robust, thick-walled, self-shielding cast iron containers is one of several which may offer more flexibility in terms of storage and disposal options but it is at an early stage of development in the UK context. Other research and development issues for storage systems brought to our attention in meetings with NDA, SLCs, British Energy and at the IoP Storage R&D meeting (CoRWM doc. 2519) include:

- Especially for older existing stores, how do we make better predictions of their lifetimes, how can ventilation systems be improved, how can conditions in the store be better monitored and better arrangements be introduced for inspecting waste packages?
- For future stores, who is performing R&D on the newer mini-store concept now being considered?
- If Scotland plans extended near-site, near-surface storage as an option in its own right then R&D will be needed to develop appropriate concepts and detailed designs.

A.17 The first point is highlighted in paragraphs 3.36-3.38 of the CoRWM Interim Storage report (CoRWM doc. 2500) which covers the lack of suitable atmosphere control in some older stores. This has led to waste container corrosion that is faster than that envisaged when the LoC was issued, due in large part to salty coastal atmospheres. As a result it is more likely that remedial action (*e.g.* overpacking will eventually be needed prior to waste transport and disposal. There is a need to assess options for improving ventilation systems and for monitoring atmospheric conditions in stores where such conditions exist or could occur in future. It is also essential that new storage systems are designed with appropriate ventilation and atmosphere monitoring provisions. They should also have appropriate arrangements and regimes for monitoring and inspecting waste packages. The industry recognises it is not able to carry out more than very limited inspection on ILW packages in some stores and that R&D is required to develop remote monitoring and inspection techniques (CoRWM doc. 2630). Some of these points are recognised in the NDA UK storage review (NDA, 2009d).

A.18 Further R&D is needed to demonstrate that existing stores will achieve the design lives claimed for them and to assess whether these lives can be extended, and if so by how much. If controlled atmosphere stores are to be required for many decades, R&D into atmosphere-independent packages (such as ceramic overpacks) may be needed. The option of using of such packages could then be compared with the controlled atmosphere option.

Management of Spent Fuels

A.19 The existing and committed UK inventory of spent or used nuclear fuels can be divided into categories depending on type and source. The categories are: Magnox fuel, advanced gas cooled reactor (AGR), pressurised water reactor (PWR) fuel, “exotic” fuels and MoD fuels. The current management strategy for each is summarised below along with the related current and planned R&D and areas in which further R&D is likely to be needed are highlighted. An option related to the long-term management of spent fuels that is rapidly gaining favour is dry storage and R&D issues connected to this are also identified below.

Magnox Fuel

A.20 Magnox fuel consists of uranium metal in a magnesium-alloy cladding. The NDA's current strategy, as embodied in the Magnox Operating Plan, MOP8 (NDA, 2009e) is to reprocess all spent Magnox fuel. The UK Inventory indicates that around 5,800 tonnes (heavy metal, tHM) of Magnox fuel remains to be reprocessed (Defra/NDA, 2008b). Some of it is in operating reactors, some in temporary dry storage in shut-down reactors and in the Wylfa dry store, and the rest is stored under water, mainly at Sellafield. The reprocessing strategy is contingent upon the Sellafield Magnox Reprocessing Plant continuing to operate until all Magnox spent fuel that can be reprocessed has been. Given the elderly nature of the Magnox Reprocessing Plant, considerable effort and resource is being expended on keeping it operating but the possibility of chronic or acute failure before reprocessing is completed (currently projected as 2016) must be considered (CoRWM doc. 2520).

A.21 Accordingly, contingency plans for any un-reprocessed Magnox fuel are required (CoRWM doc. 2520). The NDA is investigating these (NDA, 2008d; CoRWM docs. 2418, 2500, 2624) along three principal lines, namely:

- *Reprocessing through the Thermal Oxide Reprocessing Plant (THORP)* with the recovered uranium and plutonium and the associated HLW being managed in the same way as other THORP products. This would be difficult and costly, entailing modification to the THORP head end, and would require significant R&D for the necessary adaptations of the THORP process. It would also disrupt and prolong the THORP programme. For these reasons this option is currently 'shelved' by the NDA.
- *Dry storage followed by geological disposal.* This necessitates drying the spent fuel before placing it in one of the preferred forms of dry storage (para A.34). An issue is how dry to make the fuel. There is at present no capability in the UK for drying spent fuel of any kind on a large scale but there is considerable experience in other countries. The work at Hanford in the USA, where metal fuels have been successfully dried as a prelude to dry storage and eventual disposal, is of relevance to Magnox fuel. Although the Hanford process has been shown to be viable, even for seriously corroded fuel elements, it is unlikely it could be transferred to the UK for Magnox fuel without substantial R&D (CoRWM doc. 2520). The Hanford experience is with smooth zircaloy clad metal fuel. In contrast, Magnox fuel cladding has large fins which result in a much higher surface area. Magnox fuel cladding is considerably more reactive than zircaloy and hence is much more susceptible to corrosion in water. In addition, carbonaceous deposits, which may be particularly difficult to dry out, are often found on Magnox fuel. Due to the potential for continued reactivity of uranium metal further R&D would be needed on packaging the dried product for storage and geological disposal in a UK facility (CoRWM doc. 2500). Our understanding is (CoRWM docs. 2418, 2523, 2624) that the NDA is funding some R&D into the drying of Magnox fuel and into packaging it for disposal, and will evaluate this option shortly with a view to pursuing it further.
- *Encapsulation in preparation for interim storage and geological disposal.* Experience with encapsulation of relatively small amounts of reactive metals such as uranium has shown that existing cement formulations would not be

suitable for uranium metal fuels. It would thus be necessary to carry out a substantial (and successful) programme of R&D into new encapsulants, such as polymers, glasses and alternative cements, before this option could be pursued. This would need to include R&D to demonstrate that the selected encapsulation system was suitable for geological disposal.

A.22 Even in the event that the reprocessing strategy proceeds to 'completion', it is inevitable that there will be some spent Magnox fuel that cannot be reprocessed (Defra & NDA, 2008a). In particular, the corroded and degraded fuel from the legacy ponds and silos at Sellafield (CoRWM docs. 2418, 2520) will have to be treated as waste. R&D is in progress on suitable conditioning and packaging options for legacy ponds and silos waste, in parallel with the development of methods to retrieve it (CoRWM doc. 2520; NDA, 2008a). Reducing the hazards associated with the Sellafield legacy ponds and silos has been identified as a matter of urgency by the regulators and NDA has prioritised funding to undertake the necessary work as quickly as possible (NDA, 2009a, d).

AGR Fuel

A.23 AGR fuel consists of low-enriched uranium oxide pellets in stainless steel cladding with graphite sleeves. For management purposes it is divided into two tranches, referred to as "historic" and "new" (CoRWM doc. 2419). The former includes all AGR fuel loaded into reactors on and before 14 January 2005 and the latter all fuel loaded after that date. The historic AGR fuel is the property of British Energy and about three quarters of it is contracted for reprocessing through THORP with the rest contracted to the NDA to store or reprocess at their discretion. The new AGR fuel, including any arising from extensions of AGR lifetimes, is contracted to the NDA to manage as they see fit.

A.24 For economic reasons, it is unlikely that THORP will continue operation beyond its baseload reprocessing (due by 2015) and it is predicted that between 5,500 (Defra/NDA, 2008b) and 7,000 (CoRWM doc. 2520) tHM of AGR spent fuel will remain in storage at Sellafield. The current plan for AGR spent fuel is essentially for it to remain in pond storage. Apart from capacity issues, this is not a satisfactory long-term strategy and it is incumbent upon the NDA to develop an alternative.

A.25 AGR spent fuel is stored in ponds at Sellafield. Some of it is in the THORP Receipt and Storage pond alongside (overseas owned) light water reactor (LWR) spent fuel and a large number of empty multi-element bottles. The pond water chemistry cannot be kept sufficiently alkaline to prevent corrosion of the steel cladding on the AGR fuel and there is a risk of leakage into the pond water. Sellafield Ltd has introduced short-term measures to manage the situation, including the prioritisation of reprocessing for corroded AGR fuel (CoRWM docs. 2386, 2520) and work is in progress to find a longer-term solution.

A.26 In response to the regulators, the NDA is developing an “oxide fuels strategy” (NDA, 2009d; CoRWM docs. 2418, 2520, 2624) in which it will set targets for how much of the remaining AGR fuel will be reprocessed and how and where the rest will be stored. The baseline plan is wet storage pending conditioning for disposal, with dry storage being looked at as an option. However, this would require drying of the fuel which has been stored under water. As with Magnox spent fuel, no capability exists in the UK for doing this and a substantial programme of R&D will be needed in order to pursue the dry storage option.

A.27 There has been much R&D in other countries on the conditioning and packaging of LWR spent fuel for geological disposal but there are significant differences between these fuels and AGR fuel (CoRWM docs. 2480, 2520, 2533). It is of some concern that relatively little R&D has been undertaken into the conditioning and packaging of AGR spent fuel for geological disposal (*e.g.* CoRWM doc. 2520). NDA has investigated whether the Swedish KBS-3 concept could be adapted for this purpose and has identified R&D requirements for such adaptation (CoRWM doc. 2630). Another possibility worth investigating could be the encapsulation of AGR fuel pins in lead, as has been proposed (Gibb *et al.,* 2008) as a prelude to the geological disposal of LWR spent fuel pins. Other issues likely to be important include the type of canister to be used and the leaching behaviour of the fuel once it comes into contact with groundwater.

A.28 Without demonstrating that geological disposal of AGR spent fuel is feasible, AGR fuel strategies are incomplete. Given the amount of spent AGR fuel likely to require disposal and the fact that it is almost unique to the UK, it would be sensible to give AGR fuel priority in any NDA/RWMD R&D programme into the geological disposal of spent fuels, including transport to a GDF.

PWR Fuel

A.29 PWR fuel consists of low-enriched uranium oxide pellets in a zircaloy cladding. At present it is used in the UK only at Sizewell B, where the spent fuel is stored in the fuel pond. Over the scheduled 40-year lifetime of the reactor it is expected to generate around 1,200 tHM of spent fuel (Defra & NDA, 2008b), which remains the responsibility of British Energy. British Energy has no plans to reprocess Sizewell B spent fuel (CoRWM doc. 2489). It is currently seeking to increase the approved capacity of the Sizewell storage pond by re-racking but the potential for further increase is limited.

A.30 British Energy is currently investigating dry storage (CoRWM docs. 2419, 2489) with a view to having “dry cask” storage (para A.35) on site at Sizewell by 2015. Drying of PWR fuel is much simpler than drying Magnox or AGR fuel because of its robust zircaloy cladding. PWR spent fuel is dry stored in several other countries, particularly the USA, and British Energy sees an opportunity to buy into 'off the shelf' technology. A further issue relates to the fate of the stored spent fuel. There will need to be R&D on conditioning and packaging Sizewell B spent fuel for geological disposal, and this should take into account the extensive research carried out in other countries on geological disposal of PWR fuels.

Exotic Fuels

A.31 Metal, oxide and carbide fuels from a number of experimental and other reactors, such as the Windscale Piles and the Dounreay Fast Reactor (DFR) and Prototype Fast Reactor (PFR), are grouped together as ‘exotic’ fuels. Baseline plans for the management of these exist but are poorly underpinned by R&D (CoRWM doc. 2520) and the NDA is now developing an exotic fuels strategy (CoRWM doc. 2624). Dealing with such a wide range of materials is a complex problem and it is a matter of some urgency to identify the preferred options for some of them, such as the DFR fuel, because they could involve utilising the Magnox Reprocessing Plant or THORP, both of which have limited life expectancy. DFR breeder fuel has been used as an example of the approach to be followed and the preferred strategy for it has been identified to be reprocessing in the Magnox plant at Sellafield (CoRWM doc. 2523). At present it is unclear which of the other exotic fuels can be recycled and which will have to be declared as waste (some, such as the Windscale Piles fuel, already have (Defra & NDA, 2008a)).

A.32 CoRWM agrees with the NDA that it is important to have plans for dealing with exotic fuels, so that plant, infrastructure and R&D requirements are clear (CoRWM doc. 2500).

MoD Used Fuel

A.33 Naval PWR fuel consists of zirconium-clad highly enriched uranium. The used fuel is stored under water at Sellafield on behalf of MoD, which regards it as an asset, but has no current plans for reprocessing or anything beyond the status quo. Reprocessing of such highly enriched fuel could prove difficult and could not be undertaken without a programme of R&D. The stored fuel is showing no evidence of corrosion so there is less urgency for decisions to be made compared to other forms of nuclear fuel; but it cannot remain in storage indefinitely. It is encouraging that the MoD is joining the NDA groups (such as the Strategy Development and Delivery Group and the Spent Fuel and Nuclear Materials Topic Overview Group) that deal with spent fuel management (CoRWM docs. 2523, 2500).

Dry Storage of Spent Fuels

A.34 Magnox and AGR fuels are designed for use in dry environments. They can only be stored underwater for limited periods because of the risk of corrosion and degradation. Control of the water chemistry can reduce these effects but is complex, especially where different types of fuel and other materials are present in the same pond. Dry storage is an alternative that is in use for spent fuels in a number of countries, especially for LWR fuels. It has also been used in the UK but only on a very limited scale and mostly for fuels that have not been previously stored in ponds (CoRWM doc. 2480). It is potentially cheaper than pond storage, minimises degradation and would be an appropriate precursor to geological disposal.

A.35 The spent fuel is dried, usually with hot air, and sealed into steel containers under an inert atmosphere (*e.g.*, helium, nitrogen). The containers are then stored either in modular concrete vaults (called 'silos' in the USA) or in free-standing casks of concrete, steel or other materials. Vault systems are substantial buildings, often partly below ground, in which the containers are stored in vertical tubes cooled by passive buoyant advecting air that does not come into contact with the spent fuel. These can be constructed in 2-3 years. An example of such a system is the Paks MVDS project in Hungary. Casks are large cylinders, usually of concrete and steel, and can be designed for vertical (more usual) or horizontal storage. They are cooled by convection and heat radiation from their outer surface and may be stood on outdoor dispersal pads (similar to a fenced car park) exposed to the elements in remote areas or inside a simple, purpose-built building. The former is common in the USA but the latter would be more appropriate for the UK.

A.36 Although much of the dry storage technology could be bought 'off the shelf', especially from the USA, there are a number of significant R&D issues that would need to be addressed before it could be used in the UK for Magnox and AGR spent fuels. For AGR fuel, foremost among these are studies related to how dry the fuel needs to be in order to avoid corrosion of its steel cladding during storage and so be safely stored (and subsequently disposed of), and to potential drying processes (CoRWM docs. 2480, 2500, 2520, 2533). The former include studies of the fuel clad corrosion processes in the presence of residual moisture and under different 'inert' gases. USA experience of drying metal fuels and worldwide experience of drying LWR fuels is valuable but R&D specific to the UK's fuels is required.

Management of Plutonium

A.37 R&D into management of the UK's civil plutonium[22] stockpile has been an NDA priority since its inception and has, CoRWM believes, been an example of good practice which could be used as a model for future R&D programmes. It has involved collaboration between the NDA, NNL, universities and learned societies in a co-ordinated manner. The strong input from the Royal Society (Royal Society, 2007; CoRWM doc. 2374) has lent credibility to the programme as has participation in the EU-funded Euratom programme entitled Red Impact (Red Impact, 2007).

A.38 In 2008 the NDA issued a consultation paper on options for the management of plutonium and held two stakeholder workshops (NDA, 2008e). It used the results of the consultation and the workshops in preparing a paper on "credible options" for plutonium management that was submitted to Government, with supporting technical documents (NDA, 2009f, g, h, i). The 2009 NDA documents identify four high level strategy options for managing the UK's separated plutonium:

i) continued storage until 2120, then immobilise the plutonium in a suitable waste form and dispose of the waste in a geological facility
ii) immobilise the plutonium as soon as practicable, store the resulting waste, then dispose of it in a GDF when one is available
iii) sell or lease the plutonium for recycling, then dispose of the resulting spent fuel
iv) some combination of the above.

A.39 The NDA proposed that option (i) be adopted as the reference strategy for planning purposes, while further work is carried out to develop and assess the other options (NDA, 2009f).

A.40 To date the NDA has considered several immobilisation options for plutonium. These are use of a composite cement, use of a glass composite material, use of multiphase ceramics made *via* hot isostatic pressing or cold pressing and

[22] MoD also has holdings of plutonium. Any plutonium that is declared surplus to MoD requirements becomes part of the civil stockpile and is managed under civil arrangements, although it is still owned by MoD.

sintering, and making the plutonium into low specification MOX (either in a new plant that would make MOX assemblies or by modifying the Sellafield MOX plant to produce MOX in cans). The cement option is the most expensive but also the one with the largest variations in cost, depending on how much plutonium there is in each waste package. The NDA proposed to carry out a programme of work to assess the possible waste forms in more detail, particularly from the point of view of their suitability for geological disposal (NDA, 2009g, h).

A.41 So far, the NDA has not considered the option of recycling plutonium in UK reactors (either existing or new build). This is because a further "justification" exercise would be required to allow MOX fuel to be used in this country. The NDA has assumed in its analyses that recycling would occur in another country, either in an LWR or in a CANDU reactor (use of fast reactors was not considered "credible" at present, because of the long lead time.) The NDA proposed to undertake market engagement to gauge the level of interest in recycling plutonium. If the option seemed viable, the NDA would then need to discuss with Government the type of commercial arrangement that would be acceptable (NDA, 2009g, h). There would also need to be R&D on interim storage and geological disposal of MOX fuel. This R&D would be carried out by the countries using the MOX fuel.

A.42 Government intends to hold a public consultation on long-term management of plutonium starting in autumn 2009. As a precursor it is publishing two discussion papers.[23] NDA technical work on immobilisation options for plutonium is continuing. It is possible that the Government will make a decision on the preferred method for the long-term management of plutonium in early 2010 (UK Government, 2009).

Management of Uranium

A.43 The total UK civil holdings of uranium were 96,400 tonnes at the end of 2007. Almost all of this is depleted, natural and low enriched uranium. Less than 1.5 tonnes is highly enriched uranium (*i.e.* with 20% or more uranium-235). Future arisings are estimated to be about 90,000 tonnes of depleted, natural and low enriched uranium (Defra/NDA, 2008b). Uranium is stored in various locations and in many forms including as oxides, hexafluoride, nitrates, carbides and metal. The NDA is developing a strategy for managing its uranic materials and is considering both re-use and disposal options (CoRWM doc. 2418; NDA, 2009j). It has R&D in progress for immobilisation options for separated uranium.

A.44 "Hex tails" are uranium hexafluoride (UF_6) residue from the production of enriched uranium. The tails are depleted in uranium-235 to levels well below the 0.72% by weight (wt%) of natural uranium minerals, usually about 0.2 wt%. Uranium hexafluoride is a stable solid at room temperature and pressure but sublimes to a vapour at 56.5^{o}C. It also gives off hydrogen fluoride, which is hazardous, in contact with water or water vapour. Most of the UK's holdings of Hex tails are at Urenco UK Ltd Capenhurst site. Urenco plans to "deconvert" the Hex tails back to uranium oxide (U_3O_8), which is a stable solid, and store it

23 http://www.decc.gov.uk/en/content/cms/what_we_do/uk_supply/energy_mix/nuclear/issues/plutonium/plutonium.aspx

pending a decision on its long-term management. The technology for deconversion has been established in other countries. Urenco aims to build a Tails Management Facility (TMF) at the Urenco UK Ltd site at Capenhurst, consisting of a deconversion plant for Hex tails and a uranium oxide store. The planning application has been submitted and it is hoped that the TMF will start operations in 2014.

A.45 The uranium oxide could be reconverted to UF_6 if it became attractive to re-enrich it and sell it. Another option is to condition and package the oxide and dispose of it in a geological facility in the UK. CoRWM has been told that Urenco has applied for an LoC as part of the demonstration that such an option would be practicable. This will entail providing evidence that its proposed waste form would be suitable for both storage and disposal. Urenco is also supporting international work that is investigating the possibility of sending the uranium oxide back to the original producers of the ore, for disposal in exhausted uranium mines. This would require an international agreement on the transport of uranium oxide waste from the countries where it is held to the countries where ore is produced.

A.46 The Encapsulation of Metallic Uranium Steering (EMUS) Group predates NWRF (para 3.10) and was established by Sellafield Ltd. although many other SLCs participate. Its purpose is to ensure that current and future operations, which require metallic uranium conditioning for treatment, storage and disposal, have a sound technical foundation and to facilitate timely delivery of the plans of the SLCs for site clean-up. It shares information through NWRF, but it is not an official sub group.

A.47 There is a need for a UK uranics R&D strategy to include uranium held by organisations other than the NDA, such as the MoD and Urenco (CoRWM doc. 2520).

Management of Thorium

A.48 There are small amounts of thorium at various NDA sites (*e.g.* Dounreay, Winfrith). There is no market for thorium and the current strategy is to treat it as waste for geological disposal. This strategy is straightforward if the thorium is in oxide form (because the oxide is stable and insoluble). However some forms of thorium can be pyrophoric and may require conversion to a more stable form, such as the oxide for their long-term management. It is for the NDA sites to carry out R&D on the management of their thorium holdings (CoRWM doc. 2418). Winfrith plans to complete immobilisation of its thorium metal in 2009/10. Dounreay has liquid thorium nitrate, which will need to be converted to a solid for long-term storage or disposal. The site holds an LoC for the material and plans further R&D prior to its solidification.

Some Specific R&D Issues for Geological Disposal

A.49 CoRWM has neither the remit nor resources to identify all R&D required to underpin design and construction of a GDF and to develop the safety cases, which will be made to the relevant regulators. The safety cases will indicate how the GDF is anticipated to perform during the operational and post-closure periods and will demonstrate that regulatory requirements are met.

A.50 Information on what is needed in an environmental safety case (ESC) is given in the Guidance on Requirements for Authorisation (GRA) (EA & NIEA, 2009). The GRA states that an ESC should, *inter alia*:

- demonstrate a clear understanding of the GDF in its geological setting and how it will evolve over time
- include a clear outline of the key environmental safety arguments and say how the major lines of reasoning and underpinning evidence support these arguments
- make use of multiple lines of reasoning, based on a variety of quantitative and qualitative evidence, leading to complementary safety arguments
- explain how uncertainties have been considered
- include quantitative environmental safety assessments for the operational and post-closure periods
- be updated at each stage in the development of the GDF, at suitable intervals during its operation, and at closure.

A.51 CoRWM believes that both fundamental and applied research will be needed in order to develop a robust ESC.

A.52 While some international research, particularly that of a more fundamental nature, will be helpful to the UK's geological disposal programme, much of the required R&D will be site-specific and hence cannot be conducted until candidate sites are identified. However, there are a number of underpinning non-site specific areas, both applied and fundamental, where strategic investment in R&D is required. Many of these areas are well known and have been the subject of research programmes worldwide for many years (see *e.g.* MRS, 2008). Some of them are highlighted below but CoRWM also emphasises the differing and complex needs associated with the UK's diverse wastes and the fact that the geology in which a UK GDF will be located is not yet known.

A.53 While a range of detailed R&D issues are discussed below, CoRWM considers that enough is currently known about geological disposal from previous UK and international R&D programmes to engender confidence that it is the right way forward. The current state of the UK R&D scene in the areas discussed in this section was highlighted at a meeting supported by CoRWM at the University of Sheffield in April 2009 (CoRWM doc. 2619). Other issues which came up at the meeting include: prospects for deep borehole disposal as an alternative to mined repositories for HLW; the potential for crossover of knowledge from the oil, gas and mineral industries, including seismology and geophysics techniques for site characterisation; testing of modelling predictions; and assessing the characterisation of geological environments.

Migration (Sorption, Colloids and Water Flow)

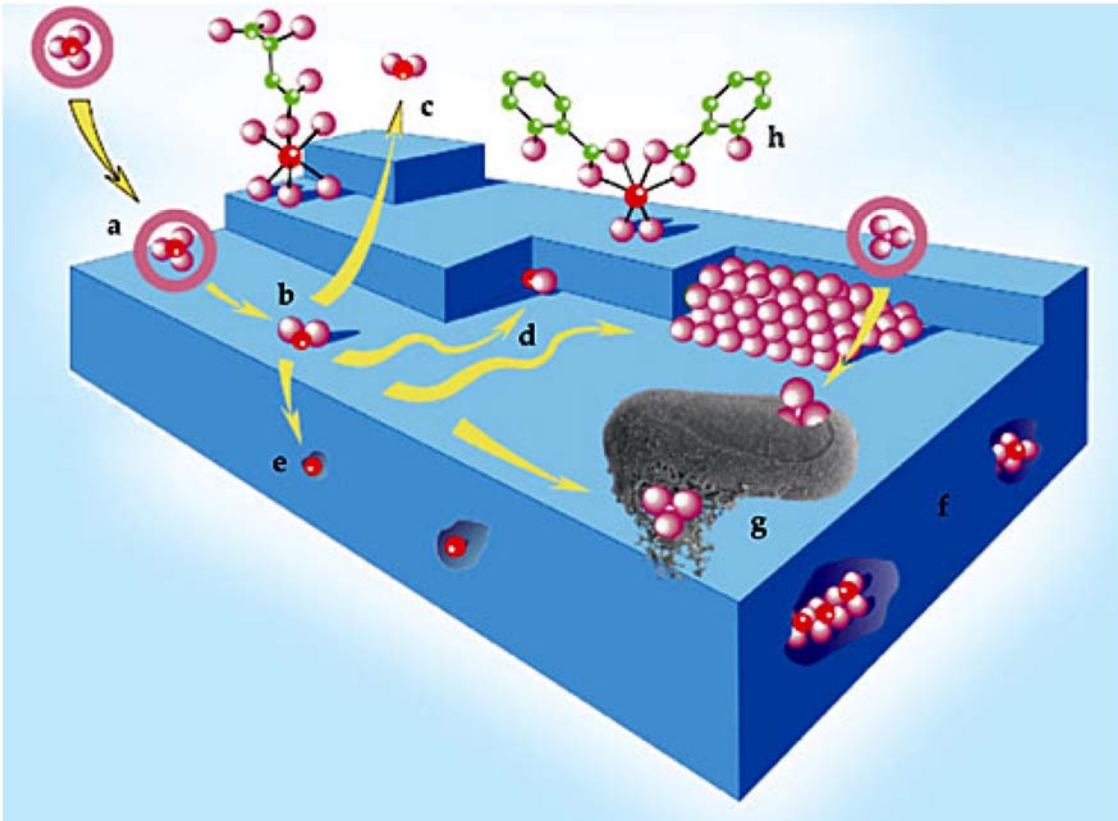
A.54 After a GDF has been closed and sealed it will resaturate with groundwater. The waste containers will slowly corrode and the radioactive species will be released from the wasteforms. These radionuclides will then interact with their environment, which will include: in the near field, backfilling materials such as cement or clay and other minerals and rocks; the engineering and chemically disturbed zones around the GDF; the host rock; and the groundwater flowing through all these. The nature of the escaping radionuclides will be complex since they may be dissolved in fluids, associated with small particles (colloids), or present in other forms. Their behaviour and their rate of migration to the far field depends on their ability to react with and become trapped on the various materials through which they pass (*e.g.* by sorption on available surfaces) and the water flow behaviour through the GDF. A review of the fundamental research required to advance geosphere understanding sufficiently to enable reliable radioactive waste disposal is provided by DePaolo and Orr (2008) who conclude that

> "*A deep understanding of the fundamental physical and chemical processes that control migration of chemical constituents underground is essential for safe and effective sequestration … of radioactive waste. Building that understanding will require a new generation of experiments and computational models… new laboratory and field techniques and perhaps most importantly, a continuing supply of broadly trained geoscientists"*

A.55 To understand and model the likely migration of radionuclides within the geosphere it is necessary to understand the fundamental properties of minerals, rocks and fluids (both liquids and gases) and their interactions. The migration of radionuclides is affected by several factors including the chemical form of the element when dissolved, its solubility, and its interactions with both mineral surfaces and with colloidal particles carried in the fluid. A wide range of adsorption processes exist (see Figure 6) and for prediction over long-time scales it is vital for models to be based on a process-based mechanistic understanding of transport phenomena. The principles governing adsorption are complex and depend critically on the nature of the mineral surface, which may vary significantly over any migration route from a GDF to the surface.

A.56 There have been a number of studies of migration, although until the geological setting of a UK GDF is known, their relevance to the UK situation is unclear. Research in this area has been a long-standing theme in the EU Euratom programme. For example, the now completed 51-partner FP6 FUNMIG project[24] involved Nirex, Loughborough University and the University of Manchester, focused on providing tools for scientifically sound performance assessment for radionuclide migration from near-field to hydrosphere/biosphere and encompassing the range of different radioactive waste disposal approaches and host-rocks types under investigation in Europe. In addition, the recently-ended NF-Pro (FP6)[25] programme had 40 partners, including RWMD, Serco, Galson Sciences Ltd., BGS, Quintessa and the Universities of Cardiff and Sheffield from the UK. The project investigated key processes operating in the near field.

[24] *http://www.funmig.com/*
[25] *http://www.nf-pro.org/*



A variety of chemical transport processes (yellow arrows) and structures exist at a mineral surface in contact with a fluid. A trace-metal ion (red) is carried in the fluid as a complex with a hydration shell (pink circle). The processes depicted include **(a)** physical adsorption, **(b)** dehydration followed by chemical adsorption, **(c)** detachment, **(d)** surface diffusion and attachment at a step, **(e)** ionic substitution with an atom in the bulk, **(f)** trapping at crystal imperfections, **(g)** the binding of atoms to an organic coating (gray), and **(h)** adsorption of an organo-mineral complex.

Figure 6. Adsorption Processes
Source: DePaolo and Orr, 2008.

A.57 Further work is needed to understand and model radionuclide migration to a level that captures the uncertainty over future behaviour so that migration can be represented appropriately in a safety case. In particular, more understanding is required of:

- radionuclide physico-chemical form (speciation)
- the spatial variability, temporal evolution and reactivity of mineral surfaces
- upscaling molecular level models to estimate bulk chemical properties, both thermodynamic and kinetic, and transport over spatial scales from nanometres to hundreds of metres.

A.58 These issues are discussed in detail in Boxes 7-9.

Box 7. Radionuclide Speciation

Many of the elements which are important in geological disposal (*e.g.* iodine, technetium, uranium, neptunium, plutonium) can access different oxidation states with very different chemical properties, and hence may be present as different complexes with bound water and other ligands (Runde, 2000). The chemical form will control solubility and subsequent sorption. In the extreme (carbon-14), speciation changes may even affect whether a radionuclide is present in the solid, liquid or gas phases. Chemical speciation is also influenced by biological processes, either directly through entrainment of a radionuclide in active metabolic processes, or indirectly, through reaction of a radionuclide with a biogenic chemical species.

A chemical reaction will only proceed when the system as a whole moves from a higher to a lower energy. A reaction which proceeds rapidly to the lower energy state is said to be under "thermodynamic control". However, the existence of an energetic driving force does not necessarily mean that the reaction will occur to any significant extent because the reaction may proceed slowly. In such a case, the reaction is said to be under "kinetic control".

It is relatively easy to predict the thermodynamic end state of a reaction, but many reactions which are important in geological disposal, for example reaction of rocks with alkaline fluids, or the crystallisation of minerals, are kinetically controlled and, because the progress of such a reaction will depend on the time elapsed, it is much harder to predict the behaviour of such systems. Several key processes relevant to geological disposal are in practice under kinetic control and some, such as colloid-mediated transport, represent major uncertainties in establishing the GDF safety case (King *et al.* 2001). Biological effects can affect the path of a reaction; for example, CO_2 is thermodynamically unstable in strongly reducing conditions but the kinetics of chemical reduction to CH_4 are so slow that the reaction essentially does not occur. However, biotransformation by some micro-organisms of CO_2 to CH_4 is efficient, so a system with appropriate biological activity will contain CH_4, whereas one which cannot support bioreduction will contain CO_2.

Box 8. Mineral Surface Reactivity

At the molecular level, the surfaces of minerals are very reactive through a range of different mechanisms. Some, such as the feldspar surface, undergo a series of pH-dependent leaching, dissolution and precipitation reactions, leading to the formation of altered and secondary layers on the surface (Chardon *et al.,* 2006) while others interact through dissolution and reprecipitation, which leads to overturn of the surface (Morse & Arvidson, 2002). These surfaces interact with solutes by a range of processes, including inner- and outer-sphere surface complex formation, surface precipitation and other poorly defined interactions. Although they differ in the detail of their mechanisms, and this has important implications for mobility, these are often collectively referred to as "sorption" reactions (*e.g.* Brown *et al.,* 2007).

Box 9. Modelling

At a spatial scale of metres to hundreds of metres, which is appropriate to geological disposal, given the complexity of both the engineered and natural components of the GDF, host rock and biosphere, and given the timescale over which the safety of the GDF must be assessed, it is necessary to use predictive computer models. These are often referred to as reactive transport models, and many of these are now very sophisticated, incorporating multiphase flow and detailed description of the system (Steefel *et al.,* 2005). However, these models inevitably incorporate considerable simplifications and approximations.

There is also a range of modelling approaches which can be used to understand interaction of radionuclides with surfaces at the molecular level, complementing experimental studies of sorption reactions. Density functional theory is well established and is now sufficiently developed to describe complex elements such as actinide ions in solid matrices or adsorbed on surfaces (see *e.g.* Skomurski *et al.,* 2006). Although such modelling is far from routine, draws heavily on very demanding experiments, and remains very challenging, it offers the prospect of understanding and predicting reactions in complex, environmentally relevant systems at a fundamental, molecular level.

The integration of this molecular scale modelling, which is soundly rooted in physical and chemical principles, and prediction over much larger spatial and time scales, which is needed to assess GDF performance, remains very difficult. Nevertheless, if the gap between these different scales and approaches can be bridged, the product will be a powerful predictive tool. The USDOE has identified three Grand Challenges in the geosciences, two of which centre around this particular question (USDOE, 2008).

Gas

A.59 The generation and movement of gases in a GDF are of concern for two reasons. One is that sufficient gas might be generated to affect groundwater movement or even disrupt the GDF. The other is that radioactive gases could move through the rocks to the surface and lead to radiation exposure of humans and other organisms. Consequently, a balance must be sought between providing sufficient gas permeability within the GDF to prevent an excessive rise in gas pressure, and inhibiting both fluid flow and the migration of trace radioactive gases into the geosphere. The principal mechanisms for generation of bulk gases are anaerobic corrosion of metals, especially steels, and decomposition of organic wastes. Radioactive gases can be formed by interactions of bulk gases with the wastes, and by decay of some radionuclides (for example, radon is a decay product of uranium).

Hydrogen

A.60 The GDF, particularly after closure and resaturation, will contain large volumes of water, either free groundwater or bound in waste encapsulants like cement, or in backfill. Radiolysis (breakdown by reaction with radiation arising from radionuclides) of water generates hydrogen gas, which is vented from most ILW waste containers. The external radiation field around ILW and HLW containers will promote water radiolysis in groundwater and backfill. There will be several hundred thousand tonnes of metals in any GDF, most of which will be steels, which are a constituent of some wastes and of most ILW containers (Royal Society, 1994). HLW containers are also made of steel and may be placed in steel overpacks for disposal. Anaerobic corrosion of metals will generate considerable quantities of hydrogen. Tritium will be released from wastes and could mix with the bulk hydrogen gas or form tritiated water, although its short half-life (12.6 years) means that is very unlikely to reach the surface in significant quantities.

A.61 Subsurface microbial communities are often well adapted to exploit hydrogen as an energy resource (*e.g.* Nealsen *et al*., 2005; Pedersen, 2002) so the fate of hydrogen is intimately linked to the evolving microbial ecology of the GDF. For example, the hydrogen supply in a GDF will be much greater than that in a pristine environment, with the potential to trigger a microbial bloom whose consequences may be difficult to predict.

A.62 BGS is the lead researcher in the ~£2M EU FORGE programme on gas migration and is supported in this by the NDA. The FORGE project is designed to characterise and quantify the conditions during geological disposal under which the formation of hydrogen and other gases will occur with sufficient pressure increase to result in radionuclide migration from the repository into the surrounding host rock. It is predicted that corrosion of ferrous materials under anaerobic conditions in a repository will lead to the formation of hydrogen. Radioactive decay of the waste and the radiolysis of water will produce additional gas. Movement of these repository gases through host rocks will occur by the combined processes of molecular diffusion and bulk advection. If the gas production rate exceeds the rate of diffusion of gas molecules in the pores of the EBS or host rock, it is possible that a discrete gas phase could form and accumulate until its pressure becomes sufficiently large for it to enter the EBS or host rock. The FORGE project is designed to characterise and quantify the conditions under which this may occur, enabling modelling to underpin GDF design that lies within a safe gas generation envelope. BGS is involved in experimental, monitoring and modelling research contributing to three of the five work packages comprising FORGE. These include its Large Scale Gas Injection Test (Lasgit), fundamental issues of gas migration in bentonite, carbonation reactions of buffer/backfill cements and their impact upon gas and radionuclide migration, the effect of stress field and mechanical deformation on permeability and fracture self-sealing, validation of critical stress theory applied to repository concepts, and baseline hydraulic and gas transport properties of Callovo-Oxfordian argillite.

Carbon-containing gases

A.63 Methane and carbon dioxide will be produced in bulk by the various mechanisms involved in the decomposition of organic materials in the wastes. The volumes of methane and carbon dioxide generated will be much smaller than the volume of hydrogen because there will smaller quantities of organic materials in a GDF than there are of metals (perhaps a few tens of thousands of tonnes of organic materials (Royal Society, 1994)). How much of the methane and carbon dioxide is radioactive will depend on how much carbon-14 there is in the wastes in the GDF and in what chemical form. This will in turn depend largely on how much irradiated graphite is present and the method of treatment prior to disposal.

A.64 Carbon gases can be exploited by anaerobic micro-organisms either as an energy resource (methane) or as a terminal electron acceptor (CO_2), so there is potential for a microbial community to cycle between these forms of carbon. The chemical behaviour will also be very different, depending on whether the carbon is present as methane or carbon dioxide. For a given pressure and pH, methane is significantly less soluble than carbon dioxide. Further, carbon dioxide solubility is particularly dependent on pH: in a high pH GDF, ^{14}C-carbon dioxide is expected largely to exist in solution as carbonate and bicarbonate ions and to form relatively insoluble calcium carbonate solid. By contrast, a neutral pH GDF, for example one with bentonite backfill, will be much less efficient at trapping carbon dioxide.

Other gases

A.65 Some ILW streams, for example Dounreay raffinates, contain relatively-high concentrations of nitrate which, in an anaerobic system, can be transformed by biological processes into gaseous nitrogen species, particularly nitrogen gas. The implications of this occurrence on GDF performance are not clear although it may be useful to estimate the inventory of nitrate proposed for the GDF and, if it is significant, to consider the likelihood of nitrogen gas generation. Similarly, sulphate will be present in cementitious materials (encapsulant and backfill), with the potential for microbial production of hydrogen sulphide. Radiolysis of polyvinylchloride (PVC), used extensively in waste packaging, generates gaseous hydrogen chloride (LaVerne *et al*., 2008). Both hydrogen sulphide and hydrogen chloride are chemically reactive and are very likely to react close to the point of generation, with the potential to promote localised corrosion, perhaps accompanied by a decrease in pH.

Criticality

A.66 A key issue in design and construction of a GDF is the amount of radioactive material present which, if it collects together over time, could have the potential to aggregate into a critical or super-critical mass and cause a nuclear fission reaction. In this discussion, the term fissile is used specifically to describe an isotope which has a significant ability to undergo fission when irradiated with thermal neutrons. Only a relatively small proportion of the GDF inventory is fissile.

A.67 The likelihood of criticality within a GDF will depend primarily on the inventory of fissile isotopes disposed, the form in which they are disposed and the long-term behaviour of the relevant wasteforms. Criticality was considered in relation to the original Nirex ILW repository concept (*e.g.* Hicks & Green, 1999). It is much more of an issue for any GDF containing spent fuel (and separated plutonium) because the fissile inventory of such a GDF would be greater by many orders of magnitude than that of an ILW repository. There has been substantial work on criticality in those countries that plan to dispose of spent fuel, for example the USA and Sweden. This is an area in which the UK can make extensive use of the R&D carried out in other countries.

A.68 Criticality can arise from either the removal of neutron-absorbing waste components, or the leaching out and accumulation of fissile material. The risk of criticality will change over time due to radioactive decay which can both remove and create fissile isotopes. As the isotopic mix changes, so the cross sections, critical mass and spontaneous fission-derived neutron flux will all change. Thus plutonium-239 (fissile; half life 24,100 years) decays to uranium-235 (fissile; half life 750 million years) but the critical mass for plutonium-239 is substantially lower than that for uranium-235. Likewise, plutonium-241 (fissile; half life 14.3 years) decays to americium-241 (non-fissile; half life 432 years).

A.69 Several transuranic elements decay by spontaneous fission to some degree, and while this is often a minor pathway (*e.g.* 5.75 x 10^{-6}% for plutonium-240), it can be very significant in some cases (*e.g.* 8.39% for curium-248). The presence of such isotopes is important in criticality because spontaneous fission maintains an elevated neutron flux and the higher the neutron flux, the easier it will be to initiate a self-sustaining criticality. The inventory of spontaneously fissioning isotopes will therefore be important. These are relatively low in AGR spent fuel but greater in higher burn-up fuels. There are uncertainties in the likely inventories of heavy actinides because the physical data for their formation are not well known.

A.70 The criticality hazard of a GDF depends on factors such as the facility design, the nature and distribution of wastes within the GDF, and the composition and geometry of the wasteforms. It may be possible to reduce the hazard, for example by including neutron poisons in waste forms or backfill, and hazard assessments are an important input to GDF design.

A.71 The assessment of criticality hazard is demanding, requiring knowledge of wasteform performance, nuclear physics data, fissile material migration in the GDF environment, and neutron transport modelling. In the absence of specific information on the GDF, wasteforms and inventory, the primary need for R&D into criticality is to preserve and develop capability for use as more details of the GDF are resolved. While we do not yet know the scope of the work undertaken, it is nevertheless encouraging that NDA has apparently recognised this need and has supported Serco Assurance and Imperial College to carry out some research.

Multiphase Fluid-Solid Interactions in Perturbed Geochemical Environments

> "*Over a wide range of scenarios, the thermodynamic properties of complex geological fluids and solids, and the reaction rates among phases and species, must be known to define the critical environmental parameters that control migration or immobilization of wastes*." (USDOE, 2008a)

A.72 It is accepted (USDOE, 2008a) that the emplacement of radioactive waste into a geochemical environment that has previously reached a steady or equilibrium state over a relatively long time will lead to reactions among minerals, pore waters, and the wastes or their engineered container/buffer system. The reactions and interactions triggered by perturbations to the original *in situ* conditions may be both sudden and gradual, because the changes in temperature and gas pressure, chemical gradients, oxidation-reduction conditions, or radiation fields are non-linear and subject to feedback effects.

A.73 Most fluid in fine-grained and/or low permeability rocks (*e.g.*, shales, bentonite, many igneous rocks), is present as nanometre-scale fluid films and in submicron-scale pores (USDOE, 2008a). This leads to mesoscopic reaction and transport rates that are governed by microscopic fluid-mineral surface environments. Transport of contaminants into these microenvironments is therefore an important first step leading to immobilisation on mineral surfaces or incorporation into minerals by precipitation, coupled dissolution-precipitation, or solid state diffusion (*e.g.* Hoskin & Burns, 2003). Prediction of whether immobilisation of radionuclides may occur under the conditions that evolve as a disposal facility and its wastes change over time is important for assessment of GDF performance.

A.74 Almost any reaction between a GDF and emplaced wastes and EBS will result in chemical changes that are both kinetically and thermodynamically regulated (*e.g.* Grambow, 2006; Geisler *et al*., 2007; Putnis & Geisler, 2007). Hence, predictive theories are required that link relevant equilibria to reaction rates and mechanisms. These need to be founded on an integration of experimental, analytical and computational approaches. A key problem in applying reactive transport modelling to a GDF lies in quantifying the relative roles of surface reactions and diffusion processes on overall reaction rates (*e.g.* Grambow, 2006). There is at present no general model that can account for how coupled processes influence transport mechanisms and chemical reactions at grain surfaces and boundaries, in fluid films, and in pore throats and pores. This means that extensive experimentation is required. Even then in the absence of an integrated and robust theoretical model the mineral reaction rates obtained will apply only close to the chemical systems for which they were measured, and the extent of process coupling in these is usually unknown.

A.75 To add to the level of complexity, multiphase fluid systems are likely to prevail in engineered systems designed for geological disposal of nuclear waste (USDOE, 2008a). However, current understanding of such multiphase systems at 40-110°C and 2-10 MPa is very limited, and generally confined to macroscopic thermodynamic models for H_2O-CO_2 and H_2O-CO_2-NaCl-KCl at low salinities. The macroscopic models do not take into account the documented effects of surface tension on thermodynamic properties of aqueous species and the partial pressures of gases or supercritical fluids. Furthermore, mass transfer between fluid phases can alter the composition of those fluids. For example, the generation of fluid (gas) from radioactive decay in a repository may displace water from pore and compacted buffer space, leaving saline brine films on mineral surfaces, and these brine films may stimulate surface chemical reactions that preferentially degrade radwaste canisters.

A.76 These considerations apply to assessment of the impact of alkaline fluids on materials deposited in a GDF, including bentonite buffer and, potentially, vitrified HLW if and when canisters corrode and fail (USDOE, 2008b; Grambow, 2006; Geisler *et al.,* 2007). As such alkaline fluids may be generated through the interaction and equilibration of groundwaters with cementitious materials, GDF designs that limit the use of cement in the environments into which HLW is to be deposited have clear advantages (NUMO, 2004).

Co-location of ILW, HLW and Other HAW in One GDF

A.77 Co-location is a term used by Government and the NDA to mean disposal of HLW, ILW and other types of HAW in a combined GDF in which there are separate parts of the facility for the various types of waste (as shown schematically in Figure 3 of the MRWS White Paper, Defra *et al.*, 2008). NDA concepts for a co-located GDF involve the assumption that the geometry of the facility is such that there will be no significant adverse interactions between the near-field of the part containing the ILW and LLW and the near-field of the part containing the HLW and spent fuel. An important question for site selection and GDF design is how this can be achieved in various geological environments. A key question is whether it is possible to demonstrate that there will be sufficiently limited interaction between the two near-fields over sufficiently long time periods for a post-closure safety case to be developed. There are a number of topics on which R&D is required in order to address these questions and hence inform a decision on whether one co-located GDF or two (or more) separate GDFs will be the most appropriate option.

A.78 ILW disposal concepts considered to date in the UK involve the use of large volumes of cement-based materials in the waste packages, the backfill and in construction of a GDF. Several concepts for the disposal of HLW and spent fuel involve the use of bentonite backfill. The cement-based materials will cause groundwaters that come into contact with them to become highly alkaline. The potential interactions between these high pH groundwaters and bentonite require further research, as do the interactions between high pH groundwaters and vitrified HLW.

A.79 At a major workshop on bentonite-cement interaction (NUMO, 2004) it was emphasised that significantly more and new experiments, and new coupled chemical diffusion–advection models, are required to understand and predict bentonite behaviour, including swelling and evolution of high gas pressures, dissolution, cementing and porosity reduction by precipitation of silica, cation and anion affinities under high pH, and overall barrier system performance. Most workers considered that low pH alternatives to Ordinary Portland Cement (OPC) and composite cement systems need development, and that systems with lower cement/bentonite ratios were less likely to be problematic than those in which the cement/bentonite ratio is high or the groundwater chemistry in a GDF environment dominated by cement interaction (NUMO, 2004).

A.80 The NUMO 2004 executive summary and conclusions, which constitutes their considered set of suggestions and recommendations for future action, is extracted below to illustrate the recognised issues:

- Additional experiments to verify present understanding should be undertaken.
- Additional information on the long-term evolution of cement-barrier systems would be desirable.
- Consideration should be given to long-term experiments.
- Analogues could yield useful information.
- There are underground laboratory facilities, such as the Mol URL in Belgium, which have been operating for 20 to 30 years and could be used to give useful information on these time-scales.
- It is desirable for new materials to be considered in place of cement and to question ‘conventional wisdom’ which states that cement is the best material to use for construction and barrier functions in many circumstances.
- It is desirable to develop low pH cements (pH ≤ 11, but not so low as to promote excessively rapid corrosion of steel materials) with particular

properties for certain applications, such as grouting where water-rock interactions at higher pH would have detrimental effects

- It is important to identify which of the possible problems that have been highlighted by experimental and theoretical investigations would actually be encountered in real repository environments.

A.81 Most investigations of the leaching behaviour of vitrified HLW have considered natural groundwaters, rather than the highly alkaline groundwaters that could be present in a co-disposal situation. As a result, there are significant uncertainties about the reactivity of borosilicate glasses in these circumstances. Whether radionuclides are immobilised through mineral precipitation or rendered mobile and then transported in alkaline but also saline fluids are issues that also need intensive study (Hoskin & Burns, 2003; Grambow, 2006; Geisler *et al*., 2007; Putnis & Geisler, 2007). UK glasses are more reactive than the French equivalents due to their high Mg content (Abraitis *et al*., 2000), illustrating the need for caution in using experimental data from overseas. There is a clear need for further experiments on borosilicate glass stability in the presence of complex alkaline and saline fluids under both static and dynamic (*i.e.* with fluid flow) conditions.

A.82 Corrosion of metals will generate gas in both the ILW/LLW and HLW/spent fuel parts of a co-located GDF. However, the amounts of gas that will be produced in the ILW/LLW part are greater because there will be more metallic waste containers, much ILW consists of metals, and some ILW is organic and will degrade to form gases (paras A.59-A.65). There is therefore an issue of whether gas generated in the ILW/LLW part of a facility could affect groundwater movement in the HLW/spent fuel part of a facility.

GDF Design

A.83 The process of GDF design is discussed in the CoRWM report to Government on geological disposal (CoRWM doc. 2550). In that report CoRWM emphasised the need to consider a wide range of disposal concepts, constructed using various techniques, at depths ranging from about 200m to more than 1km. R&D may be required to enable the options (including co-location) to be evaluated and compared at the conceptual level.

A.84 Options for GDF designs cannot be developed in any detail until potential sites have been identified and assessment of these sites has begun. An integrated process of GDF design, site assessment and safety case development work is then required to provide input to design and siting decisions (CoRWM doc. 2550). R&D requirements will be identified in the course of this process. In the meantime, useful studies could be undertaken to define the influence that the form of the underground openings and excavation and support methods have on design. In relation to tunnel and shaft design the quality of the rock mass and the *in situ* stress conditions will greatly influence the size, shape, support requirements and the proximity of openings to one another. It is considered that research is required in the following areas:

- Response of the rock mass to excavation and extent of any disturbance of the rock adjacent to underground openings.

- Long-term stability and performance of underground openings.
- Long-term operation and maintenance of GDF tunnels and shafts.

Geosphere Characterisation

A.85 MRWS Stage 5 involves undertaking surface based investigations at the site of any proposed GDF (Defra *et al*., 2008). This is part of the process of geosphere characterisation which involves obtaining geological, hydrological and environmental data related to the development of a GDF. The purpose of collecting the data is to support the development of a safety case and will underpin the engineering design of the facility.

A.86 NDA is currently progressing a Geosphere Characterisation Project which was started in 2004 by Nirex with the purpose of demonstrating that it was practicable to characterise a site for development of a GDF. Under the NDA the current aims of this project are to maintain and develop an understanding of the approaches to the design and implementation of the investigations (both surface and sub-surface) that would be required and prepare for such a project.

A.87 The characterisation of a potential site or sites for a GDF is a major multi-disciplinary project requiring a wide range of skills many of which are specialist. The NDA status report on the Geosphere Characterisation Project (NDA, 2007) indicates to CoRWM that the complexity and magnitude of the task is recognised and that techniques and procedures are being developed to deliver the project.

A.88 The status report indicates that site investigations will be focused on obtaining data that are pertinent to the dual tasks of engineering design and the development of a safety case while avoiding data that has no relevance to these objectives. In doing so it will be necessary to identify what the data needs are for the project and then establish what the state-of-the-art practices are with respect to data collection, investigation equipment, analysis, interpretation and application.

A.89 The Geosphere Characterisation Project will then review these practices and their applicability to the UK's range of geology, the proposed disposal concepts and the availability of skills and supporting infrastructure (laboratories *etc*). RWMD has started this process by identifying the principal subject areas in which data will be required and it has commenced the assessment of state-of-the-art practices in some of these. The areas in which data are required have been identified by review of current and previous investigations both in the UK and overseas. The establishment of current best practice in each subject is being undertaken by the NDA technical supply chain.

A.90 It is CoRWM's view that the processes established within the Geosphere Characterisation Project are well planned and the objectives are clear. In the context of this report, CoRWM's interest lies in whether the review of state-of-the-art practices in subject areas is effectively highlighting gaps that require R&D, and whether such work is being, or will be, actively pursued.

A.91 CoRWM is aware that the NDA has appointed technical consultants with a series of framework contracts to support the development of the Geosphere

Characterisation Project. Work has commenced in developing and understanding of the information needs of the project and current best practices. The status report presents overviews of the assessment of geochemistry, deep drilling, wireline testing and groundwater monitoring instrumentation. These subject areas were selected for early study by the NDA because it was recognised through dialogue with overseas WMOs that these are the most significant challenges to the implementation of a geosphere characterisation programme.

A.92 The status report (NDA, 2007) sets out areas for possible R&D in these subject areas, a summary of which is as follows:

Geochemistry (Intellisci, 2008)

- Research is required into the methods and equipment for sampling groundwater and down hole monitoring of *in situ* redox and pH.
- Research is required to define the chemical descriptions and models proposed to describe the EBS (near field), the geosphere and the biosphere. Similarly work is required to define the models of site-scale hydrology, hydrogeology and paleohydrogeology and how these can be tested and calibrated.
- Research and development is suggested in relation to the sampling of groundwater concurrent with drilling operations to ensure that "first strike" samples can be obtained from discrete target sampling zones.

Deep Site Investigation Borehole Drilling (EPS International, 2007)

- The optimal drilling method proposed was the use of hybrid drilling rigs suitable for both test/sample drilling and coring. These rigs are not readily available and while no research is required there needs to be developmental work with regard to rig design and borehole casing strategies.

Geophysical Wireline Logging, Logging-While-Drilling & Wireline Testing

- The status report highlights the fact that there is variable accuracy among various techniques for down hole data acquisition. It is likely therefore that some research is required to establish absolute accuracy.

A.93 CoRWM considers that the process of identifying the information needs summarised above is sound and that research identified in future through this process should be undertaken. Currently it is unclear to CoRWM whether R&D arising from this process is progressing or is planned or whether the skills have been identified to undertake the work. In defining the research needs it is important to recognise that any GDF may not be sited in hard crystalline rock but, for example, in low permeability mudrocks.

A.94 The status report (NDA, 2007) states that studies for 2007-08 comprised geomechanical testing, groundwater sampling, radionuclide migration properties and geophysical surveys. CoRWM considers that through the adopted process information gaps will be identified that require R&D. Among these will be the following issues:

- The performance of any rock mass is dictated to a large extent by the characteristics of naturally-occurring fractures. These vary in scale from a few millimetres to tens of metres. They are generally formed as a result of stresses applied to the rocks over geological time and their presence has a significant effect on the geomechanical behaviour of the rock mass. To understand the influence of these features fully it is considered that their genesis should be understood. This is an area where site specific research in the related fields of structural geology and rock mechanics would aid site characterisation.

- The current distribution of stress within a rock mass is influenced by the distribution, frequency and nature of the fractures present. Research into the relationship between fracture distribution and stress fields would aid in site characterisation.
- Understanding the controls on identification and description of the distribution of permeability in low-permeability rock units will be essential to the characterisation of a potential GDF site.
- Research will be required in relation to understanding, in a fractured hard rock, the connectivity and transmissivity of the network of fractures. In addition research will be required into any lithological and structural controls on permeability distribution.
- Water passing through fractures in the rock mass is influenced by the surface characteristics of the fracture surfaces. This will change depending upon the *in situ* stress conditions. Research to understand the influence of fracture wall roughness and *in situ* stress would be useful in the characterisation process.
- Geophysical techniques will be employed during site characterisation to understand the spatial variability both horizontally and vertically of the various rock types and geological structures at any proposed site. This will assist in understanding groundwater movement and an initial assessment of rock mass and material parameters. 3D seismic investigation and other geophysical techniques have been developed for mine planning over recent years as highlighted at the RWIN Meeting in April 2009 (CoRWM doc. 2619). It is considered that research into the use of these techniques in relation to possible GDF sites could inform geosphere characterisation and assist in GDF layout and the design.

Microbiology

A.95 Biological, and particularly microbiological processes, have considerable potential to influence performance of a GDF, for example through accelerated degradation of *e.g.* cemented wastes (Avaim *et al.,* 2004; Rogers *et al.,* 2003), corrosion of steel containers (Landoulsi *et al*., 2008; Xu *et al*., 2008), perturbation of biogeochemical conditions, generation of colloids and complexants (Gaona *et al*., 2008; Glaus and Van Loon, 2008) and modification of flow paths (Suchomel *et al*., 1998; Ross *et al*., 2007).

A.96 The microbial ecology of the GDF will be complex for several reasons. First, it is very likely that there will be an indigenous microbial community in the host rock formations. This will be perturbed during construction and exposed to a very diverse array of immigrants, many of which could potentially colonise. On closure and resaturation, when anaerobic conditions are reinstated, the new community will evolve further. Evolution in community composition and genomes will be driven by factors such as pH (potentially very high), temperature, the radiation field, water availability (possibly low in a highly compacted bentonite buffer or an evaporite geology) and generation of hydrogen as an electron donor. In any event, the microbial community will certainly not return to its pristine state. Thus, microbial processes represent major uncertainties in the performance of a GDF.

A.97 While many aspects of a GDF's microbial ecology will be site specific, there remains a requirement to conduct generic research and build essential capability, for example in techniques for the sampling and characterisation of subsurface microbial communities, which are technically very difficult (Pedersen, 2002); the ecology of high pH, anaerobes and thermophiles; or the ecology of radioactive, hydrogen-rich systems.

Temporal Evolution of Geosphere

A.98 Temporal evolution of the geosphere is poorly understood over timescales of one hundred to one million years. Direct experimental observations and human induced perturbations (*e.g.* effects of oil and gas extraction or mining) are all based on short time periods of less than 100 years (often substantially less), whereas observations of geosphere evolution based on geological analogues are on long timescales (10 thousand to 100 million years).

A.99 Temporal evolution of the geosphere will potentially produce significant changes in groundwater chemistry, regional groundwater gradients, rock hydraulic properties, geochemical properties (including mineralogical surfaces for adsorption), mechanical loading, microbial ecology and sea level. Evolution of the geosphere may involve gradual change such as mineralisation of fracture surfaces causing a gradual decrease in local permeability and increase in mechanical strength, or may be much more rapid as result, for example, either of climate change causing rapid global temperature change or of earthquake activity. Isotope geochemistry can provide data on evolution of past geochemical environments (over 100 to one million year timescales). However, it is not possible to determine from these data the *rate* of individual mineralisation episodes (*e.g.* short episodic pulses of rapid fluid movement versus constant time averaged flow rates); there is also no clear basis for using such data to predict the future.

A.100 To better characterise geosphere evolution and reduce uncertainty in model predictions, CoRWM believes that a fundamental mechanistic understanding is required of the processes governing physical, chemical and microbiological evolution of the geosphere. Further, to validate such models, new field analogues should be sought that illuminate the role of individual processes in geosphere evolution and are applicable to the timescales appropriate for geological disposal.

Radionuclide Movement in the Biosphere

A.101 In the geological disposal context "biosphere" means soils, surface waters, sediments, the atmosphere and the animals and plants that live in these parts of the environment, including humans. It is clear that, over the timescales of interest in geological disposal, it is not possible to predict how the surface environment at any particular site will change, nor how plants and animals will evolve. The approach used for the purposes of developing GDF safety cases is to carry out calculations based on a range of possibilities for temporal changes in the surface environment, all with the characteristics and behaviour of humans, other animals and plants taken to be as they are in similar environments today. This is known as the “reference biosphere” approach (Health Protection Agency, 2009). Typical safety case calculations employ several reference biospheres, each for a different climate state that could occur at the future at a GDF site. The states differ in aspects such as temperature and rainfall, and, for coastal sites, sea level.

A.102 The models and data required for the reference biosphere approach largely exist. The models have been developed over many years using experimental and observational data (for example, on the movement of radionuclides routinely discharged to air and sea from nuclear facilities). Since the whole ‘calculational’ approach is stylised, it is unnecessary to perform uncertainty analyses.

A.103 The adoption of the reference biosphere approach means that there is a limited requirement for biosphere R&D for geological disposal safety case purposes. This is not to say that such R&D is not needed for other purposes, or that the knowledge gained in other contexts should not be used for GDF safety cases. There may also be a need for R&D to improve predictions of radionuclide movement through the geosphere-biosphere interface (for example, movement from rocks to soils and sediments).

APPENDIX B REFERENCES

CoRWM Documents

Note: All CoRWM documents are available on the CoRWM website, *www.corwm.org.uk*.

Number	*Title*
700	Recommendations to Government, 2006
2266	CoRWM Work Programme 2008-2011, June 2008
2323	Working Group C Work Plan, April 2008
2373	Note of meeting with NDA on R&D issues, 29 April 2008
2374	Note of plutonium follow-up meeting, Royal Society, 22 April 2008
2386	Note of meeting with Sellafield Sites Ltd, 19 June 2008
2389	Position Paper on R&D for Conditioning, Packaging and Interim Storage of Higher Activity Wastes and Management of Spent Fuels, Plutonium and Uranium, June 2009
2408	CoRWM comments on draft NDA-RWMD R&D Strategy, January 2009
2414	Note of meeting with Office for Civil Nuclear Security, 23 July 2008
2418	Note of meeting with NDA on spent fuels, plutonium and uranium, 8 August 2008
2419	Note of meeting with British Energy, 11 August 2008
2443	Note of meeting with NNL, 1 September 2008
2444	Meeting with Adrian Bull, Chair NSAN NW & NE Employer Steering Group, 3 August 2008
2455	Note of R&D meeting at Geological Society, 11 September 2008
2456	Note of meeting with BGS, 26 September 2008
2459	Note of meeting with NDA on LoC Process and Waste Package Specifications, 6 October 2008
2464	Note of meeting with EA and SEPA on waste conditioning, packaging and storage, 17 October 2008
2480	Note of Radioactive Waste Immobilisation Network (RWIN) technical meeting on radwaste storage R&D, 16 October 2008
2484	Note of meeting on scientific issues in site selection and characterisation, Geological Society, 13 November 2008
2488	Report of 30 October 2008 PSE event
2489	Note of visit to Sizewell B, 23 October 2008

Number	*Title*
2500	Interim Storage of Higher Activity Wastes and the Management of Spent Fuels, Plutonium and Uranium. CoRWM Report to Government. March 2009
2515.2	CoRWM's 2009-12 Work Programme, March 2009
2519	Note of Institute of Physics / CoRWM Interim Storage Meeting, 26 November 2008
2520	Note of meeting with HSE and EA on spent fuels, plutonium and uranium, 9 December 2008
2523	Note of meeting with NDA on spent fuels, plutonium and uranium, 11 December 2008
2524	Note of meeting with RCUK, Swindon, 3 December 2008
2540	Log of responses to consultation on outline Interim Storage report
2550	Geological Disposal of Higher Activity Radioactive Wastes. CoRWM report to Government, July 2009
2562	Log of responses to consultation on full draft of Interim Storage report
2563	Report of CoRWM 19 February 2009 stakeholder workshop on the draft Interim Storage report
2581	Storage R&D consultation response log, June 2009
2619	Note of Radioactive Waste Immobilisation Network (RWIN) technical meeting on geological disposal R&D, 23 April 2009
2624	Meeting with NDA on CoRWM Interim Storage Tasks for 2009-10, 11 June 2009
2630	Log of responses to consultation on CoRWM's report on national research and development for interim storage and geological disposal of higher activity radioactive wastes, and management on nuclear materials, October 2009
2677	Report of CoRWM 9 September 2009 stakeholder workshop on draft R&D report
2688	Note of visit to Harwell re LoC Process, February 2008

Other Documents

Note: All documents are available on the website of any organisation listed, unless otherwise stated.

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APPENDIX C GLOSSARY AND ACRONYMS

Glossary of Terms

Notes
1. The Glossary defines terms in the way that CoRWM uses them. Differences from definitions given in publications by the Government, the regulators, the NDA and others are intentional.
2. Definitions are in normal text; additional comments and examples are in square parentheses [ ] and italics.

Active facility	A facility where radioactive materials can be used. [*Such facilities are subject to safety, security and environmental regulation.*]
Advanced Gas-Cooled Reactor (AGR)	A UK designed, gas-cooled reactor with a graphite moderator. [*It uses enriched uranium oxide fuel with steel cladding and graphite sleeves. The primary coolant is carbon dioxide.*]
Applied research	Investigation directed primarily towards a specific practical aim or objective, which can involve using existing knowledge and understanding or acquiring new knowledge.
Basic research	See "Fundamental research".
Becquerel (Bq)	The standard international unit of measurement of radioactivity, equivalent to one disintegration per second. [*Related units are the:* *kilobecquerel (kBq) – one thousand Becquerels* *Megabecquerel (MBq) – one million Becquerels* *Gigabecquerel (GBq) – one thousand million Becquerels* *Terabecquerel (TBq) – one million million Becquerels.*]
Biosphere	That part of the environment where most organisms live. [*Includes soils, surface waters and their sediments, and the atmosphere.*]
Chemically disturbed zone	A region surrounding the engineered zone of a "geological disposal facility" that is affected by release of leachate. [*Particularly significant where cementitious backfill is used, since the high pH effluent from the GDF will cause extensive reaction with the host rocks.*]
Co-disposal	Generally, disposal of wastes with differing physical and chemical characteristics in the same facility. Now specifically used in the UK by Government, CoRWM and others to mean disposal of new build waste in the same facility as existing and "committed" waste. [*Often used in radioactive waste management literature to mean "co-location".]*

Co-location	Disposal of "high level waste", "intermediate level waste" and other types of "higher activity waste" in a combined "geological disposal facility" in which there are separate parts of the facility for the various types of waste. *[For example, there could be one part of the facility for intermediate level waste and another part for the high level waste and spent fuel.]*
Committed waste	Radioactive waste that will arise in future from the operation or decommissioning of existing nuclear facilities. [*As distinct from existing waste, which already exists, and new build waste, which will only arise if new facilities are built.]*
Conditioning	Any process used to prepare waste for long-term storage and/or disposal. [*Usually by converting it into a suitable solid form e.g. incorporation in glass (vitrification), encapsulation in cement*.]
Contingent strategy	A strategy that can be used if it becomes clear that the "Reference strategy" is no longer appropriate. [*Colloquially, "Plan B". In most radioactive waste management situations several contingent strategies are required, in order to address various possible future scenarios ("Plans C, D etc."*).]
Deep borehole disposal (DBD)	Disposal of waste in boreholes more than 1000m deep. [*Also known as very deep geological disposal and very deep disposal.*]
Desk-based studies	Review, summary, collation or evaluation of existing knowledge, information, facts and research outcomes. *[In the context of the UK geological disposal site selection process, assessing the suitability of sites using existing knowledge about the geology, surface environment, communities etc.]*
Development	Progressive, systematic use of knowledge and understanding gained from "research" directed towards the production or improvement of materials, devices, systems or methods. [*Includes the design and development of processes*.]
Disposal	Emplacement of waste in an appropriate facility without the intention of retrieving it. [*Retrieval may be possible but if intended the appropriate term is "storage".*]
Disposable	A waste package is disposable if it can be safely removed from a store, transported to a disposal facility and emplaced in that facility, and if it will play its planned role in ensuring the post-closure safety of that facility.

Encapsulation	A conditioning process in which radioactive waste is physically enclosed in a non-radioactive material that prevents radionuclides from moving. [*The most commonly used encapsulants are types of cement. Others include polymers.*]
Engineering disturbed zone	A region surrounding the engineered part of a “geological disposal facility” that has been affected by construction of the facility. [*For example through stress or fracturing*.]
Enriched uranium	Uranium in which the mass content of the isotope uranium-235 is above the level in natural uranium ores (0.72% by mass).
Exotic fuel	Term used by the UK for any type of nuclear fuel that is not from a commercial nuclear power reactor. [*Mainly fuels from research reactors and nuclear powered submarines*.]
Far-field	The “geosphere” beyond the “near-field”. [*i.e. the rocks and subsoil undisturbed by the presence of the geological disposal facility.*]
Fundamental research	Original, exploratory investigation involving experimental or theoretical work undertaken primarily to acquire new knowledge and understanding of phenomena and observable facts without necessarily having any immediate application or use in view.
Geological disposal	Generally, emplacement in the Earth’s crust with no intent to retrieve. Used specifically in the MRWS programme to mean “disposal” of radioactive waste in an underground facility, where the geology (rock structure) provides a barrier against escape of radioactivity and where the depth, taken in the particular geological context, substantially protects the waste from disturbances arising at the surface.
Geological disposal concept	Any variant of geological disposal, including the use of a “mined repository”, “deep boreholes” and more than one “geological disposal facility”.
Geological disposal facility (GDF)	Any facility used for geological disposal. [*Includes mined repositories, natural caverns, disused man-made caverns or mines, and deep boreholes*.]
Geological disposal facility design	The detailed drawings and specifications that will allow construction of a “geological disposal facility”. *[Includes nuclear, civil, mechanical, electrical. Materials, chemical, geotechnical and geological engineering aspects.]*
Geological repository	See “Mined repository”.

Geosphere	Solid portion of the earth consisting of the crust and part of the upper mantle. *[Often used in the geological disposal context to mean rocks, subsoil and the water and organisms in them].*
Hex tails	Uranium hexafluoride residue from the production of enriched uranium. [*Hex tails are depleted in uranium-235 to levels well below the 0.72 wt% of natural uranium, usually about 0.2 wt%. Uranium hexafluoride is a stable solid at room temperature and pressure but sublimes to a vapour at 56.5 °C. It reacts vigorously with water or water vapour.*]
Higher activity waste (HAW)	Radioactive waste with activity above the thresholds for low level waste (LLW), *i.e.* above 4 GBq/tonne alpha activity or above 12 GBq/tonne beta gamma activity. [*It is usually also taken to include LLW unsuitable for near-surface disposal.*]
High level waste (HLW)	Radioactive waste in which the temperature may rise significantly as a result of its radioactive content, so that this factor has to be taken into account in the design of waste storage or disposal facilities. [*In practice the term is only used in the UK for the nitric acid solutions arising from reprocessing spent fuels and for the vitrified form of the solutes in these solutions.*]
Historic waste, historical waste	See “legacy waste”.
Host community	A community in which a geological disposal facility may be built. [*It is a community in a small geographically well-defined area, such as town or village, and includes the population of that area and the owners of the land.*]
Hot cell	A heavily shielded containment in which manipulations of highly radioactive materials can be carried out using remote handling techniques.
Immobilisation	A conditioning process in which radioactive waste is chemically incorporated into a non-radioactive material so that radionuclides cannot move. [“*Vitrification” and incorporation in ceramics are types of immobilisation processes.*]
Interim storage	Storage of radioactive waste prior to implementing a final management step, such as “geological disposal”.
Intermediate level waste (ILW)	Radioactive waste exceeding the upper activity boundaries for “low level waste” (*i.e.* over 4 GBq/tonne alpha activity or 12 GBq/tonne beta gamma activity) but for which its heat output need not be taken into account in the design of storage or disposal facilities.

Legacy facility	A nuclear facility constructed several decades ago where waste has been generated or stored.
Legacy waste	Radioactive waste that arose several decades ago. [*A subset of existing waste; sometimes called "historic waste" or "historical waste". The term is usually reserved for wastes kept in, or that have arisen in, legacy facilities.*]
Low level waste (LLW)	"Radioactive waste" with activity levels that do not exceed 4 GBq/tonne alpha activity or 12 GBq/tonne beta gamma activity. [*Subsets of LLW include "very low level waste" (VLLW) and exempt waste (i.e. "radioactive waste" with activity levels below those in the various Exemption Orders made under the Radioactive Substances Act).*]
Low Level Waste Repository (LLWR)	The UK national disposal facility for low level waste. [*Located near the village of Drigg in Cumbria.*]
Magnox reactor	A UK designed gas-cooled reactor with a graphite moderator. [*It uses uranium metal fuel of natural isotopic composition with a magnesium alloy cladding.*]
Mined repository	A facility specifically excavated and constructed for the "geological disposal" of radioactive waste. ["*Mined and engineered repository" is a more correct description. Most designs consist of shafts or adits leading to tunnels and vaults.*]
Near-field	The part of a disposal facility near or in contact with the "waste packages", including filling or sealing materials and those parts of the host rock whose characteristics have been or could be altered as a result of the presence of the disposal facility.
Near-surface disposal	Disposal at or close to the surface of the Earth. [*Includes underground disposal in the Earth's crust at depths less than a few tens of metres, and emplacement in engineered structures at or just below ground level. Formerly called "shallow land burial" or emplacement in a "near surface repository".*]
Neutron transport modelling	Simulation of the pathways, energetics and lifetimes of neutrons. *[Used particularly in the control of criticality which is mediated by neutrons.]*
Overpack	An additional container for a waste package. [*Usually to make it more suitable for storage, handling, transport or disposal.*]
Package	See "Waste package".

Packaging	Placing waste into a container for long-term storage and/or disposal. [*In most cases this includes conditioning but sometimes waste is simply placed in containers, with or without compaction to reduce its volume*.]
Primary research	The obtaining of knowledge, facts and data that did not previously exist. [*All fundamental and much applied research is primary.*]
Pond	A water-filled structure in which nuclear fuel is stored. [*Usually made of concrete, the water provides cooling and shielding*.]
Pressurised water reactor (PWR)	A nuclear reactor in which water is used as the coolant and moderator. [*The fuel is enriched uranium oxide with "zircaloy" cladding. PWRs operate above atmospheric pressure to prevent the water boiling.*]
Public	People who have no particular interest in, and are not affected by, radioactive waste management. [*CoRWM distinguishes between "stakeholders" and the public.*]
Radioactive waste	Radioactive waste is defined in the Radioactive Substances Act 1993. In essence it is any substance for which there is no further use and in which artificial radionuclides are present at any level and/or natural radionuclides are present above the levels given in Schedule 1 of the Act. [*Note that spent fuels, plutonium and uranium are not radioactive wastes unless it has been decided that there is no further use for them and they are declared to be wastes*. *The Radioactive Substances Act definition of radioactive waste is under review and it is expected that a revised definition will be put in place in 2010.*]
Radioactive waste management	All the activities involved in managing radioactive wastes. [*Includes minimising arisings, all types of treatment (e.g. decontamination, sorting, segregation), "conditioning", "packaging" and "disposal"*.]
Raw waste	Waste that has not been conditioned.
Recoverability	The ability to remove wastes from a closed disposal facility by mining, drilling boreholes *etc*. [*Unlike "retrievability", recoverability does not entail the inclusion of any specific design features in a disposal facility.*]
Reference strategy	A strategy that is based on realistic assumptions about the future and that represents the course of action that is to be followed unless circumstances change. [*Colloquially, "Plan A". See also "Contingent strategy"*.]

Repository	A facility where waste is emplaced for disposal. [*Often used as shorthand for "mined repository", but also used in other contexts, e.g. the UK's Low Level Waste Repository (LLWR)*.]
Research	An investigation directed to the discovery of some fact or principle by a course of study or scientific enquiry.
Retrievability	An ability to withdraw wastes from a disposal facility that is achieved by means designed into the facility other than simply reversing waste emplacement. [*See also "reversibility" and "recoverability".*]
Reversibility	The ability to withdraw wastes from an open disposal facility by reversing the emplacement process.
Rock Characterisation Facility (RCF)	An underground facility for use in characterising the physical, chemical, mechanical and hydrological suitability of the geological environment for "geological disposal". [*A term used mainly by Nirex for the facility it proposed to construct in Cumbria.*]
Safety assessment	An assessment of whether a nuclear facility or operation is or, if particular actions are taken, will be safe.
Safety case	The complete set of arguments that demonstrates that a nuclear facility or operation is or, if particular actions are taken, will be safe.
Secondary research	Review, summary, collation or evaluation of existing knowledge, facts and outcomes of basic and applied research.
Scientific research	The application of the scientific method to obtaining new information to explain the nature, properties or behaviour of something in the universe around us.
Silo	A structure used for storage or disposal of radioactive waste. [*The term is applied in the UK mainly to concrete structures (buildings) used for temporary storage of wastes, but it can also apply to vertical shafts in rock used for underground storage or disposal*.]
Spent fuel	Fuel that has been used in a nuclear reactor and for which there is no further use as fuel.
Stakeholder	A person or organisation who has an interest in or is affected by radioactive waste management. [*In the context of CoRWM's work, stakeholders include waste producers, regulators, non-governmental organisations, local authorities and communities near existing nuclear sites and potential disposal sites*.]
Stakeholder fatigue	A situation in which stakeholders are overwhelmed by communications and consultations on a particular topic, and do not respond to requests for their views.

Stillage	A metal frame used to hold drums of radioactive waste.
Storage	Placing wastes or other materials in a facility with the intention of retrieving them at a later date.
Surface-based investigations	Investigations of a potential geological disposal site that are carried out from the surface, rather than underground. [*For example, seismic investigations and boreholes.*]
Tonne	One thousand kilograms.
Underground Research Laboratory (URL)	An underground facility for "research" into "geological disposal". [*Some URLs are at prospective disposal sites, others are in geological settings similar to those proposed for geological disposal but remote from potential disposal sites.*]
Underground Research Facility (URF)	A site- or host rock specific underground facility for characterisation and R&D related to geological disposal.
Very low level waste (VLLW)	Very low level radioactive waste (VLLW) is LLW that has radioactivity levels well below the maximum for the category. It can be disposed of with non-radioactive waste, rather than being placed in the Low Level Waste Repository or other specialised facility. [*There are two types of VLLW: low volume and high volume. Low volume VLLW is radioactive waste that can be disposed of safely to an unspecified destination with municipal, commercial or industrial waste (so-called "dustbin disposal"). It has an activity not exceeding 400 kBq in any $0.1m^3$ and no individual item in the waste should have an activity above 40 kBq. These levels are increased by a factor of ten for tritium or carbon-14 (i.e. 4 MBq in $0.1m^3$ and 400 kBq per item, where the limits apply to tritium and carbon-14 taken together). High volume VLLW is radioactive waste that can only be disposed of to a specified landfill site. Its activity level must not exceed 4 MBq/tonne or 40 MBq/tonne for tritium.*]
Vitrification	The process of converting wastes into a glass or glass-like form.
Voluntarism	An approach to siting geological disposal facilities that involves communities voluntarily expressing an interest in holding discussions with Government, then deciding whether to participate any further.
Waste hierarchy	The hierarchy of principles used in waste management. These consist of: (1) non-creation of wastes where practicable; (2) minimisation of arisings; (3) recycling and reuse; (4) disposal.
Waste package	A container and all its contents . [*Includes the waste, any encapsulating material, any capping grout, etc*.]

Zircaloy	An alloy of zirconium used for cladding nuclear fuel.

List of Acronyms

AECL	Atomic Energy of Canada Ltd
AGR	advanced gas cooled reactor (A type of reactor with a graphite core, and uranium oxide fuel in steel cladding with a graphite sleeve.)
ALARA	as low as reasonably achievable
ALARP	as low as reasonably practicable
ALS	Advanced Light Source (at University of California Berkeley, USA)
ANDRA	Agence Nationale des Déchets Radioactifs (French state-owned agency for radioactive waste management)
ANRE	Agency for Natural Resources and Energy (Japan)
APM	adaptive phased management (of spent nuclear fuel, Canada)
APS	Advanced Photon Source (at Argonne National Laboratory, USA)
ASCC	atmosphere assisted stress corrosion cracking
ASN	Autorité de Sûreté Nucléaire (French regulator)
AWE	Atomic Weapons Establishment (at Aldermaston). (AWE plc is the company that runs Aldermaston and Burghfield under contract to the Ministry of Defence.)
BAT	best available techniques
BE	British Energy
BERR	Department for Business, Enterprise and Regulatory Reform (now part of the Department for Business, Innovation and Skills)
BGS	British Geological Survey
BIS	Department for Business, Innovation and Skills
BNES	British Nuclear Energy Society
BNFL	British Nuclear Fuels Ltd
BNG	British Nuclear Group

BNGSL	British Nuclear Group Sellafield Ltd
BPEO	best practicable environmental option
BRGM	Bureau de Recherches Géologiques et Minières (French equivalent of BGS)
BTC	BNFL Technology Centre (now the Central Laboratory) at Sellafield
BWR	boiling water reactor
CANDU	Canadian deuterium uranium reactor (a reactor with natural uranium fuel and heavy water (deuterium oxide) as the moderator and coolant)
CASE	Co-operative Award in Science and Engineering (scheme to support PhD research in UK)
CEA	Commissariat à l'Energie Atomique (French government-funded technological research organisation)
CEGB	Central Electricity Generating Board
CNE	French national R&D evaluation commission
CNRS	Centre National de la Recherche Scientifique (French government-funded national centre for scientific research)
CoRWM	Committee on Radioactive Waste Management
CPD	continuing professional development
CRIEPI	Central Research Institute of the Electric Power Industry (Japan)
CRP	Co-ordinated Research Project (run by IAEA)
CRR	Centre for Radiochemistry Research (BNFL URA at Manchester University)
DBD	deep borehole disposal
DECC	Department of Energy and Climate Change
DECOVALEX	Development of Coupled THCM Models and their Validation against Experiments (an international project)
Defra	Department for Environment, Food and Rural Affairs
DFR	Dounreay Fast Reactor or Directorate of Fisheries Research (part of MAFF)

DfT	Department for Transport
DIAMOND	Decommissioning, Immobilisation and Management of Nuclear Wastes for Disposal (a consortium of universities carrying out research, funded by RCUK)
DIUS	Department for Innovation, Universities and Skills (now part of the Department for Business, Innovation and Skills)
DOE	Department of Energy (USA)
DoE	Department of the Environment (UK, subsequently the Department for Environment, Transport and the Regions, DETR))
DRP	Direct Research Portfolio (the directly funded NDA research programme)
DSSC	disposal system safety case (being developed by NDA)
EA	Environment Agency (for England and Wales)
EARP	Enhanced Actinide Removal Plant (at Sellafield)
EBS	engineered barrier system
EC	European Commission
EDF	Electricité de France
EDZ	engineering disturbed zone
EIA	environmental impact assessment
EMUS	Encapsulation of Metallic Uranium Steering Group (established by Sellafield Ltd)
EPS	Encapsulated Product Store (at Sellafield, there are three stores: EPS1, EPS2 and EPS3)
EPSRC	Engineering and Physical Sciences Research Council
EU	European Union
FEPs	features, events and processes (to be considered in post-closure safety cases for GDFs)
FHP	fuel handling plant
FORGE	Fate of Repository Gases (an EU project)

FP	Framework Programme (of the European Union)
FSD	Food Sciences Division (part of MAFF)
FUD	Forskning, Utveckling och Demonstration (Research, Development and Demonstration programme, Sweden)
FZD	Forschungszentrum Dresden (federally-supported research centre, Germany)
GBq	gigabecquerel (a unit of radioactivity)
GDF	geological disposal facility
GLEEP	Graphite Low Energy Experimental Pile (a research reactor at Harwell)
GOCO	Government owned, contractor operated
GRA	Guidance on Requirements for Authorisation (for disposal of solid radioactive wastes, produced by the environment agencies)
HAW	higher activity waste
HAWS	higher activity waste strategy
HLW	high level waste
HMIP	Her Majesty's Inspectorate of Pollution
HPA	Health Protection Agency
HSE	Health and Safety Executive
IAEA	International Atomic Energy Agency (a United Nations agency)
IGSC	Integrated Group on the Safety Case (of NEA's RWMC)
ILW	intermediate level waste
INE	Institut für Nukleare Entsorgung (Institute for Nuclear Waste Disposal, federally-supported research centre at Karlsruhe, Germany)
INSU	Institut National des Sciences de l'Univers (French national institute for earth sciences and astronomy, maintained by CNRS)
IOMMM	Institute of Materials, Minerals and Mining
IoP	Institute of Physics

IPSE	Institute for Particle Science and Engineering (BNFL URA at Leeds University)
IRSN	Institut de Radioprotection et de Sureté Nucléaire (French agency that advises ASN on radiological and nuclear safety
ISL	Immobilisation Science Laboratory (BNFL URA at Sheffield University)
ITRG	Independent Technical Review Group (Canada)
ITU	Institut für Transurane (European institute for transuranic elements, Karlsruhe, Germany)
IVO	Imatran Voima Oy, (Finnish nuclear power company, now Fortum)
JAEA	Japanese Atomic Energy Authority
JRC	(European Union) Joint Research Centre
KNOO	Keeping the Nuclear Option Open (a consortium of universities carrying out research, funded by RCUK)
KTA	Knowledge Transfer Account (an EPSRC funding scheme to encourage knowledge transfer from universities to industry)
LLW	low level waste
LLWR	Low Level Waste Repository (near Drigg, in Cumbria)
LMI	labour market intelligence (research)
LoC	Letter of Compliance (previously Letter of Comfort)
LTP	lifetime plan (produced for each NDA site)
LWR	light water reactor (a generic term, includes BWRs and PWRs)
MAFF	Ministry of Agriculture, Fisheries and Food
MEP	Magnox Encapsulation Plant (at Sellafield)
METI	Ministry of Economy, Trade and Industry (Japan)
MKG	Miljöorganisationernas Kärnavfallsgranskning – (Swedish NGO office for nuclear waste review)
MoD	Ministry of Defence
MOP	Magnox Operating Plan (the current plan is the eighth, MOP8)

MOX	mixed oxide fuel (contains uranium and plutonium oxides)
MPC	Materials Performance Centre (BNFL URA at Manchester University)
MRC	Medical Research Council
MRP	Magnox reprocessing plant (at Sellafield)
MRWS	Managing Radioactive Waste Safely (the UK programme for the management of higher activity wastes)
NAS	(USA) National Academy of Sciences
NDA	Nuclear Decommissioning Authority
NDARB	Nuclear Decommissioning Authority Research Board on nuclear decommissioning and waste clean-up
NEA	Nuclear Energy Agency (part of the Organisation for Economic Co-operation and Development)
NERC	Natural Environment Research Council
NGO	non-governmental organisation
NIEA	Northern Ireland Environment Agency
NII	Nuclear Installations Inspectorate (part of HSE)
NNL	National Nuclear Laboratory
NRI	Nuclear Research Index (compiled by HSE)
NSAN	National Skills Academy for Nuclear
NSG	Nuclear Skills Group
NTEC	Nuclear Training Education Consortium (UK)
NuSAC	Nuclear Safety Advisory Committee (now disbanded, advised HSE)
NUMO	Nuclear Waste Management Organisation (Japan)
NVQ	National Vocational Qualification
NWAT	Nuclear Waste Assessment Team (within the Environment Agency)
NWMO	Nuclear Waste Management Organisation (Canada)
NWRF	Nuclear Waste Research Forum (a group convened by the NDA)

OCNS	Office of Civil Nuclear Security (part of HSE)
OECD	Organisation for Economic Co-operation and Development
ONE	(USA) Office of Nuclear Energy
OPC	ordinary Portland cement
OPECST	Office Parlementaire d'Evaluation des Choix Scientifiques et Technologiques (French Parliamentary Office for evaluation of scientific and technical options)
P&T	partitioning and transmutation
PACE	Programme sur l'Aval du Cycle Electronucléaire (French programme of nuclear research)
PCM	plutonium contaminated material
PDRA	post-doctoral research associate
PFR	Prototype Fast Reactor (at Dounreay)
PIA	Preliminary Investigation Area (Japan, for a GDF)
PNNL	Pacific Northwest National Laboratory (USA)
PVC	polyvinylchloride
PSE	public and stakeholder engagement
PWR	pressurised water reactor
RADREM	Radioactivity Research and Environment Monitoring (Committee of UK DoE)
RAEng	Royal Academy of Engineering
RCEP	Research Councils Energy Programme or Royal Commission on Environmental Pollution
RCF	rock characterisation facility
RCUK	Research Councils UK (co-ordinating body for the various Research Councils)
R&D	research and development
RRG	Research Review Group (advises HSE on nuclear safety research)

RS	Royal Society
RSC	Royal Society of Chemistry
RWMAC	Radioactive Waste Management Advisory Committee
RWMC	radioactive waste management case (a safety case for a proposed waste conditioning and packaging process) or Radioactive Waste Management funding and research Centre (Japan) or Radioactive Waste Management Committee (of NEA)
RWMD	Radioactive Waste Management Directorate (of NDA)
SAC	Scientific Advisory Committee (of RCUK)
SEPA	Scottish Environment Protection Agency
SGHWR	Steam Generating Heavy Water Reactor (an experimental reactor at Winfrith)
SISB	Science and Innovation Strategy Board (NERC advisory committee)
SIXEP	Site Ion Exchange Plant (at Sellafield)
SKB	Svensk Kärnbränslehantering AB (Swedish nuclear fuel and waste management company)
SKI	Swedish Nuclear Power Inspectorate (now part of SSM)
SLC	site licence company (a company that runs an NDA site, under contract to the NDA, and holds the nuclear site licence)
SMS	strategy management system (of the NDA)
SNIFFER	Scotland and Northern Ireland Forum for Environmental Research
SNWF	Swedish Nuclear Waste Fund
SSEC	sub-surface exclusion criteria
SSI	Swedish Radiation Protection Institute (now part of SSM)
SSM	Strålsäkerhetsmyndigheten (Swedish Radiation Safety Authority)
SSRL	Stanford Synchrotron Radiation Laboratory (USA)
STFC	Science and Technology Facilities Council
STUK	Säteilyturvakeskus (Finnish radiation and nuclear safety authority)

TBuRD	Technical Baseline and underpinning R&D Document (produced by each SLC for its sites)
THCM	thermal-hydraulic-chemical-mechanical (coupled processes)
tHM	Metric tonnes of Heavy Metal (uranium and plutonium)
THORP	Thermal Oxide Reprocessing Plant (at Sellafield)
TMF	Tails Management Facility (to be built at Urenco's Capenhurst site)
TSB	Technology Strategy Board (of BIS)
TVO	Teollisuuden Voima Oy (Finnish nuclear power company)
UKAEA	United Kingdom Atomic Energy Authority (now used only as an acronym, mainly as part of the names of the organisations into which the Authority was split)
URA	University Research Alliance (*e.g.* with NNL)
URF	underground research facility
URL	underground research laboratory (or underground rock laboratory)
USDOE	United States Department of Energy
USGS	United States Geological Survey
USNRC	United States Nuclear Regulatory Commission
VPS	Vitrified Product Store (at Sellafield)
WAGR	Windscale AGR (an experimental reactor at Sellafield)
WIPP	Waste Isolation Pilot Plant (a geological disposal facility in New Mexico, USA)
WMO	waste management organisation
ZEBRA	Zero Energy Breeder Reactor Assembly (an experimental facility at Winfrith, now dismantled)

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