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Nirex Report

The viability of a phased geological repository concept for the long-term management of the UK's radioactive waste

nirex

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1 EXECUTIVE SUMMARY AND INTRODUCTION

Radioactive waste exists in the UK now. Some of it will remain hazardous for hundreds of thousands of years. Regardless of any decision on future nuclear energy, steps need to be taken now for its safe long-term management.

This report sets out why Nirex believes that the UK's long-lived radioactive waste should be placed in a Phased Geological Repository located between 300 and 1000m deep in stable rock. This would allow the natural process of decay to take place before radionuclides reach the surface in sufficient amounts to exceed the stringent safety requirements set by UK regulators.

The report takes the form of an Executive Summary and Introduction, followed by increasing levels of detail as we lay out the reasoning behind our views.

Viable solutions have been developed for long-term radioactive waste management. Many countries have high activity, long-lived radioactive wastes to manage. Geological disposal is the preferred option of all countries that have made a decision for the long-term management of such wastes. Most of these are now developing concepts that also incorporate retrievability and a phased approach to implementation.

In the UK, Nirex has carried out extensive development work on geological disposal of radioactive waste and more recently on its Phased Geological Repository Concept and a concept for the UK's high level waste and spent fuel. Retrievability and monitoring are essential requirements for many stakeholders and are now an integral part of the Nirex concept. The incorporation of monitoring and retrievability into a phased approach combines the flexibility of storage with the long-term passive safety of geological disposal.

Whilst technical solutions have been available for many years, there has never been successful implementation of those solutions in the UK. This report summarises why Nirex believes that its Phased Geological Repository Concept (PGRC) is the viable technical option for the long-term management of the UK's higher activity radioactive waste that can and should be implemented now.

The concept is viable in that:

- The repository system is entirely based on tried and tested technology routinely used in the mining, construction and nuclear industries.

- Its system of multiple barriers can be relied upon to provide long-term isolation and containment of the waste and hence assure long-term safety and environmental protection.

- The long-term performance has been evaluated using well established assessment tools and the results show that all relevant UK regulatory criteria can be met.

- Whilst there is further work to be done, none of the remaining issues present a fundamental threat to the viability of the concept.

- It provides a monitored, retrievable underground storage system as a positive step towards the provision of a long-term management solution that will not require continuing actions or intervention by future generations.

The UK can proceed now with implementation:

- The geological characteristics required from a site are well understood and are afforded by a significant proportion of the deep geology in the UK.
- Repository concepts are based on well developed science and technology in the UK and overseas.
- Lessons learned from past experience, extensive dialogue and links with overseas programmes that are gaining acceptance within their communities have now provided the UK with a good understanding of the overall requirements for implementation.

The repository concept should be implemented now because:

- The waste exists. It is an ethical issue and the technology to implement a solution is available now.
- Existing storage arrangements for radioactive wastes are vulnerable to terrorist attack and natural disasters and many of the facilities are unsatisfactory and long past their design life.
- The skills, resources and experience needed to implement the PGRC are available now but would need to be re-established in the future if no action were to be taken now.

This report is the product of a major review (Appendix 1) undertaken by Nirex to review the status of the PGRC as a viable option for the management of the UK's radioactive waste. This concept review included analysis of:

- Our own safety and environmental assessments of the concept.
- Regulators' scrutiny of our work and ongoing dialogue with a broad range of stakeholders including feedback on our programme under our Transparency Policy.
- Previous reviews and criticisms of our work such as the 1997 Rock Characterisation Facility Local Planning Inquiry Inspector's report, the report of the 1994 Royal Society Study Group and other related information, e.g. reviews by the House of Lords' Committee on Science and Technology (1999) and by UK Centre of Economic and Environmental Development (UKCEED, 1999).

The results of this concept review are recorded in a series of around 30 'Context Notes'. These underpin this report. They describe the current status of all aspects of the concept and reflect the hundreds of millions of pounds invested in developing this concept.

This report also identifies, and aims to be transparent about, the remaining scientific and technical issues that will require further work. Whilst this work is necessary, we believe there are no outstanding issues that fundamentally threaten the viability of the concept.

This report sets out Nirex's views based on 20 years of experience on the development of long term radioactive waste management options. We emphasise, however, that we fully support the necessity for the current Government review of radioactive waste management policy and the work of the Committee on Radioactive Waste Management (CoRWM). This report has been prepared as an input to CoRWM and to provide information for other interested parties.

We invite and would welcome feedback and further discussion on any aspects of this paper.

2 THE WASTE

2.1 Introduction

Radioactivity was discovered at the end of the nineteenth century and radioactive materials have been in use ever since then. During the Second World War the development of nuclear weapons led to the production of uranium purification facilities, various reactor systems and nuclear fuel reprocessing capabilities. In addition the UK developed a number of reactor types for the generation of electricity using nuclear energy. Because of the type of fuel selected and the development of a number of reactor systems, the UK has a large volume and diverse range of radioactive waste.

Radioactive materials are hazardous because of the emissions associated with radioactive decay. The risk from radioactive materials reduces over time as the total activity decays. Some radioactive materials will remain hazardous for hundreds of thousands of years and therefore require long-term isolation. Other radioactive materials will decay to harmless levels in a matter of a few years and therefore require isolation for a shorter time period.

The UK has signed the IAEA Joint Convention on the Safety of Spent Fuel and on the Safety of Radioactive Waste Management and thus has obligations to provide regular updates on stocks and future arisings of spent fuel and radioactive waste. To meet its obligations, data on waste are collected via the UK Radioactive Waste Inventory. Information on spent fuel and other radioactive materials is gathered separately by DTI.

Since its formation in 1982, Nirex has been responsible for compiling the UK Radioactive Waste Inventory on behalf of the Government. The first Inventory was published in 1984 and has been progressively refined and improved since then. The UK Radioactive Waste Inventory is recognised as a model which is now being followed by other countries, such as France.

The quantity of waste declared as a volume of conditioned waste in the 2004 UK Radioactive Waste Inventory[1] is 2.3 million cubic metres (m^3). However the scope of the Inventory is limited to those materials which have been declared as waste by the waste producers. The total quantity of radioactive materials in the UK is estimated to be of the order of 20 million m^3 of unconditioned material. Details of these other materials potentially requiring long-term management have been compiled by Nirex in a separate report [1] and are summarised in section 2.2.4.

2.2 Quantities of radioactive materials

Of the total conditioned waste volume reported in the 2004 Inventory (2.3 million m^3) only about 4% (100,000m^3) would be prevented from arising if all nuclear activities had stopped on 1 April 2004 (see Figure 1). The remaining 96% (2.2 million m^3) of waste consists mainly of contaminated soils, building structures (e.g. concrete and metals), and reactor components (e.g. graphite and metals).

[1] To be published by early 2006.

Figure 1
Total radioactive waste in 2004 inventory

Total volume
2.3 million cubic metres

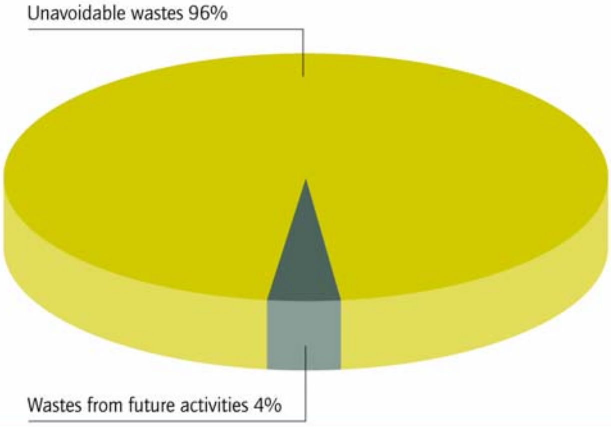


Table 1
Categories of radioactive waste in the UK

High Level Wastes (HLW)	Intermediate Level Wastes (ILW)	Low Level Wastes (LLW)	Very Low Level Wastes (VLLW)
Wastes in which the temperature may rise significantly as a result of their radioactivity, so this factor has to be taken into account in the design of storage or disposal facilities.	Wastes exceeding the upper boundaries for LLW, but which do not need heat to be taken into account in the design of storage or disposal facilities.	Wastes other than those suitable for disposal with ordinary refuse, but not exceeding 4GBq (gigabecquerels) per tonne of alpha, or 12GBq per tonne of beta/gamma activity.	Wastes that can be disposed of with ordinary refuse, each 0.1 cubic metre of material containing less than 400kBq (kilobecquerels) of beta/gamma activity or single items containing less than 40kBq.

2.2.1 High Level Waste

HLW is produced initially as nitric acid solutions containing the highly radioactive waste products of reprocessing spent nuclear fuels. Historical HLW continues to be stored in the liquid form in old stainless steel tanks, which require constant surveillance. Some HLW has been converted to glass in stainless steel canisters of 150 litre capacity, which are stored in an air-cooled modern engineered store and require less surveillance. The total volume in store on April 2004 was 1.890m^3, comprising 1,430m^3 of liquid HLW and 456m^3 of waste conditioned as glass (equivalent to 3,037 packages). Based on current plans, when all the liquid HLW has been conditioned, there will be 1,340m^3 of waste.

The nuclear safety regulator, the Health and Safety Executive's Nuclear installations Inspectorate (HSE – NII) has imposed a programme to convert stocks of liquid HLW to glass. New HLW is blended with existing liquid and vitrified. The backlog of stored liquid HLW is slowly being worked through.

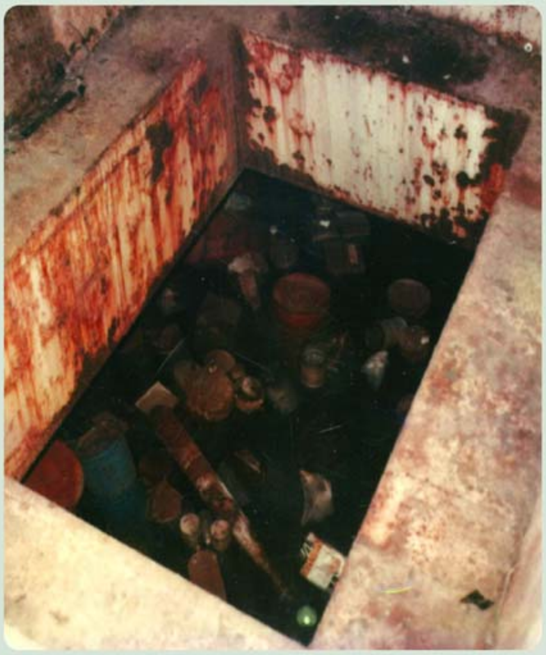
2.2.2 Intermediate Level Waste

ILW consists of metal items such as nuclear fuel casing (from nuclear fuel elements) and nuclear reactor components, graphite from reactor cores, and sludges from the treatment of radioactive liquid effluents. There are smaller quantities of organic materials, soil, glass and ceramics. The volume of ILW in store on 1 April 2004 is 82,500m^3, most of this waste is at Sellafield. A particular concern is the significant volume of ILW created in the 1940's, 1950's and 1960's that has been loose tipped into old facilities. Most of this waste is kept under water and requires continuous surveillance. Many of these facilities (see Figure 2, showing a storage facility with the protective cover removed) have long passed their design life, have deteriorated and some are leaking. The recovery and packaging of these wastes needs to be progressed urgently. Since 1990, most ILW arisings at Sellafield have been packaged and stored.

Packaging of UK ILW wastes typically consists of encapsulation in 500 litre stainless steel drums, 3m^3 stainless steel containers or large concrete boxes. These are specified by Nirex. On 1 April 2004, there were 16,400m^3 of conditioned waste.

When all ILW in store and predicted to arise has been packaged and conditioned there will be 241,000m^3 conditioned volume.

Figure 2
An existing ILW store



2.2.3 Low Level Waste

Most LLW is disposed of to the Drigg shallow disposal facility as it arises. Overall the LLW in the Waste Inventory consists of soil, building rubble and steel items such as ducting, piping and reinforcement produced from the decommissioning of nuclear reactors and other nuclear facilities and the clean up of nuclear sites. Organic materials also arise, including discarded protective clothing, paper towels and plastic wrapping, and current LLW arisings consist mainly of paper and plastics. Historically LLW was dumped in pits. Since 1959 most LLW has been loose tipped at Drigg and Dounreay. Approximately 1 million m^3 of waste has been sent to Drigg or Dounreay. The predicted remaining capacity of Drigg is 750,000 m^3, which is less than half the reported volume of waste suitable for disposal to Drigg. The Government is currently reviewing options for managing this waste.

The volume in store on 1 April 2004 was reported to be 20,900 m^3 conditioned volume. When all LLW in store and predicted to arise has been packaged and conditioned there will be 2,040,000m^3. conditioned volume.

2.2.4 Other Radioactive Materials and VLLW

Plutonium

There are currently 93 tonnes of separated plutonium in the UK, most of this material is held in store at Sellafield in oxide form as a powder. A small quantity may be returned to overseas countries. Some plutonium is held for military purposes. The total quantity of separated plutonium will increase to approximately 140 tonnes under current reprocessing assumptions. In addition there is plutonium within spent fuel.

Uranium

There are currently 100,000 tonnes of separated uranium held in a number of stores, principally at Springfields, stored in a number of forms including powder. A small quantity may be returned to overseas countries. Some uranium is held for military purposes. The total quantity of separated uranium will increase to approximately 150,000 tonnes under current reprocessing assumptions. In addition there is uranium within spent fuel.

Spent fuel

Approximately 5,000 tonnes of UK spent nuclear fuel are currently held in stores at Sellafield, Dounreay and a number of reactor sites. Some of this fuel is planned to be reprocessed. There will also be more spent fuel generated from continued power generation. Under current plans it is estimated that 4,700 tonnes of spent fuel will not be reprocessed.

Contaminated land

Estimates of land contaminated with radioactivity have been made but are very uncertain. The UK's Radioactive Waste Management Advisory Committee (RWMAC)[2] estimated the total amount in the UK to be of the order of 18 million m^3 (36 million tonnes) of unconditioned material. Most of it is at Sellafield, Dounreay and Aldermaston.

Radioactive sources

Approximately 10,000 sources are in use in the UK now, mainly for medical and industrial purposes. Most of these are returned to the manufacturers after use. Record keeping in this area has often been poor, resulting in the loss of sources. Radioactive sources exist in a wide variety of forms, from small metallic objects to gases and liquids.

VLLW

Small quantities of waste (less than 0.1m^3 with low activity - less than 400kBq) can be routinely disposed of to domestic landfills. There are approximately 5 such sites in use in the UK. VLLW may be lightly contaminated miscellaneous items such as laboratory equipment, gloves and medical wastes.

Miscellaneous

Some organisations have disposed of radioactive waste under other arrangements, either on a nuclear licensed site or local tips (estimated to be 10,000 m^3), or (before it was banned) in the sea (33,000 m^3).

Some radioactive waste can be incinerated either at purpose built incinerators located on nuclear sites or domestic incinerators.

All nuclear facilities may discharge radioactivity to the environment via liquid and aerial effluents under strictly controlled authorisations set by the UK regulators. These materials are not reported in the United Kingdom Radioactive Waste Inventory.

Decommissioning of nuclear facilities

At the end of their lives, nuclear facilities are decommissioned. This involves removal of redundant buildings and clearance of the site. Assumptions regarding the timing of decommissioning vary although most of the waste exists now, and is reported in the 2004 Inventory to be 1.6 million m^3. These wastes have been included in the volumes given against the various categories above.

Decommissioning of old facilities which are now long beyond their design life is very challenging. The early stores for radioactive waste were designed to be filled but emptying was not considered. The structure of these old facilities may be inadequate for decommissioning, and hence there is a requirement to build new facilities to remove and process the waste, as well as to decommission these old buildings. Wastes within old facilities are often poorly characterised. Records of the waste may have been destroyed, or are inadequate.

Recent facilities have been designed with decommissioning in mind and to minimise the radioactive waste arisings.

3 OPTIONS FOR DEALING WITH THE WASTE

The UK Government is currently undertaking a review of long-term radioactive waste management policy (Managing Radioactive Waste Safely - MRWS). As part of this review the Government has established the Committee on Radioactive Waste Management (CoRWM). CoRWM's task is to review the range of possible long-term waste management options and recommend a preferred option to Government in mid-2006. We fully support the work of CoRWM and the necessity for due process in assessing and selecting a preferred option through stakeholder and public engagement.

This section sets out options and presents some of the arguments that have led us to the view that a phased geological repository is our preferred option. This is not intended to cut across or overlap with the work of CoRWM. Rather it is undertaken in support of our mission[2] and has already been made available as an input to CoRWM.

3.1 Long-term waste management options

A range of long-term waste management options has been investigated world-wide for radioactive waste. Nirex has been working on options since its creation in 1982 [3]. Based on a review of the literature and stakeholder discussions Nirex has identified a range of waste management options. A comprehensive description of the long-term waste management options for radioactive wastes is provided in Nirex Report N/050[3] [4]. The Phased Geological Repository Concept is described in Section 4. Descriptions of other options are given below.

Long-term storage

Long-term storage would involve the construction of purpose-built facilities either above ground or underground. The radioactive waste would be contained by ensuring, through a combination of a controlled environment in the store[4] and waste package design, that the waste packages would not degrade significantly during the storage period. Long-term storage would make the monitoring and retrieval of wastes relatively straightforward. The long-term performance of the wastes and the store itself relies upon continued institutional control and means that the stores and packages would have to be refurbished or replaced periodically. Hence, information on the stores would have to be available to future generations, who would need the knowledge, capability and resources to undertake the necessary actions.

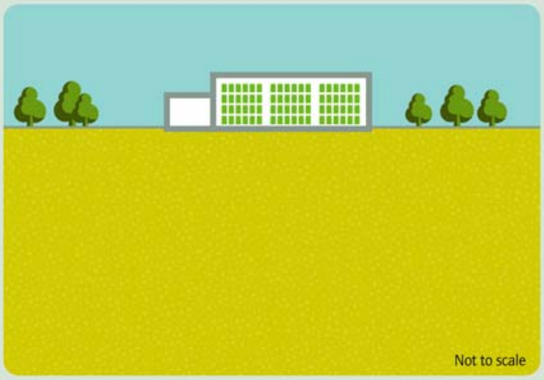
By precedent from currently operating interim storage arrangements, this option could be considered for all categories of waste.

[2] "In support of Government policy, develop and advise on safe, environmentally sound and publicly acceptable options for the long-term management of radioactive materials in the UK".

[3] This report and other information gathered in preparing this report has been fed into CoRWM for use in the identification and assessment of options.

[4] Suggestions for long-term surface storage include: conventional stores that are replaced about every 100 years or 'monolith' stores that are intended to remain intact for tens of thousands of years.

Figure 3
Surface storage



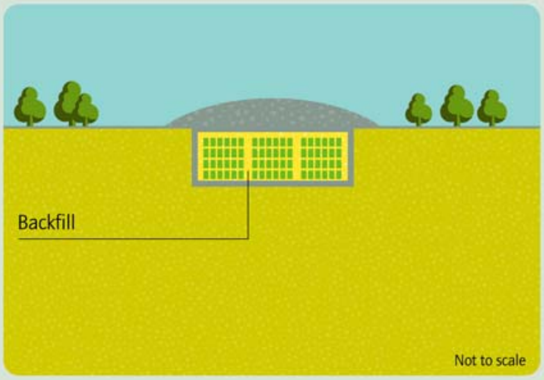
Near-surface disposal

Near-surface disposal at ground level

Near-surface disposal at ground level involves the construction of vaults cut into the ground and lined according to present-day practice (e.g. concrete and/or impermeable membrane). Waste in containers is placed in the vaults; when full the spaces around the waste packages in the vaults are backfilled; and when the disposal capacity of the whole facility has been reached, it will be covered with an impermeable membrane or low-permeability clay and capped with top soil. Many such facilities are in operation and often include controlled drainage systems [4].

Such facilities are considered suitable for the disposal of LLW and short-lived ILW (containing no significant amounts of radionuclides with a radioactive decay half-life greater than 30 years).

Figure 4
Near-surface disposal at ground level

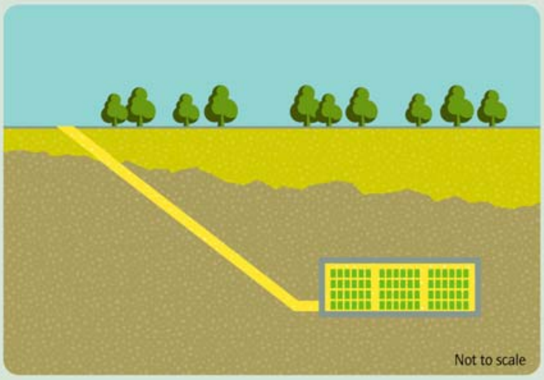


Near-surface disposal below ground level

Near-surface disposal in caverns below ground level involves the excavation of rock cavities at depths up to of order 100 metres below ground. The cavities can be in the form of tunnels, vaults, or silos; they may be lined with concrete and, sometimes, clay. Access to the excavated cavities for emplacement of waste is via an inclined tunnel or a vertical shaft. When the excavated cavities are filled with waste packages, the remaining spaces around the packages may be backfilled, but this is not always required. At an appropriate time after the facility has reached its disposal capacity engineered seals would be placed in the access-ways, and possibly at the access points to the various excavated cavities. The remainder of the access-ways would be backfilled. Several such facilities are already in operation [4].

As in the case of near-surface disposal at ground level, such facilities are typically considered suitable for the disposal of LLW and short-lived ILW.

Figure 5
Near-surface disposal below ground level



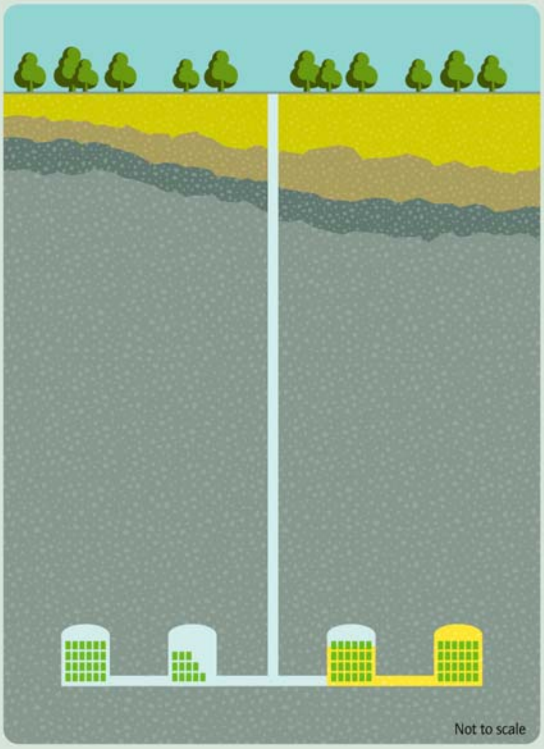
Deep geological disposal

Deep geological disposal would involve the excavation of tunnels or vaults at depths typically between 250 and 1,000 metres below ground in a suitable "host" rock. Access to the mined cavities for emplacement of waste is via an inclined tunnel or a vertical shaft. In most concepts for deep geological disposal, the engineered waste package is surrounded at an appropriate time by a backfill (which can be a cement-based grout or, in the case of disposal in salt, crushed salt) or a "buffer" material (typically a clay which swells on contact with water).

The choice of the design and materials of the waste container and of the backfill or buffer material is dependent upon the type of waste to be disposed of and, in some instances, the choice of host rock. After waste emplacement, sealing and backfilling would be carried out.

Deep geological disposal has been considered internationally for the isolation and containment of long-lived radionuclides in wastes such as vitrified HLW and spent nuclear fuel. In the UK and elsewhere it has also been considered for the disposal of ILW and LLW containing long-lived radionuclides.

Figure 6
Deep geological disposal

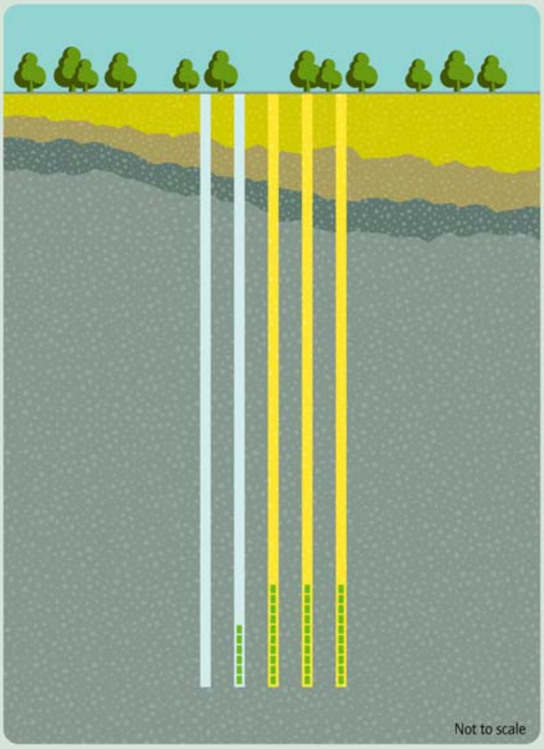


Deep borehole disposal

Deep borehole disposal would involve accessing a suitable "host" rock by drilling a borehole of suitable diameter typically to depths of several kilometres. Subsequently waste packages would be lowered into the borehole with the option to separate waste packages by layers of a suitable backfill or buffer material. Typically waste would not be placed in the top two kilometres of the borehole which would be sealed and backfilled with suitable materials.

Consideration of this option has been undertaken for certain categories of waste, but the technological resources required would make the option unattractive for high volume/low activity waste types. In contrast, the option has received considerable attention as a possible means of disposal of unwanted plutonium [5].

Figure 7
Deep borehole disposal

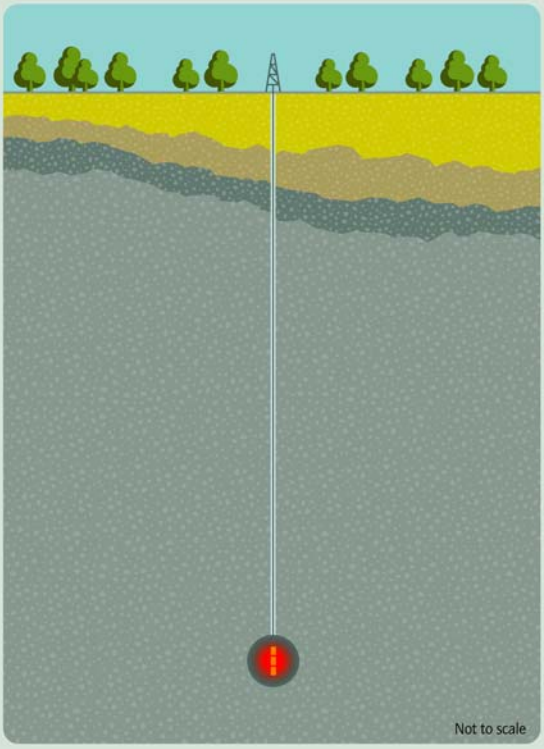


Rock melting

Rock melting would involve the introduction of heat-generating waste into a suitable rock mass (either by means of a borehole or placement, via a shaft or tunnel, in an excavated cavity). The heat generated by the waste needs to be sufficient to melt the surrounding rock after which, either the radionuclides are then dissolved in the molten rock and immobilised when the rock solidifies, or the rock solidifies around a container, in which the wastes were placed, providing a natural seal.

By definition, this option has been considered for highly heat-generating wastes, in particular vitrified HLW or its precursor liquid form.

Figure 8
Rock melting

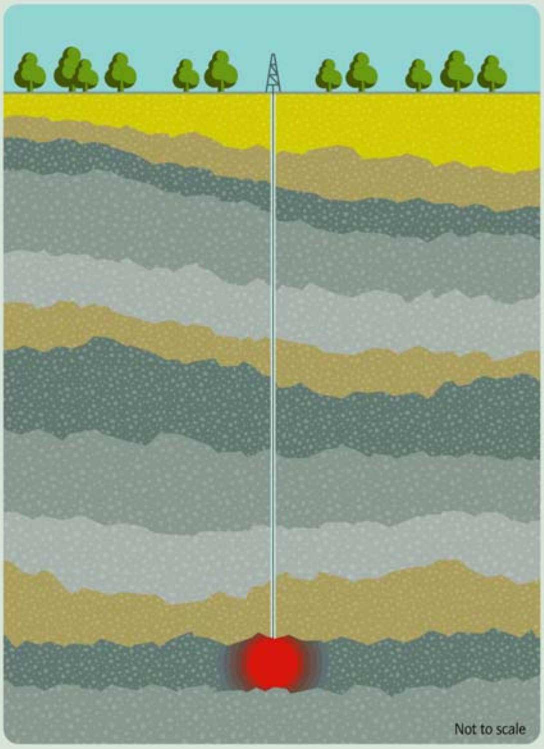


Direct injection

Direct injection would involve the injection of liquid radioactive waste, typically via a borehole, into a layer of rock deep underground.

This option has been used for liquid HLW in Russia. In theory, this option could be considered for all categories of waste provided they were in the form of a solution or slurry.

Figure 9
Direct injection



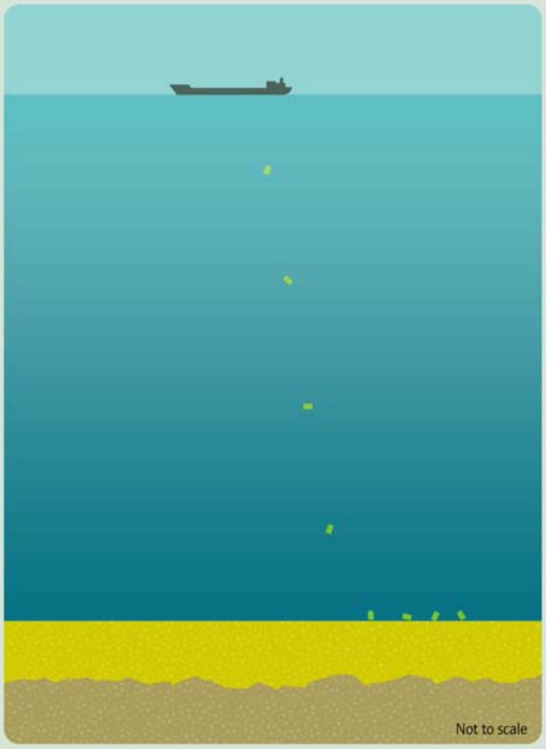
Disposal at sea

Disposal at sea would involve radioactive waste being dropped into the sea in suitably designed packages such that the packages either:

- implode on reaching a certain depth (as a result of the over-pressure) releasing their contents; or
- sink to the seabed intact.

This option has been used in the past for the disposal of ILW and LLW by a number of countries (including the UK). It has not been considered for HLW.

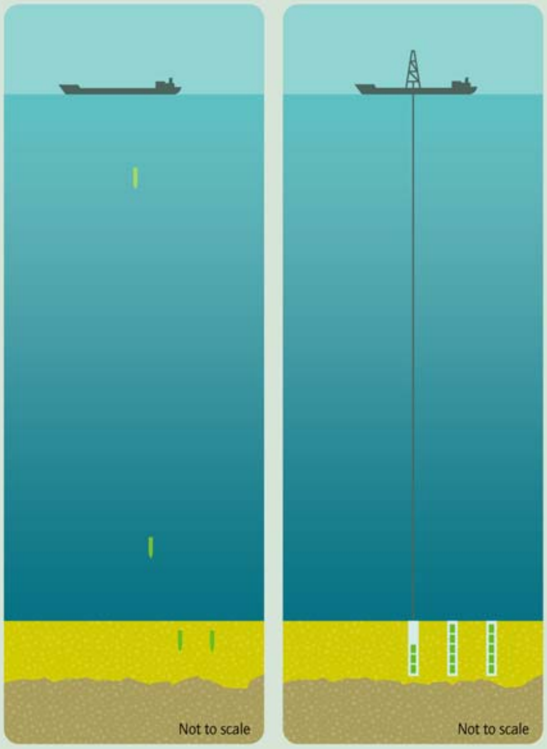
Figure 10
Disposal at sea



Sub-seabed disposal

Sub-seabed disposal would involve the emplacement of wastes in suitable geological formations beneath the deep ocean floor. Two concepts considered correspond to deep geological disposal and deep borehole disposal as described above, and the same analysis can be made as to the wastes considered. A third concept within this broad option involves the placing of waste packages in sediments on the deep ocean floor at depths typically of order a few tens of metres. This can be achieved by dropping the wastes from a ship in the form of a "penetrator" (designed to bury itself in the seabed sediments) or by drilling placement.

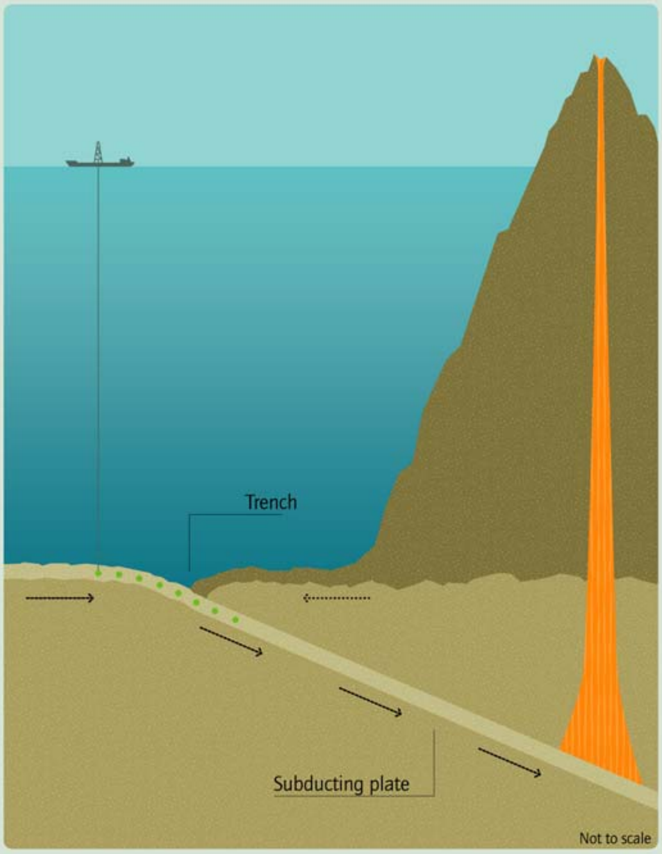
Figure 11
Sub-seabed disposal (two concepts)



Disposal in subduction zones

Disposal in subduction zones would involve the placement of wastes close to a boundary between two tectonic plates in the Earth's crust, such that the wastes are drawn deep into the Earth beneath an overriding lower density plate. Such converging plate boundaries are found below deep ocean trenches and would require disposal from a ship.

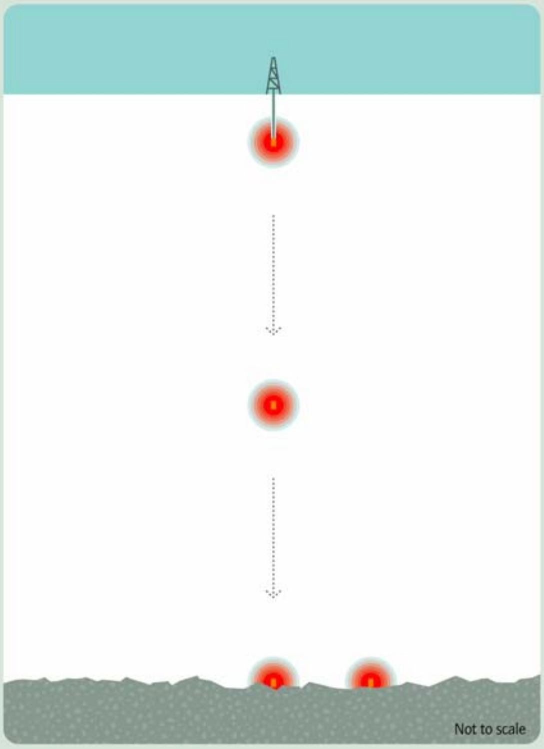
Figure 12
Disposal in subduction zones



Disposal in ice sheets

Disposal in ice sheets would involve placing heat-generating wastes in stable ice sheets (such as those found in Greenland and Antarctica). The properties of the wastes would be such that they melt the surrounding ice and move downwards under gravity with the melt water subsequently freezing above it to create an isolation barrier. Ice melting, by definition[5], has been considered for heat-generating wastes, mainly vitrified HLW or spent fuel.

Figure 13
Disposal in ice sheets



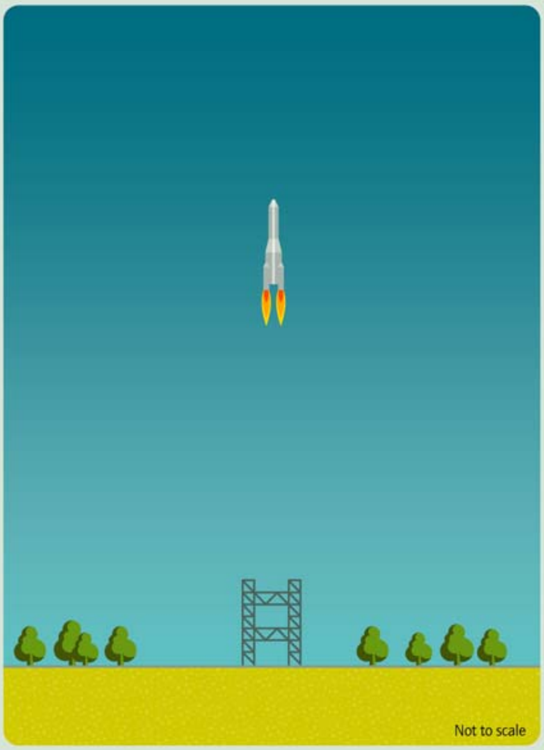
[5] Surface storage has also been proposed in ice-sheets. Wastes would not melt down into the ice but would be incorporated into the ice sheet by snow and ice accumulation.

Disposal in outer space

Disposal in space would involve the launching of radioactive waste into space, beyond the influence of the Earth's gravitational field (a variety of ultimate destinations have been discussed).

Consideration of this option has only been investigated for waste types of small volumes and high activity.

Figure 14
Disposal in outer space



3.2 Credible long-term waste management options

Nirex believes that ethically it is the responsibility of this generation to deal with its radioactive waste and it should not burden future generations or other countries. Credible options allow this generation to deal with it, and it should and can be dealt with now on behalf of the public.

Many of the options above are not viewed by Nirex as credible as they would:

- Contravene international laws and agreements;
- Involve the transfer of UK waste overseas;
- Require the use of speculative or experimental technology.

This therefore screens out the following options:

- Disposal at sea – The London Dumping Convention (LDC) [6], that the UK has signed up to, prohibits indefinitely the dumping of all radioactive wastes at sea.

- Sub-sea bed disposal (not accessed from land). The London Dumping Convention also prohibits sub-sea bed disposal, except for facilities that are accessed from land. Nirex has taken legal advice on this issue. This legal advice suggests that the London Dumping Convention and other relevant international conventions[6] do not preclude the long-term disposal of radioactive waste in sub-sea bed formations which are accessed by tunnel from the UK land-mass [7].

- Subduction zones – Similarly to sub-sea bed disposal, this option would also be ruled out by international agreements and treaties if not accessed from land. Subduction zones are not available in UK coastal waters.

- Disposal in ice sheets – To implement this option would require transfer of UK wastes overseas. This option has been rejected by countries that have signed the Antarctic Treaty [8] (which includes the UK).

- Disposal in outer space – To implement this option would require international agreement. The UK has also signed up to “The Outer Space Treaty” of 1967 [9], an international treaty outlawing “harmful contamination” of celestial bodies. Space disposal is likely to be in breach of this treaty [10]. The other issues that challenge the credibility of this option are the cost of implementation and the risk of space-craft failure.

Some of the other disposal options discussed above are also not suitable due to the characteristics of the waste.

- Direct injection – This option requires wastes to be in liquid or slurry form and is therefore precluded for the majority of UK radioactive wastes and materials as they are solid. In addition, the Nuclear Installation Inspectorate’s passive safety principles require that wastes that are initially liquids be solidified [11].

- Rock-melting – Rock-melting has only been suggested for highly heat generating wastes. This option would also require the use of speculative or experimental technology.

- Near-surface disposal – The near-surface disposal option has been developed and implemented for short-lived wastes. It is not suitable for any HLW and there would only be a very small amount of short-lived ILW for which this option would be suitable.

Therefore although many options have been proposed for long-term management of radioactive waste, we believe that the only credible options are variants on geological disposal or storage.

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[6] UNCLOS and The Convention for Protection of the Marine Environment of the North East Atlantic (OSPAR).

3.3 Pros and cons of credible options

Radioactive wastes are currently stored in surface stores at over thirty sites in the United Kingdom. The storage option allows wastes to be monitored and retrieved relatively straightforwardly. However, if the storage option is to address the need to protect humans and the environment for hundreds of thousands of years whilst long-lived radionuclides decay to safe levels, then this option requires continued active management. Reliance on the stability of society with the necessary skills and funding to maintain a suitable environment for the wastes over such time periods is not credible. Surface stores also leave the waste vulnerable to man-made and natural events [12]. For example, there is an increasing amount of data on climate change, including sea level rise. Global sea levels are currently rising at about 1 to 2mm per year [13]. Long-term interim storage at existing coastal sites may therefore not be feasible. Overall, long-term storage of this type for hundreds of years or indefinitely is not viewed by Nirex as a suitable option because it would not be ethical to leave our waste for future generations to deal with indefinitely. Storage is only credible as a temporary measure until a repository can be made available.

This view is shared in other countries. For example, the Municipality of Oskarshamn, Sweden, where spent fuel is stored in the Central Interim Storage for Spent Fuel (CLAB), has expressed the view that extended supervised storage in a facility requiring daily supervision, active cooling and other institutional measures to stay safe is not an acceptable long-term solution. In arriving at that view [14] knowledge about deterioration of nuclear installations in the former USSR was debated and the vulnerability of the long-term stability in our societies was seen as a threat larger than the stability of the two billion year old crystalline rocks in Sweden.

Geological disposal provides a viable long-term solution that does not rely on continued management. The waste is also much less vulnerable to the effects of terrorism and major changes to the surface environment. In geological disposal the waste is separated from the environment by hundreds of metres of rock and multiple engineered barriers. The skills and experience to implement this option are available now. However, some stakeholders are concerned that disposal is an irreversible step that should not be taken and could foreclose better options that may be available in the future.

Nirex has therefore investigated these issues to develop a waste management option that combines the flexibility of storage with the long-term passive safety of geological disposal. The PGRC has been developed to take advantage of the strong safety benefits of geological disposal whilst addressing public concerns about retrievability. Time is required in the decision-making process for stakeholders to gain confidence in geological disposal as a viable option. In the UK, there has been public demand for retrievability and a staged approach to decision making. Most other countries with radioactive waste are also proposing geological repository concepts that incorporate some degree of retrievability and a phased approach to implementation.

4 THE PHASED GEOLOGICAL REPOSITORY CONCEPT FOR ILW/LLW (PGRC)

4.1 Overall description

Nirex has developed its Phased Geological Repository Concept (PGRC) to provide safe, long-term management for ILW and for LLW that is not suitable for disposal in existing near-surface facilities.

Before 1997 many stakeholders had asked Nirex to incorporate retrievability into its geological repository concept. These requests were resisted and we argued that if necessary the waste could be mined out of the facility. We were missing the point.

One of the lessons learned was that Nirex needed to listen to stakeholders' views and allow them to influence our work. Through dialogue, including a series of workshops, we established what was being asked for in terms of retrievability. Instead of refuting or ignoring these requests Nirex did the research and found that it could deliver the retrievability that was being asked for:

- in terms of technical feasibility; and

- without compromising safety.

It is not only the UK that has seen the demand for and acceptance of retrievability. For example an EC funded project on retrievability [15] was undertaken in 2000 with representatives from ten national waste management organisations. Nine of those organisations are now incorporating retrievability into their disposal concepts. Only Germany has not adopted retrievability.

With retrievability for up to several hundred years built into it the concept is a multi-barrier, phased and reversible approach, based on storing waste deep underground, where it is much less vulnerable to disruption by man-made or natural events. The concept is designed to prevent, or at worst slow down to a safe level, the release of radio-toxic substances to the environment whilst the natural process of radioactive decay occurs. The incorporation of monitoring and retrievability means that choices on how, and if to proceed towards closure of the facility are offered to future generations without placing an undue burden on them. Monitoring and retrievability are discussed further in Section 4.2.

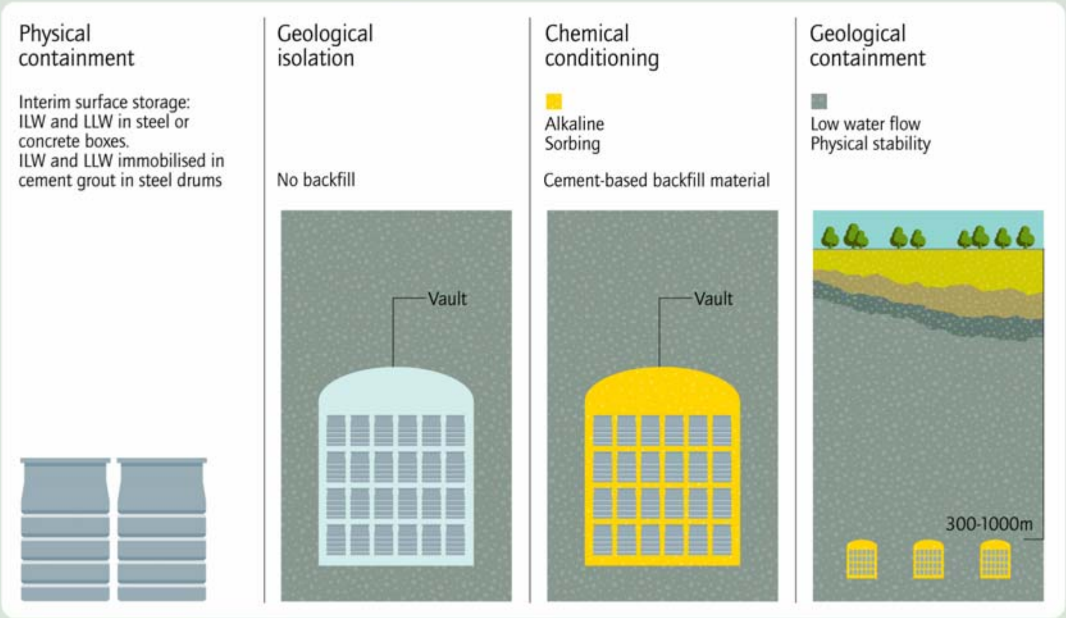
Typically the wastes are immobilised in a cement-based grouting material within a standardised, highly engineered stainless steel or concrete container. The resulting packages are an integral part of the PGRC and have to meet performance standards specified by Nirex that are derived from the concept.

The typical stainless steel thicknesses used for waste containers are expected to resist penetration by corrosion under repository conditions for many thousands of years [16]. In the absence of any other process that might degrade the container, any release of radionuclides to groundwater would be via a gas-release vent (when this is installed), and would be controlled by diffusion of radionuclides in the encapsulating grout within the container. This would only occur once a continuous groundwater phase had been established between the wasteform and the backfill. Calculations have shown [17, 18] that diffusion along this pathway would greatly limit any releases of radionuclides to the backfill to tiny fractions of the inventory within the waste container. Combining these results with calculations used in the generic long-term safety assessment, the “Generic Post-closure Performance Assessment” (GPA) [19], shows that more than 90% of the initial inventory of radionuclides would decay inside the container during the first thousand years after repository closure.

No credit is taken for this containment in the reference case repository system model used in the GPA. Instead, it is conservatively assumed that there is an instantaneously evenly distributed solution of dissolved radionuclides throughout groundwater that is assumed to saturate the repository immediately after closure, and that this is available for transfer into the rocks around the repository. Even using this cautious approach, it is calculated that no more than 1% of the initial radionuclide inventory would be outside the repository in the geosphere at any time and that containment and retardation in the repository itself ensures that the remaining 99% decay in situ.

The geological barrier would be selected so that the rock surrounding the repository would have a long and slow groundwater pathway back to the surface, and, ideally, favourable geochemical and mineral properties to prevent or delay the movement of the radionuclides along that pathway. In that way the possible release of radionuclides from the repository to the surface would be prevented or, in a few cases, limited, and the majority of radionuclides released from the repository would decay away deep underground.

Figure 15
Phased geological repository concept



In our long-term safety assessment studies, we calculate the effect that these long-term, low-level releases might have on the health and safety of people living on the surface in the vicinity of the repository at the time the releases might occur. The results of these assessment studies show that we could meet the rigorous safety and environmental criteria set by the UK regulators in up to 30% of the UK landmass.

The concept would be implemented in a number of phases, each of which is described below.

4.1.1 Phase 1 – Packaging the waste

Current policy is that Intermediate Level Waste should be packaged to Nirex standards. This means that the waste can be packaged now in a form that is suitable for long-term management. This includes surface storage, transport to a repository and then emplacement and storage underground in a phased geological repository. The packages provide the first of the multiple barriers – the main safety function being physical containment.

Figure 16
Nirex standard ILW package

BNFL

Phase 2 – Surface storage

Packaged wastes are generally stored at the site of origin in surface stores. Those stores generally have a design life in the order of 50 years. Nirex issues guidance on appropriate storage conditions to ensure that the waste packages remain suitable for subsequent underground storage in a phased geological repository [20]. This provides a marked improvement on the conditions for storing raw wastes. However, because some of the waste remains hazardous for hundreds of thousands of years, such stores do not provide a long-term management solution

Figure 17
Surface storage of packaged wastes

BNFL

Phase 3 – Transport

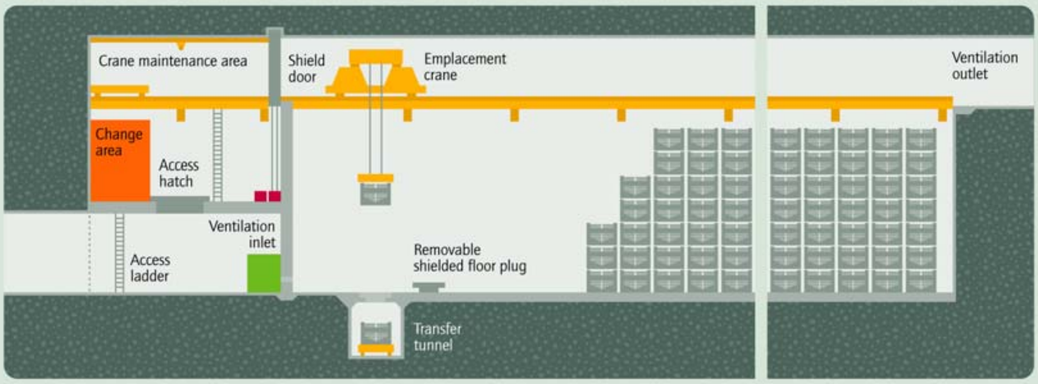
Figure 18
Waste package transport

The concept provides for the transport of waste packages to a repository. A transport system has been developed based upon internationally recognised standards developed by the IAEA [21] and incorporated in EU and UK legislation. There is extensive worldwide experience of the safe transport of radioactive materials to these standards. Transport to a repository need not be restricted to road and rail. Sea transport is being considered to minimise the movement of radioactive materials on land.

Phase 4 – Waste emplacement

To isolate this hazardous waste from the environment, waste is emplaced in deep underground storage vaults. The vaults would be constructed in a stable geological environment that offered conditions necessary to provide geological containment at a later date. The storage vaults would be similar in design to existing surface stores with carefully controlled environmental conditions. This in itself would provide a significant barrier of several hundred metres of rock so the waste is less vulnerable to natural disasters or terrorist attack.

Figure 19
Retrievable underground storage facility



Phase 5 – Monitored retrievable storage

In this phase the waste would continue to be stored underground. The repository and its contents would be monitored and the waste would be retrievable. Our studies indicate that this phase could be maintained (at a cost) for several hundreds of years with the main consideration for closure being societal rather than scientific or engineering [22]. This gives future generations a wide range of options. They could proceed to the next phase, continue with this phase or retrieve the packages if desired.

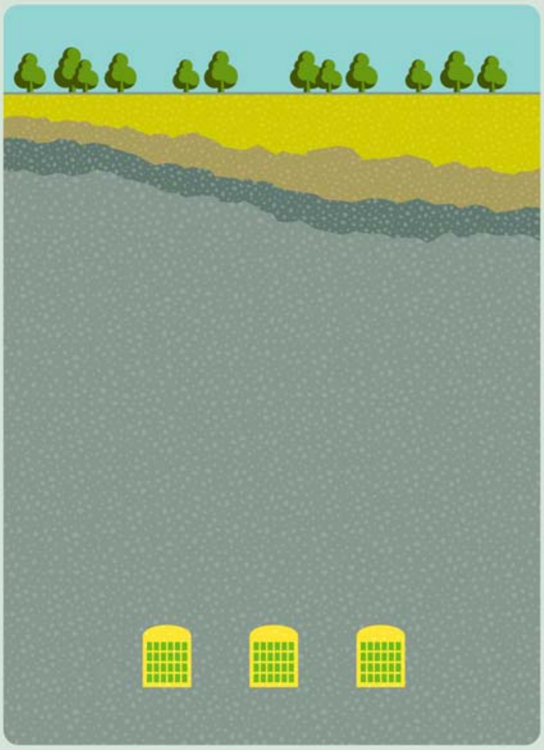
Phase 6 – Vault Backfilling

When and if there is sufficient confidence in the system, the repository vaults could be backfilled with a specially developed cement-based material. This material is designed to provide a very effective barrier against the movement of radioactive materials into the groundwater that is present in rocks deep underground. It achieves this by increasing the alkalinity of the groundwater and because the grains of cement provide a very large surface area onto which many radionuclides attach. Not all of the vaults need to be backfilled at the same time, monitoring of a backfilled vault can continue alongside phase 5. Waste packages could still be retrieved at the end of this phase, albeit with increased difficulty.

Phase 7 – Repository closure

When backfilling has been completed, the repository can be closed and sealed. The vaults, connecting tunnels and repository access ways would be backfilled and closed using high integrity seals. This barrier would retain or slow down the fraction of the radioactivity that we calculate could eventually escape from repository vaults.

Figure 20
Geological containment



Phase 8 – After closure

The multiple barriers introduced in earlier phases provide the long-term containment of radioactivity in the repository without the need for continuing maintenance and would thus protect human health and the environment. This does not mean the repository would be forgotten and Nirex is working with its equivalent organisations overseas to develop plans for very long-term monitoring of the performance of a closed repository.

A fuller summary of the PGRC is given in Nirex Report N/074 [23].

4.2 Monitoring and retrievability

4.2.1 Motivation for monitoring and retrievability

The geological repository concept was conceived as a means of providing robust containment and isolation of radioactive waste in the very long term not relying on actions by future generations. There is, however, a balance to be struck between avoiding placing responsibilities on future generations and respecting their competence and right to make decisions. Discussions around this topic, which we see as an ethical issue, have been taking place in international radioactive waste management circles since the late 1980s, for example, as crystallised in principles proposed by the Swedish National Council for Nuclear Waste (KASAM), which included the point that:

> " *… a repository should not be designed so that it unnecessarily impairs future attempts to retrieve the waste, monitor or repair the repository." [24]*

In the years since, the balance has moved more towards acknowledging future uncertainties and providing flexibility to this and future generations on how to deal with long-lived radioactive waste.

In 1995 the Radioactive Waste Management Committee of the OECD Nuclear Energy Agency published a 'collective opinion' on the environmental and ethical basis for geological disposal [25]. In that document it states that:

> *"Retrievability is an important ethical consideration since deep geological disposal should not necessarily be looked at as a totally irreversible process, completely foreclosing potential changes in policy. In this context , it should be noted that the sealing of a site and its access will always require a specific decision and that such a decision could be delayed until well after the end of the waste emplacement operations to continue to allow reversibility and flexibility in the process if considered necessary.*"

In the UK, it was the view of the House of Lords Select Committee on Science and Technology in their investigation into radioactive waste management in 1999 that:

> *"the preferred approach is phased geological disposal in which wastes are, following surface storage, emplaced in a repository in such a way that they can be monitored and retrieved. The repository would be kept open while data are accumulated, and only closed when there is sufficient confidence to do so". [26]*

Similarly, the UK CEED National Consensus Conference on Radioactive Waste Management in 1999 concluded that:

> *"Radioactive waste must be removed from the surface and stored underground, but must be monitorable and retrievable". [27]*

Nirex, through dialogue on its own programme, has recognised the importance of retrievability and monitoring to many stakeholders and has consequently undertaken work to address this [28, 29, 30].

4.2.2 Nirex work and strategy for retrievability

Nirex has carried out technical studies to investigate the practicalities of delivering retrievability and monitoring within a geological repository concept and the technical, operational and cost implications of doing so [31, 32]. It has also participated in international studies through which it has accessed experience related to retrievability and monitoring in other countries [15, 33]. Based on this experience, Nirex has developed a flexible strategy for achieving retrievability of the waste [22]. Monitoring and retrievability are now central to the PGRC, and Nirex has included requirements related to the delivery of monitoring and retrievability in its Waste Package Specification [34] and Generic Repository Design [35].

The Nirex strategy is that retrievability should be achievable at all stages during the development of the PGRC. Emphasis is placed, however, on the period during and after completion of waste emplacement and before vault backfilling. During this period, the waste is fully accessible and can be easily retrieved by reversal of emplacement operations, using the same installed equipment. The waste is monitorable and the concept demands monitoring to ensure that the condition of the waste, vaults and installed equipment remains satisfactory.

Nirex envisages that the repository may be held at this step in its implementation until such time as society is ready to take the decision to move towards closure, or to define some other course to manage the waste safely. Nirex's technical studies indicate that a repository can be designed to be held in such condition for up to about 100 years by initial design measures and routine maintenance activities similar to those required during the operational period. If a longer period of monitored, retrievable storage is required, then this could be achieved by the construction of additional vaults and a rolling programme of waste transfer between vaults and refurbishment of the emptied vaults. The repository could be kept open for hundreds of years.

The key technical requirements to ensure satisfactory underground storage conditions and the capability to retrieve the waste are:

- the emplacement vaults must retain sufficient structural stability for storage and waste retrieval operations;

- waste packages and stillages must retain sufficient integrity to be lifted and removed from the vaults;

- the emplacement/retrieval equipment and other in-vault systems, must remain operable, or be maintainable and/or renewable;

- the groundwater management system must prevent direct contact of groundwater with waste packages and also minimise degradation of vault rock stabilisation systems; and

- the vault environment must be controlled, e.g. with adequate ventilation, to provide suitable conditions for extended storage and, if necessary, waste retrieval operations.

We believe that these conditions can be readily met in the UK.

To assess and maintain the condition and effectiveness of the above, and also to ensure the underground facilities, services and safety of workers, a comprehensive programme of monitoring and maintenance would be needed, as well as the capability to recover from accidents and fault conditions. This, in turn, requires continued commitment to maintaining the operating organisation and regulatory functions, and corresponding financial commitments. In particular, the technical capability to proceed towards final closure must be maintained to give assurance that a state of passive long-term safety can be reached.

Maintaining the emplacement vaults in an open condition for an extended period has some influence on waste package and local geological conditions that could potentially influence the backfilling operations and post-closure performance. Nirex has made exploratory studies of the relevant issues [36, 37], and concluded that, for its reference conceptual design, potential impacts are manageable and need not have any significant impact on long-term safety. These issues will have to be assessed on a site- and design- specific basis.

After vault backfilling, retrieval of the waste packages would still be possible, and Nirex has carried out tests to confirm this [38], but additional equipment would be required and the retrieval would be more costly. Even after the repository is closed and sealed, the waste could be retrieved by conventional mining techniques. However, this is considered unlikely because the decision finally to close the repository would not be taken unless long-term safety was assured and all reasons for keeping the waste accessible for longer had been assessed and dismissed.

4.2.3 Benefits of monitoring and retrievability

The prime reason for incorporating monitoring and retrievability into the Nirex PGRC has come from stakeholder concerns. For some stakeholders, this is pragmatic concern over taking irreversible, or difficult to reverse, actions in the face of residual uncertainties, i.e. that we are moving too fast and, if faulty, the situation would be difficult to remedy. For other stakeholders, it springs from an ethical argument that future generations who will have to live with the solution should, as far as is practical, be given an opportunity to share in or revoke the decisions we are making now.

Nirex considers that the PGRC, with the incorporation of retrievability and monitoring, allows an ethical balance to be struck between:

- making progress now towards a permanent solution for providing long-term safety; and

- allowing future generations the opportunity to change or modify the implementation so as to better meet their requirements and preferences.

The concept aims to combine the flexibility of storage options with the long-term passive safety of geological disposal.

4.3 Regulation of the packaging of ILW

On 1 January 2004 improved arrangements relating to the conditioning of intermediate level wastes on nuclear licensed sites were introduced by the UK's nuclear regulators [39]. These arrangements require that safety cases covering the operation of plants built for the purposes of retrieval and conditioning of intermediate level waste, also address the disposability of the waste packages thus produced. This change ensures that the long-term management of waste packages is considered before they are manufactured.

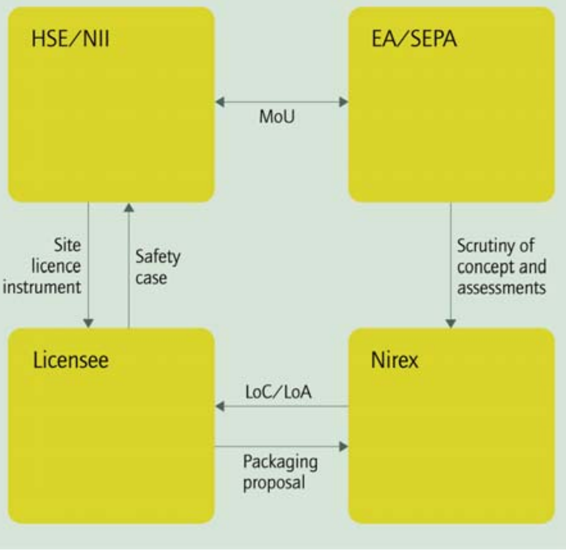
To support this new requirement, the Environment Agency of England and Wales and its counterpart in Scotland, the Scottish Environment Protection Agency, have established Nuclear Waste Assessment Teams (NWATs) that will advise the HSE-Nuclear Installations Inspectorate on waste package disposability, in accordance with relevant statutory provisions and Memoranda of Understanding between the Agencies and HSE. The arrangements recognise the important role of the Nirex Letter of Compliance (LoC) process and Nirex assessment is seen as the primary vehicle for demonstration of disposability. To enable the regulators to gain a full understanding of the LoC and underlying assessments, Nirex's work is now subject to scrutiny by the NWATs. A series of reviews have been initiated and findings are being published.

The regulatory arrangements are recognised within the Government's updated policy on the decommissioning of UK nuclear facilities issued in September 2004 [40] . The policy statement covers all (existing and new) nuclear industry facilities and their sites. This includes power stations, other reactors, research facilities, fuel fabrication and reprocessing plants and laboratories on nuclear licensed sites. It also includes fusion research facilities and, where appropriate, facilities on sites owned by the Ministry of Defence, nuclear submarines and their liabilities. The policy update confirms that operators should continue to process decommissioning wastes in accordance with Letter of Compliance arrangements.

The improved regulatory arrangements are illustrated in Figure 21.

In March 2005 NII, EA and SEPA issued 'Guidance to Industry' on the operation of the revised arrangements [41]. In summary the revised arrangements require that site operators produce an "ILW Conditioning Proposal" for all wastes on their sites. This should set out the strategy for retrieval, conditioning, storage and ultimate disposal of wastes and should form an essential component of the safety case for the plant and proposed waste products.

Figure 21
Regulatory arrangements for ILW packaging

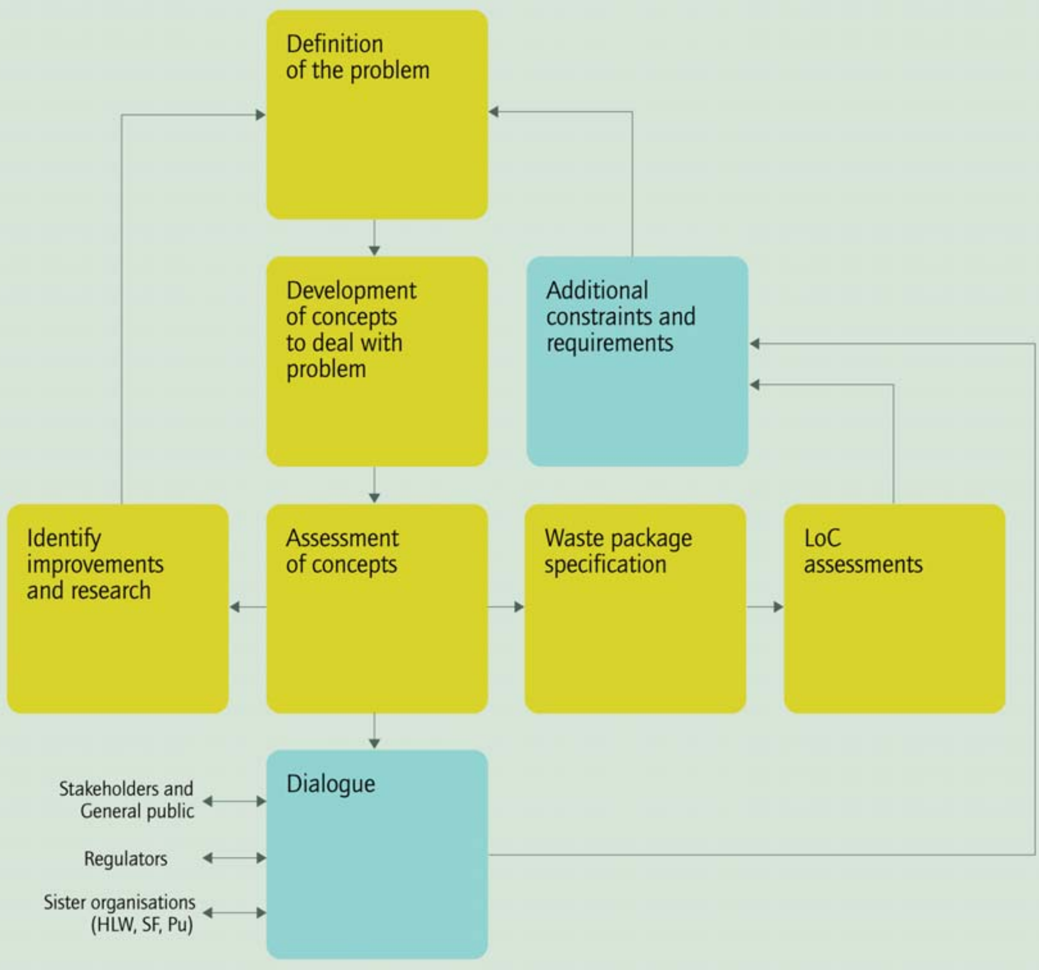


The regulators normally expect licensees to seek an assessment via the Nirex Letter of Compliance (LoC) process (see section 4.6) unless ultimate disposal to an existing disposal facility is planned. The LoC process is therefore an important input to the licensees' ILW conditioning proposals.

4.4 Iterative development of the Phased Geological Repository Concept

Figure 22 shows the iterative process that is applied to the development of the Phased Geological Repository Concept.

Figure 22
Iterative development of the PGRC



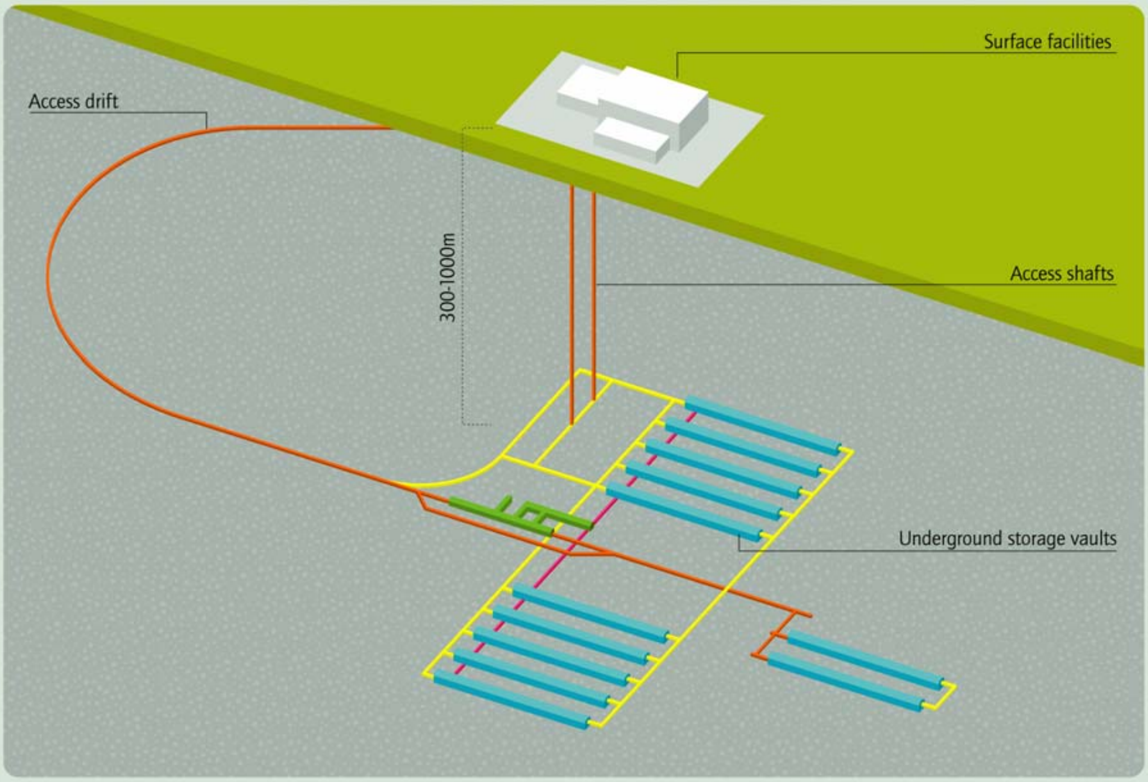
4.4.1 Definition of the problem

The process begins with the definition of the problem. This includes details of the nature and quantities of radioactive waste requiring long-term management, regulations that apply to the various phases of the concept, requirements identified from dialogue with a wide range of stakeholders and constraints derived from assessments of the safety and environmental performance of the concept. The definition of the problem is updated as new information becomes available e.g. the publication of a new UK Radioactive Waste Inventory.

4.4.2 Development of Concepts

Having defined the problem, conceptual designs are then developed to deal with the problem. These include designs of waste packages, transport packages, transport system and the repository itself. A key driver in the design is that proven technology is used for all system components hence the proposals are realistic and achievable using today's technology. A study has been reported that systematically compares all elements of the PGRC with proven technology [42].

Figure 23
Phased Geological Repository Design



The generic repository design (Figure 23) has been based on real data obtained from Nirex's investigation of Sellafield as a potential repository site. However, different rock types offer different qualities and present different challenges in terms of repository construction and repository safety and environmental performance [43, 44]. Hence Nirex has investigated the implications for the generic design concept of constructing a repository in a range of different host geological environments that might be suitable for a repository in the UK [45].

Four main rock mass types were considered:

- igneous and metamorphic rocks (e.g. at Sellafield) – the strongest rocks for construction – such as granite, basalt, quartzite and slate;
- strong sedimentary rocks such as sandstone, limestone and dolomite;
- weak sedimentary rocks such as mudstone, siltstone and stiff clay; and
- evaporites such as rock salt, potash, gypsum and anhydrite.

The generic design would be broadly compatible with igneous and metamorphic rocks and also strong sedimentary rocks in the UK.

Nirex has examined the basis of design for geological repositories in clays and evaporites [46]. In such rocks, the cross-section of stable underground openings would be reduced, and/or more substantial rock support measures might be required, e.g. concrete or metal lining sections. The development of a geological repository in clays and evaporites is feasible; this is confirmed by work from other national repository programmes, e.g. in France, Germany, Belgium and Switzerland.

It should be noted that the repository designs described at this stage of the concept development are generic and would be subject to future changes in configuration and to optimisation. Host rock properties, hydrogeology and specific characteristics of the waste can all affect the repository design configuration.

4.4.3 Assessment of concepts

This part of the iterative process is described in more detail in section 5. Assessments of safety and environmental protection provided by the concept are undertaken covering transport to a repository, repository operations and long-term, post-closure performance. The results of these assessments are compared with regulatory criteria in order to demonstrate compliance. Carrying out these assessments enables Nirex to:

- Derive waste package specifications for compatibility with the concept as described in section 4.5.
- Assess individual waste packaging proposals for compatibility with the concept under the Letter of Compliance (LoC) process described in section 4.6. The LoC assessments can also lead to the identification of additional constraints and requirements to help improve the definition of the problem (for example better information on the waste being packaged).
- Identify future research requirements and priorities as described in Section 6. The results of the research then lead to an improved definition of the problem.

The descriptions and assessments of the concept are subject to dialogue with a wide range of stakeholders. This dialogue is essential to gain an understanding of others' views on the viability of the concept. Such dialogue allows stakeholders access to and influence on our work programme and can lead to additional requirements and constraints and identify research requirements for example:

- The demand for monitoring and retrievability by external stakeholders (see Section 4.2) [26, 27, 28, 29, 30] resulted in a focused programme of work [31, 32, 22] leading to the incorporation of retrievability and monitoring in the concept. Dialogue with other national waste management organisations and international bodies has shown that this is now a common theme in the development of repository concepts [15, 33, 47].
- There is now continuing scrutiny of Nirex's work by the regulators (see section 4.3) which is a key driver in shaping our future research programme.
- Formal links with our 'sister' organisations overseas provide us with access to a vast body of work on geological repository concepts – the results of that work are used in further development of our own concepts.

4.5 Waste Package Specification and standard containers

The design of waste packages and materials used in their construction must be robust enough to ensure the integrity of the packages throughout the further stages of waste management and also meet requirements for efficient and safe handling, including transport through the public domain.

To facilitate this, Nirex has developed:

- a Generic Waste Package Specification (GWPS), which defines the standard waste containers and specifies the characteristics and performance requirements for the complete waste package;

- guidance on practical approaches to meeting the WPS; and

- guidance on a range of issues of relevance to production of conditioned waste packages.

4.5.1 Waste Package Specification

The Nirex Generic Waste Package Specification (GWPS) [34] is derived from the Phased Geological Repository Concept. It has been developed over many years in compliance with national and international standards and regulations for the safe packaging, storage, transport and disposal of radioactive waste, and in consultation with waste-producing organisations [48]. The GWPS sets criteria for identified parameters related to:

- the waste container – handling, radiological protection, durability and identification; and

- the wasteform – radioactivity, and chemical, physical, mechanical, thermal and biological properties.

It also defines the quality assurance controls to be applied to waste package production and the measurements and records required. The GWPS is supported by guidance on practical approaches to meeting its requirements, e.g. container materials, wasteform development, manufacture and data recording and measurement processes.

The GWPS being generically based on the PGRC, incorporates various safety margins so that, as progress is made towards a specific site and design, the GWPS can become more focused and eventually issued as Waste Acceptance Criteria (WAC) for an operating repository. This progressive refinement, from generic WPS to facility-specific WAC, is consistent with recommendations issued by the International Atomic Energy Agency [49].

The Nirex GWPS and the guidance documentation are subject to periodic review to ensure that they remain up-to-date. The review takes into account: the ongoing development of the PGRC; improvements in the scientific understanding and data; experience and technical insights gained from the LoC assessment process (see Section 4.6); and any relevant changes in legislation and regulatory guidance.

4.5.2 Standard containers

When a waste container is filled with conditioned waste, the complete assembly is termed a package. Nirex has defined two generic types of waste package:

- unshielded packages, which owing to radiation levels or containment requirements require remote handling and must be transported in a shielded transport container; and

- shielded packages, which have built-in shielding (if needed) and/or contain low-activity materials so that packages can be handled using conventional techniques and are transport packages in their own right**.**

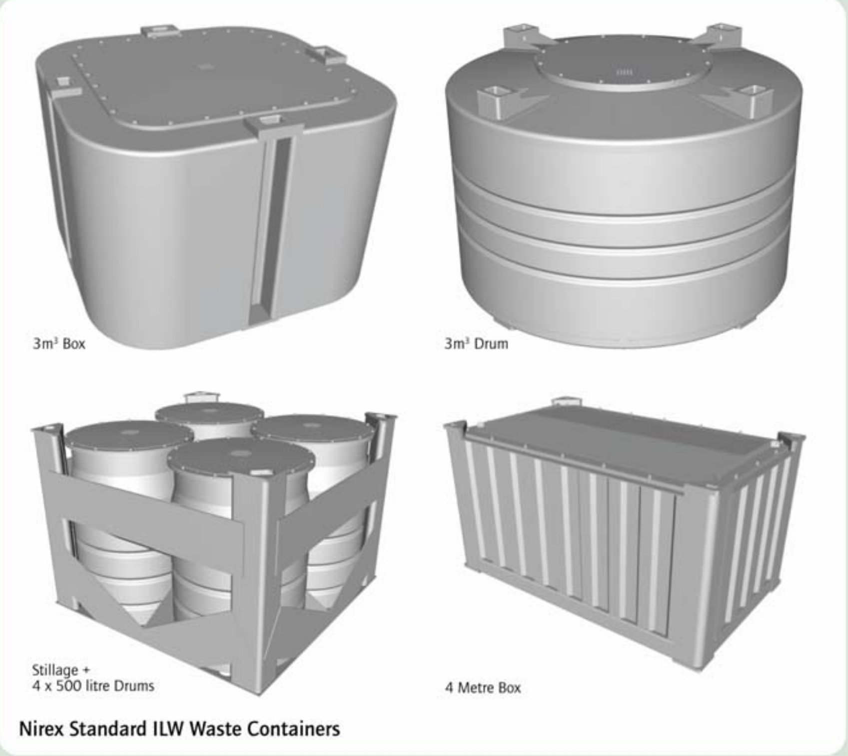
Nirex has developed a range of standard waste containers (Figure 24) that will meet the needs for the intermediate-level and low-level wastes predicted to arise in the UK.

The standard range comprises

- three “unshielded” containers – the 500 litre drum, the $3m^3$ box and the $3m^3$ drum;

- two “shielded” containers – the 4 metre box and 2 metre box.

Figure 24
Nirex standard waste containers for ILW and LLW



The standardisation of waste container designs is good practice. It simplifies quality control and package handling arrangements, and allows operations to be optimised around a limited number of package variants. The standardised exterior envelopes and handling features facilitate the design of the waste handling and transport equipment as well as general features of storage facilities and the repository vaults. Standardisation also provides efficiency by allowing development costs to be shared.

4.5.3 Wasteform and container materials

Waste packages must be designed to provide safe containment of radioactive material during transport, handling and storage (above and below ground), and in the event of accidents. This requires stable wasteforms and strong, corrosion-resistant container materials.

A combination of desirable characteristics has made cement-based wasteforms the most favoured for waste packaging in the UK. Cement formulations are easily produced, stable and long lived, and can be designed to tolerate the expected range of radiological, chemical and thermal conditions [50]. The UK and world-wide nuclear industry has had extensive experience with cement-based materials for the immobilisation of ILW and LLW.

The container is a key component of the complete waste package. To allow retrievability, the container must retain its strength, containment and capability for safe handling throughout periods of storage both above and below ground. Stainless steel is the material favoured by Nirex for waste containers because of its excellent resistance to corrosion. Nirex has carried out considerable research on the corrosion properties of stainless steels [16], and is managing research to investigate remaining corrosion issues.

4.6 Letter of Compliance assessment process

Nirex assesses waste producers' proposals for waste packaging for compatibility with the PGRC and compliance with the GWPS through the Letter of Compliance (LoC) process. This process, which was formerly known as the “Letter of Comfort” process, has been operated since the mid-1980s. Since January 2004, the process has been brought under regulatory scrutiny (see Section 4.3) and the LoC process is now embedded in the regulatory arrangements for the treatment and packaging of intermediate-level waste in the UK.

The regulatory arrangements require that nuclear site operators produce a safety case for any conditioned waste packages that will be produced. The Nirex assessment of the waste package will be provided to the site operator as a disposability assessment, describing why (or why not, as the case may be) Nirex believes the packaged waste to be compliant with plans for transport, operations (including a monitored storage phase) and final closure of the PGRC. The disposability assessment provided by Nirex will be incorporated into the site operators’ overall safety case for consideration by the regulators. For further description of this process see [51].

The issue of a Letter of Compliance is not a one-off event but is one step in the process of managing radioactive wastes. The LoC signifies that packaging of the waste can be undertaken in compliance with Nirex standards and specifications and will lead to waste packages that would be compliant with the requirements of the PGRC.

The waste packaging process will lead to the generation of information and records which with the LoC will form the “package record” that will follow the waste package through subsequent stages of its life. The package record shows stakeholders that:

- packages have been assessed against the requirements of the PGRC and issued with a LoC;
- packages have been produced against a defined Waste Product Specification (WPrS);
- data on the waste package have been generated and recorded;
- processes have been undertaken in accordance with controlled quality management systems (QA); and
- independent checks have been made to confirm that the operator has actually produced the packages according to Nirex's standards.

These elements of the package record play an essential role as the waste package passes from one phase of management to the next. They are essential to making the safety cases for a repository.

It can be seen that the LoC and assembled package record has to be maintained, added to and updated appropriately throughout subsequent phases of the package lifetime. Nirex has also identified the need for periodic review of issued LoCs so that LoCs and associated package records are kept "live" and never more than say 10 years old. Nirex is currently discussing the scope of periodic reviews with appropriate regulators. Finally it should be noted that all necessary parts of the package record are defined within Nirex documentation and will be strengthened by the improved regulatory arrangements discussed previously.

Progress made in assessing and endorsing waste packaging proposals is described in the Nirex annual report on waste packaging interactions, e.g. [52]. The total conditioned volume of ILW declared in the UK Radioactive Waste Inventory is 241,000 m^3. As of March 2005, some 40% of waste has been assessed through the LoC process and of about 22% has been issued with a final LoC, although only about 8% has been conditioned and packaged.

4.7 Compatibility of packaged waste with future waste management

The packaging or repackaging of radioactive wastes is costly and implies significant radiation dose commitments. Nirex, regulators and the industry therefore need maximum assurance that waste packages being produced now will not require re-packaging in the future. The Nirex GWPS and LoC assessment process, described above, are designed to give that assurance.

4.7.1 Compatibility with alternative management options

It is possible that future Government policy may specify some alternative long-term waste management concept be adopted for some, or all, of the ILW and LLW currently packaged according to the GWPS.

Nirex has reviewed the international literature and identified a range of options, see Section 3, that have been suggested for the long-term management of radioactive waste[7], and

[7] The options identified are broadly the same as those subsequently identified by CoRWM.

carried out a preliminary review of the extent to which wastes, conditioned and packaged in line with the GWPS, could be compatible with these alternative options [53].

The feasibility and safety of managing Nirex-specified waste packages in each of the alternative options were considered qualitatively, and each option classed as:

- Compatible – waste packaged to the GWPS would be fully compatible with the option, (essentially phases of the PGRC or very similar in requirements);

- Not foreclosed – if waste is packaged to the GWPS these options would not be ruled out (a reversal of packaging steps would not be required but in some cases additional packaging steps would be needed);

- Precluded – options that are not readily compatible with the waste and/or package specification.

It was concluded that, of the long-term management options identified in Section 3, only four would be precluded; these included disposal in ice sheets, rock melting, direct injection (of liquid waste) and transmutation. This was mainly on grounds that the basic characteristics of the waste would be incompatible with the option.

The question of continuing to package waste according to the GWPS during the current review of radioactive waste management policy has been discussed at workshops sponsored by the Radioactive Waste Policy Group (RWPG) operated under the auspices of Defra. It was concluded that the waste should continue to be packaged under the LoC arrangements, and it would not be acceptable to defer packaging to await CoRWM's review of options [54].

5 SAFETY AND ENVIRONMENTAL PROTECTION PROVIDED BY THE PGRC

Assurance of the safety and environmental protection afforded by the PGRC is obtained from analysis of scientific and technical information and understanding, and associated quantitative assessments. These analyses and assessments have been documented in respect of:

- transport of waste to the repository;
- operation of the repository;
- the long-term, after the repository has been backfilled, sealed and closed (post-closure);
- nuclear criticality; and
- non-radiological environmental impacts.

Although it is important to provide assurance on all of these aspects, the key test of a repository concept is the evaluation of the level of safety and environmental protection it will provide in the long term. There is ample precedent from operating nuclear transport systems and from the operation of nuclear facilities both in the UK and internationally, that these operations can be carried out in compliance with modern health and safety and environmental protection standards, and that there are established methods for carrying out the necessary analyses to demonstrate that compliance. Therefore, the main focus of this section concerns the long-term safety of the PGRC.

5.1 Long-term safety of the PGRC

The long-term safety of the PGRC is based on the isolation and containment functions of its combination of man-made and natural barriers. It also depends on the scientific and technical information and understanding of the characteristics and behaviour of the geological and engineered systems and materials comprising these barriers. Numerical models have been developed to analyse the isolation and containment of radionuclides as the repository system evolves in the long term and to show the effect of uncertainties in information or understanding on this analysis. The outputs of these models are the calculated releases of radionuclides from the PGRC, eventually to the surface environment. This allows calculation of potential radiological consequences of these releases for comparison with the relevant regulatory standards.

International and UK safety requirements

The United Nations organisation, the International Atomic Energy Agency (IAEA), has a Radioactive Waste Safety Standards (RADWASS) programme that is aimed at establishing a coherent and comprehensive set of principles, requirements and recommendations for the safe management of radioactive waste. These are published as IAEA Safety Standard Series documents, to provide an internationally agreed framework for the setting of national safety standards and for the development of management, technological and analytical systems for the safe management of radioactive wastes. The Safety Standards document of most specific relevance to the PGRC is that dealing with ‘Safety Requirements for the Geological Disposal of Radioactive Waste’ [55]. It proposes a long-term safety standard, that

> *'the estimated average dose or risk to members of the public, who may be exposed as a result of the disposal facilities in the future, shall not exceed a dose constraint of 0.3 mSv in a year or a risk constraint of order of 10^{-5} per year.'*

In the IAEA context this means a risk to a person of 1 in 100,000 per year of a serious health effect. In the UK, a more conservative dose to risk ratio is adopted that gives a radiological risk to a person of 1 in 55,000 per year of developing either a fatal cancer or serious hereditary defect.

The IAEA Safety Requirements document also proposes the basis for establishing that estimate, and the associated confidence in the safety of a geological repository, as follows (paragraph 3.24):

> *"An understanding of the performance of the disposal system and its safety features and processes evolves as more data are accumulated and scientific knowledge is developed. Early in the development of the concept, the data and the level of understanding gained should provide the confidence necessary to commit the resources to further investigation. Before the start of construction, during emplacement and at closure, the level of understanding should be sufficient to support the safety case for fulfilling the applicable regulatory requirements. In establishing these requirements, it is important to recognize that there are multiple components of uncertainty inherent in modelling complex environmental systems and that there are inevitably significant uncertainties associated with projecting the performance of a geological disposal system."*

The OECD-NEA has co-sponsored the "Safety Requirements" document and published a companion report explaining to a technical audience the nature and purpose of the long-term safety case for geological disposal [56].

The UK environment agencies have set requirements for the land-based disposal of radioactive wastes [57], in particular that the assessed radiological risk to an individual should be less than one-in-a-million per year. This means a risk to a person of less than 1 in a million per year of developing either a fatal cancer or a serious hereditary defect. This compares to the 1 in 55,000 per year risk constraint implied by the IAEA Safety Requirements. The environment agencies note that it is also between one hundred and one thousand times below the radiological risk to which members of the population are exposed as a result of natural background radiation levels in the UK. This means that the risk to a person from natural background radiation is between 1 in 10,000 and 1 in 1,000 per year of developing either a fatal cancer or a serious hereditary defect. The UK environment agencies recognise the uncertainties associated with calculating radiological doses and risks in the very long term and require to be satisfied with the quality of the science and engineering used in developing a proposal for a repository. They also require that the calculation of radiological doses and risks is complemented and supported by multiple lines of evidence.

Performance assessment methodology

The understanding of the performance of the repository is documented as a "performance assessment". The structure of a performance assessment and the methods and tools to be used in its development have been the subject of much analysis, exploiting, where relevant, risk analysis in other technological areas such as chemical plants, aircraft design etc. A substantial literature has developed in relation to geological repositories, which has been most recently summarised by the IAEA and NEA reports outlined above. Nirex has developed its approach to performance assessment to conform with best practice, as laid out in those documents and their underpinning information.

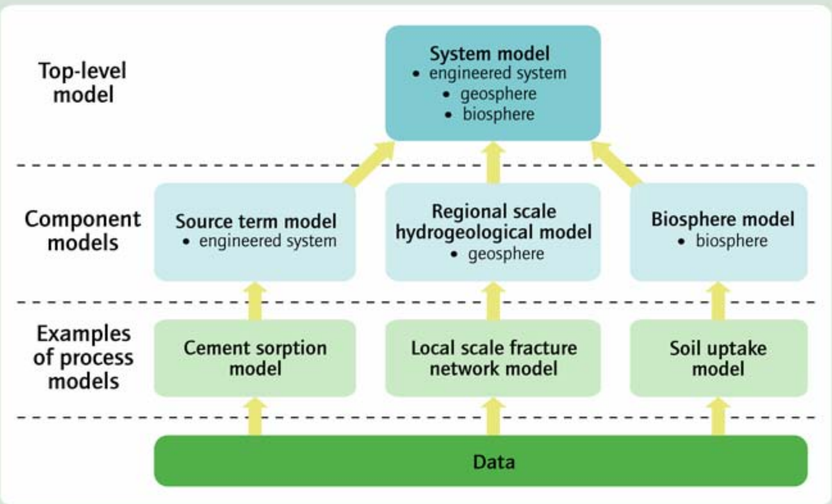
The Nirex approach is based on a series of analytical steps, starting with a wide-ranging consideration of all the features, events and processes (FEPS) that could possibly affect the long-term safety of a repository. This step is a formal, structured process involving independent experts in the relevant fields of science and technology whose inputs in identifying FEPs are recorded in a highly traceable manner. The Nirex FEPs were compared with international FEP lists [58] to ensure they provided a comprehensive description of all the potential issues affecting the long-term safety of the repository.

The FEP analysis leads to an hypothesis of general behaviour of the system, focussing on the different ways in which radionuclides could leave the repository and enter the accessible environment, with consequent potential for radiation exposure of humans. This hypothesis is represented by a series of conceptual models. Conceptual models are qualitative (not numerical) descriptions of the repository system and its evolution over time that reflect the understanding of the chemical, physical and (more-specifically) hydrogeological processes affecting the repository. Conceptual models are developed to represent the main processes occurring within each of the different components of the repository system, namely:

- the engineered system (also known as the near field) – comprising the underground vaults, waste packages, backfill and other materials;
- the geosphere – comprising the rocks in which the repository is constructed and those that surround them, extending to the surface; and
- the biosphere – the near-surface and surface environment, including the atmosphere, water bodies (terrestrial and marine), the soil and the upper part of underlying bedrock.

The process understanding that underpins these models is obtained from the Nirex research programme (see Section 6), from the accumulated international scientific and technical information and understanding, and from scientific evidence as reported in the peer reviewed literature. The Nirex research programme is structured around the current status of knowledge concerning important safety-related processes and the formal identification of outstanding issues in relation to those processes. Data at this 'process level' can be used to construct and populate process models. These are the most detailed models in a safety assessment model hierarchy that is illustrated in Figure 25.

Figure 25
Model hierarchy, examples of different levels of models



The aim of the detailed, process level models is to develop and demonstrate a depth of understanding and provide the relevant parameters for the component and system level models. For example, a process level model may represent the detailed chemistry of the wastes, this may feed into a higher-level model representing the whole of the engineered system, which in turn will supply information to a model of the complete repository system. It is the top-level repository system model that is used to calculate the overall performance of the system.

Because of the uncertainty regarding the future, it is necessary to consider a range of alternative scenarios. An internationally accepted approach, also adopted by Nirex, is to consider a ‘base case’ or ‘reference’ scenario that represents the natural, or expected, evolution of the repository system in the absence of any major disturbances and a range of variant scenarios. Variant scenarios can be used to consider, for example, the effects of drilling in the vicinity of the repository or a criticality scenario.

All the above stages are encompassed within the Nirex scenario development methodology; this has been published [59, 60] and received a favourable formal international peer review from an OECD-NEA expert group [61]. A conclusion from that group was that:

> *“The specification, in the Nirex methodology, of the conceptual models in terms of FEPS and their interactions is subsequently used to assess the applicability of already existing models and to identify potential needs for further model development. Even if no further model development is judged necessary this approach enhances confidence in the assessment models.”*

The use of performance assessment in development of the PGRC

Performance assessment is being performed iteratively throughout the development of the Phased Geological Repository Concept and its implementation:

- to synthesise and test the current level of scientific understanding and data for the given design concept or possible repository at a site;
- to demonstrate understanding of the projected long-term performance of the repository and its safety, and identify factors that are most important to that performance and safety and related uncertainties;
- to identify those aspects on which greater understanding or data are needed. Research and data requirements can then be specified for future iterations to reduce, or better quantify, uncertainties in order to obtain better substantiated estimates of performance;
- to identify possible repository design or layout modifications to improve performance or to avoid specific uncertainties; and
- to demonstrate that the Concept meets regulatory requirements and will remain safe over all timescales.

The understanding of system performance and safety gained from the performance assessment forms part of the overall case for the safety and environmental protection afforded by the repository. A safety case is the formal compilation of evidence, analyses and arguments that quantify and substantiate a claim that a radioactive waste repository is safe [56].

Basis for generic assessment

At present, there is no site selected for the development of a repository in the UK. Nirex has, therefore, developed a Generic Post-closure Performance Assessment (GPA) [19]. This is based on a range of geological characteristics consistent with conditions that could be found in up to 30% of the UK landmass. The GPA is used to test the generic design, and to test the compatibility and safety of waste producers' packaging proposals in support of the LoC assessment process.

A fundamental feature of the Nirex approach is that the characteristics of the generic site are deliberately pitched to give a repository performance at the 10^{-6} risk target so as to include as wide a range of sites as possible.

Alongside the development of a strong theoretical basis for the PGRC, Nirex also has significant experience gained in developing performance assessments that are site-specific, particularly from the investigation of the Sellafield site between 1991 and 1997, e.g. as described in Nirex 95 [62] and Nirex 97 [63]. The Nirex 97 assessment has been subject to formal peer review [64]. That review concluded:

> *"Nirex 97 is an impressive achievement, both for Nirex and for the field of performance assessments of deep repositories."*

The review went on to note that Nirex 97 could have been made more accessible by improved presentation. Nevertheless, the reviewers believed that the capability and computer programs developed in Nirex 97 would be readily transferable and provide a sound basis for future assessments, whether for Sellafield, or for other sites.

The way that performance assessment might be applied to different stages of a programme is described in a Nirex Report [65], which also sets out the general approach and features of the Nirex performance assessment methodology.

Performance assessment of the PGRC

For the Nirex Geological Repository Concept three main pathways that could lead to radiation exposures have been identified. These are:

- the groundwater pathway – migration of dissolved radionuclides and radionuclides associated with colloids in groundwater;

- the gas pathway – transport of radionuclide-bearing gas generated in the repository; and

- the human intrusion pathway – exposure during drilling or excavation activities or resulting from the deposit of radioactivity at the surface, as a result of such activities.

Groundwater pathway

Figure 26 shows the calculated annual individual radiological risk from the groundwater pathway for the Generic Performance Assessment (GPA) reference case [19], showing contributions from individual radionuclides.

In the absence of site-specific information, a set of three parameters has been used to describe the key features of groundwater flow in the geosphere. These are:

- Q, the volumetric flow of groundwater through the engineered system;

- T, the travel time for water to move from the engineered system to the biosphere; and

- F, the volumetric flow of water in the near-surface geological units that will mix with water that has travelled from repository depth.

Values have been chosen for these parameters so that the peak calculated radiological risk in the reference case assessment will be just less than the one in a million per year that defines the regulatory standard. Thus the peak risk in Figure 26 is $9x10^{-7}$ (or 1 in 1.1 million) per year which effectively defines the requirements from any potential repository site.

Figure 27 shows the results of a variant calculation conducted in the GPA for the case where the ILW (and LLW unsuitable for near-surface disposal) resulting from the final stage of decommissioning of nuclear power plants would be put into the same repository. The peak risk is unchanged from that in Figure 26, but the risks calculated to arise about 10,000 years after repository closure are slightly higher. This is mainly because of the increased inventory of chlorine-36 in the repository as a result of including these wastes.

The combination of values chosen for the hydrogeological model parameters Q, T and F in the Generic Performance Assessment are consistent with ranges of combinations of these values for various geological systems found in the United Kingdom – that is, sites affording suitable hydrogeological conditions are not uncommon and could be found in a number of areas.

As stated above, previous studies by the British Geological Survey (BGS) have shown that potentially suitable conditions can be found in up to 30% of the UK's deep geology [43]. Nirex has recently commissioned the BGS to use its updated national geoscience database and geoscientific knowledge and experience to review the values ascribed to Q, T and F and the UK geological systems where these would be expected to be satisfied.

Figure 28 shows the equivalent calculated risk, to that in Figure 26, for the Reference Assessment Model for the Nirex 97 assessment of a potential repository at the Sellafield site [63]. The peak calculated risk was $1.2x10^{-7}$ (or 1 in 8.3 million) per year. However, this occurred at 50 million years after closure when such calculations, based on assumed persistence of the Earth's current surface geology, can have little basis. The peak risk calculated for the Sellafield site up to one million years after closure was $1.3x10^{-8}$ (or 1 in 77 million) per year. At Sellafield, measured parameter values and their associated uncertainties were available to describe groundwater flow at the site. In effect the calculated radiological risks correspond to measured Q, T and F values for Sellafield and are well below the risk that defines the regulatory standard.

At times around 10,000 years to 100,000 years post-closure, the risk is dominated by chlorine-36 and iodine-129. These radionuclides are soluble and mobile (that is, they are not strongly retarded or retained by processes such as sorption to solid surfaces), which is why they give rise to a risk at relatively early times.

Much later, on timescales of a million years, the risk is dominated by the daughters of the naturally-occurring uranium-238 that is present in significant quantities in the wastes, most notably radium-226 and thorium-230. Uranium, thorium and radium have low solubilities under the chemical conditions expected in the repository, and are likely to sorb or adhere strongly to the rocks in the geosphere (the rock around the repository) and to the repository backfill.

The uncertainties in the behaviour of uranium, thorium and radium are all included in the quantitative assessment by the construction of probability density functions (PDFs) for their solubilities in water and their sorption onto repository backfill and minerals on the surfaces of rock pores and fractures in the geosphere. A systematic description of the treatment of the identified uncertainties relating to all the processes involved in the assessment of the PGRC is beyond the scope of this report. However, an example is given below of how this is done for uranium-238 which dominates the risk calculations at very long times in the future.

The peak radiological risk calculated to arise from the release of the daughter products of uranium -238 is strongly affected by the values assigned to uranium solubility in the repository. Uranium has a low solubility in the alkaline water that is in equilibrium with cement, as used in the backfill material, but the presence of organic materials in some ILW has the potential to produce organic complexants as degradation products. These complexants can increase the solubility and decrease the sorption of uranium with a consequent higher calculated radiological risk than if the organic materials were not present. The peak risk is dominated by a small number of ‘realisations’ in the probabilistic assessment in which a combination of unfavourable values has been sampled from the relevant solubility and sorption PDFs. It is likely that a combination of further research and model refinement would result in lower calculated risk.

If the uranium-238 inventory were to increase significantly, for example, as a result of separated uranium, depleted uranium or spent fuel being re-classified as wastes, it would not necessarily tend to a proportional increase in the calculated risk. It should be possible to put these materials in repository vaults separate from ILW containing organic materials and from contact with complexants. The lower solubility and higher sorption values that would then apply would mean that adding these materials to an overall repository inventory would not have a significant effect on the radiological risk from uranium -238 and its daughters.

Figure 26
Annual individual risk vs time for GPA reference case

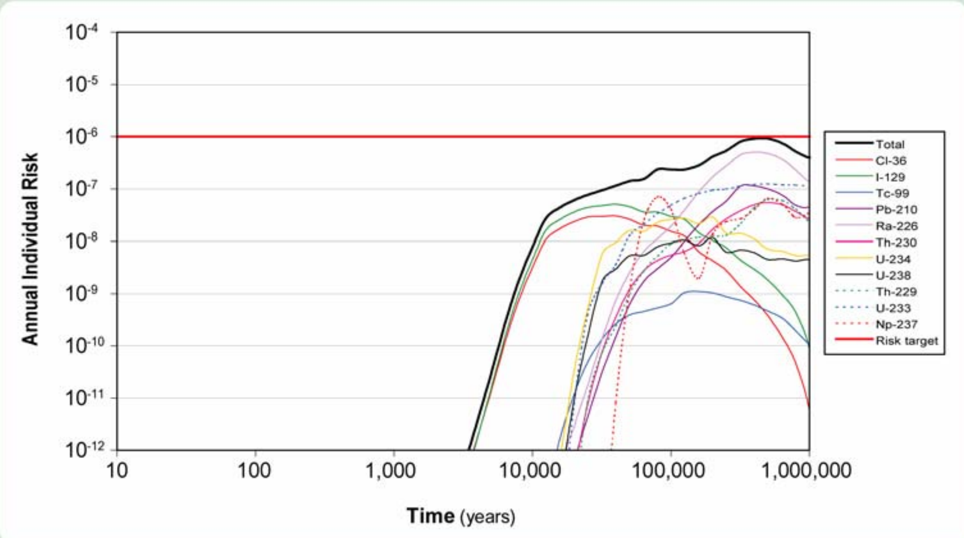


Figure 27
Annual individual risk vs time for final stage decommissioning wastes added to GPA reference case

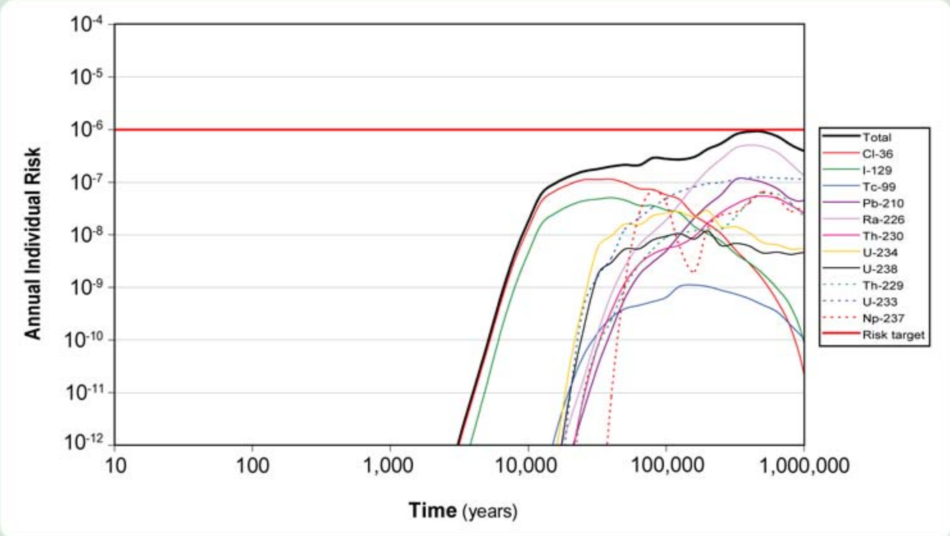
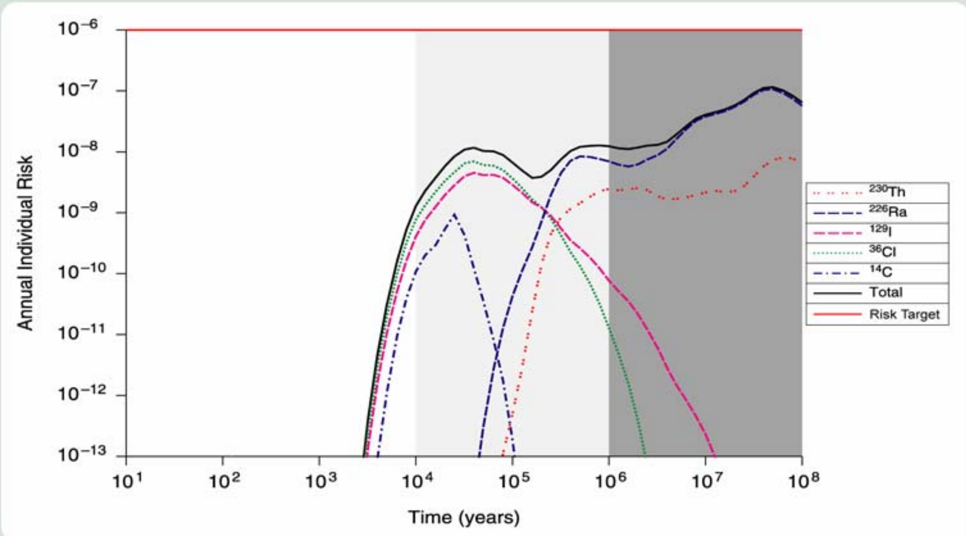


Figure 28
Annual Individual Risk vs Time for the Nirex 97 Reference Assessment Model



Gas pathway

As discussed in section 6.2, the wastes for disposal in the PGRC contain materials that could form gas when they degrade. It is therefore important to assess the level of potential gas generation and the ways it could affect the overall safety of the repository.

Post-closure performance assessments have consistently shown that there would be no significant risk from overpressurisation due to gas generation for a repository in a hard fractured host rock and no flammability hazard at the surface is expected to arise from gas generation. Risks from the gas pathway are dominated by the radiological impact of carbon-14 in the form of methane.

Carbon-14 has been identified as a key issue in the PGRC and further work is planned, which may include the identification of siting requirements. However, on balance, Nirex believes that carbon-14 is not a threat to the viability of the Phased Geological Repository Concept.

Calculations have been carried out to scope the potential impact of carbon-14 and the results are shown in Figure 29. Two curves are shown, reflecting alternative scenarios. The lower (blue) curve shows the calculated risk from carbon-14 if it all dissolves in groundwater and is released to the biosphere in solution.

Some of the gas generated in a repository could dissolve in groundwater and the migration of gas in the geosphere would depend on the site geology. In many geological settings, some form of gas retardation may be expected. Other waste management organisations such as Nagra (Switzerland) and Andra (France) have taken account of gas retardation in the geosphere in their performance assessment calculations. For example in the Nagra model, gas is retarded in the upper geosphere and then dissolves in an aquifer [66].

Nevertheless a situation can be envisaged where gas forms and is not dissolved in the groundwater, as was assumed for example by SKB in its 1995 Template for Safety Reports [67]. In Figure 29, the upper (yellow) curve scopes the impact of a scenario where carbon-14 is released as gas and all methane generated is released directly to the biosphere as gas, taking no account of delay in the geosphere. This scenario has not been researched to the same extent as the groundwater scenario. Therefore, in order to undertake a scoping calculation, a number of assumptions have been made.

Where possible, the calculations are based on the best understanding of gas generation rates. Where there is uncertainty, assumptions have been chosen to maximise the generation of methane in the period after repository closure, as any gas generated before this time does not lead to a post-closure risk. The calculation includes sources of carbon-14 which were qualitatively recognised in the GPA, but for which understanding and model development has only recently allowed their inclusion in scoping calculations. The calculation has been carried out on the following basis:

- The calculation is based on the 2001 National Inventory including final stage decommissioning wastes [68].

- An analysis of the Inventory has been undertaken to estimate the proportion of carbon-14 present within different materials (e.g. steel, graphite) within each waste stream.

- All carbon-14 is conservatively assumed to remain in the wastes until it arrives at the repository, i.e. none is released during the initial packaging and storage of the wastes. However, gas generation during the operational period and during repository backfilling is assumed to occur and to be managed through the ventilation system.

- The repository is assumed to resaturate with water over a 5 year period following repository closure, and this water is available to react with the waste, causing corrosion. After this 5 year period, unlimited groundwater is assumed to be available.

- The carbon-14 in metals was assumed to be evenly distributed throughout the metal and to be released as the metal corrodes. The initial surface area of the metal waste is uncertain and would vary between waste streams; for the calculation metal wastes are represented as spheres, of a size determined by expert judgement.

- The metal corrosion rates are dependent on temperature. For this calculation we have applied a temperature of 35^{o}C throughout the operational and post-closure periods. Metals would experience a higher temperature (and higher corrosion) than this during the backfilling period and the gas generated would not contribute to the post-closure risk.

- All of the carbon-14 in the metallic wastes is assumed to be released as methane. (Some metal carbides could produce acetylene, but this is thought to give rise to a similar or slightly lower radiological risk than if it is assumed to be methane).

- Organic materials that contain carbon-14 were assumed to be degraded by microbes and by radiolysis. The rates of these reactions are uncertain and the rates used in the calculation were derived by expert judgement.

- Organic waste degrades to form a mixture of carbon dioxide and methane; it is assumed that the carbon dioxide reacts with cement in the repository and does not contribute to the calculated risk from gas.

- It is conservatively assumed that all of the carbon-14 in the graphite is released, with 1% released as methane and the remainder as carbon dioxide[8]. In these calculations, we have assumed that methane is generated at a rate one order of magnitude lower than the detection limit achieved in recent experiments, up to a total of 1% of the graphite inventory of carbon-14. (If the detection limit itself were used the gas would only be released for a very short time after repository closure).

- The generated gas is assumed instantaneously to break through the overlying rocks to reach the biosphere.

- It is assumed that people will be growing and consuming crops on the land above the repository immediately after it has been closed, whereas in reality buildings would have to be demolished and the site cleared, and the regulators envisage a period of institutional control over the site.

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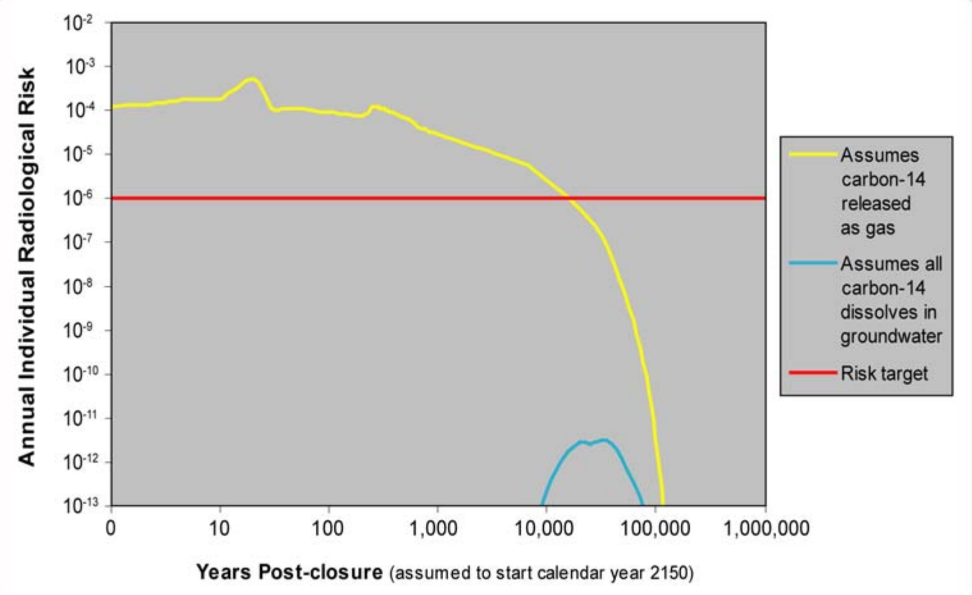
[8] Experiments show that 0.001% to 1% of the carbon-14 in graphite could be released as methane and that this is likely to be a short-term release; however, a lower but longer-term release rate has not been ruled out and has been assumed in these calculations.

- The radiological risk from the gas that is released to the biosphere is calculated using the biosphere factors used in the GPA. The biosphere factor for carbon-14 in the form of hydrocarbon gases has recently been reviewed and revised. The new biosphere factor has a dependence on the rate of release of non-active methane, which means that at longer times when the rate of non-active methane degradation has decreased, risks could be higher than that shown here. The peak risk would not be affected, however.

Figure 29
Annual individual risk vs time for carbon-14 dissolved in groundwater and for the scoping calculation for carbon-14 released as gas



The yellow curve contains contributions from methane produced from the corrosion of the more chemically reactive metals; the degradation of organic materials; irradiated graphite; and the corrosion of irradiated steels and Zircaloy. These contributions to the calculated risk are discussed further below.

The peak risk in the first 100 years (as calculated above) arises from the corrosion of uranium, with Magnox corrosion as another key contributor. In practice these metals will have undergone some corrosion prior to repository closure and their post-closure corrosion rate could be limited by water availability as the repository resaturates. Improving our understanding of these issues could reduce the peak post-closure risk modelled in the calculations.

Organic wastes containing carbon-14 contribute to the peak radiological risk calculated at around 250 years post closure. Although these wastes are declared in the Inventory, they may not come to a repository in this form as they could be re-used or treated in some other way, which could reduce their capability to generate methane gas. Organic wastes are calculated to completely degrade over a timescale of about 10,000 years, after this time the only sources of radioactive methane that remain are irradiated steels and Zircaloy.

The calculated risk from irradiated graphite makes a relatively lower contribution to the yellow curve (with a calculated risk of ~10^{-5} per year for about the first five hundred years).

Nirex has an ongoing programme of experiments on irradiated graphite and it is possible that improving the experimental detection limits could lead to a lower post-closure gas generation rate from graphite than that assumed for the scoping calculation. However, the accuracy of the inventory of carbon-14 in graphite has been questioned and this issue is also being reviewed and discussed with waste producers as part of the future work programme.

Corrosion of irradiated steels contributes significantly to the risk calculated above, especially after the other sources are degraded. Further research is required to determine the distribution of carbon-14 in irradiated steels and the form in which it is released during corrosion, which is uncertain. If the carbon-14 was heavily concentrated at the metal surface and it was released as methane, there might be an increase in the risks calculated (but only for a short time).

The calculation of the yellow curve assumes that methane generated in the repository would be directly released to the biosphere, taking no account of delay in the geosphere. In practice, some or all of the methane could dissolve in groundwater, depending on site conditions. If all the carbon-14 were to dissolve into groundwater and be released to the biosphere in solution, then the calculated risk is shown by the blue curve in Figure 29. Gas could also be retarded in the overlying rocks; for example many geological environments would include overlying sediments, which offer the potential to disperse gas migration from the repository, reducing the hazard from repository-derived gas. Also sedimentary rocks can often contain impermeable layers, such as mudrocks, which would be expected to retain gas.

As described in section 6.2, Nirex has an ongoing programme of research on carbon-14, which is improving our understanding of these issues. Further work is still required, which includes: work to assess the extent to which gas would dissolve in groundwater; work to assess the extent to which different geological environments (as measured by the presence of highly impermeable layers in the overlying strata) have the potential to retard gas migration; and work to reduce uncertainties in the rates and quantities of gaseous carbon-14 generated.

If, through further work, the calculated rates and quantities of carbon-14 containing methane generated were not to be significantly reduced, compared with those used in the scoping calculation presented here, it could be necessary to establish siting criteria that would ensure that significant gaseous release to the biosphere would be unlikely. Additional work is required to assess the extent to which different geological environments in the UK have the potential to retard gas migration and to determine how this could be assessed as part of a site characterisation programme. The implications of these criteria would need to be assessed and included within the requirements for the generic geology in the PGRC.

Although further work is planned which may include the identification of specific siting requirements, on balance Nirex believes that carbon-14 is not a threat to the viability of the phased geological repository concept.

Human intrusion pathway

International guidance has been provided on the siting of geological repositories to reduce the likelihood of inadvertent human intrusion, for example in [55]:

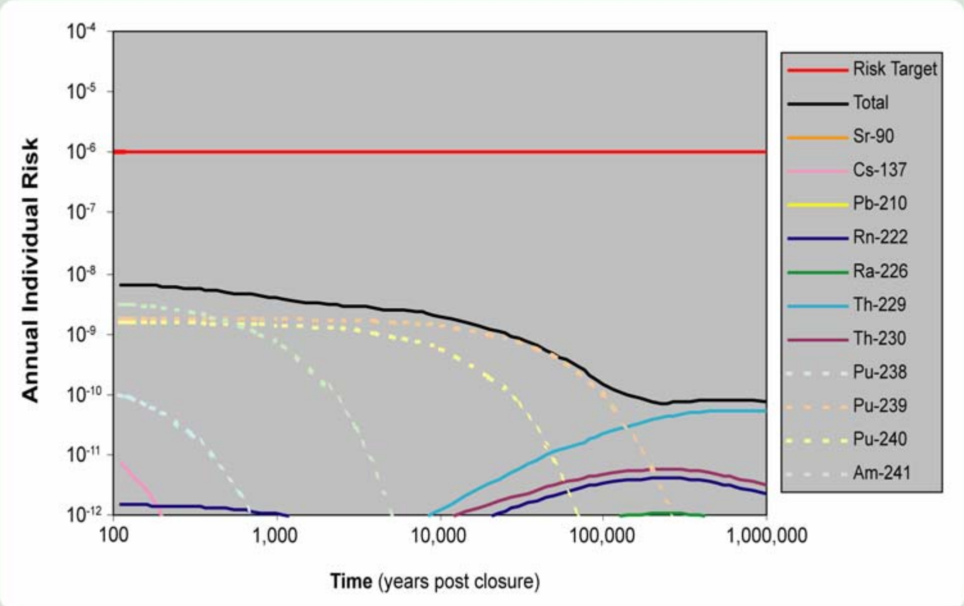
> *"Location away from known areas of underground mineral resources is desirable to reduce the likelihood of inadvertent disturbance of the geological*

disposal facility and to avoid resources being made unavailable for exploitation".

In practice this means selecting a geological host environment that holds little potential interest for exploration for minerals or other resources. Therefore the GPA considers the human intrusion pathway as a variant scenario, i.e. it is not expected to occur and hence not part of the base scenario.

In the human intrusion scenario, two potential exposure routes arising from drilling in the vicinity of the repository have been considered: 1) the geotechnical worker, who examines contaminated drill core; and 2) the site inhabitants who are exposed to radiation from discarded contaminated drill core. The peak radiological risk to the geotechnical worker, for an intrusion 100 years after repository closure, is 6.6×10^{-9} (or 1 in 152 million) per year and the peak calculated for a site occupier, after 200,000 years, is 9.3×10^{-7} (or 1 in 1.1 million) per year. Figure 30 gives the risk profile for the geotechnical worker.

Figure 30
Calculated annual risk in the geotechnical worker scenario, for intrusion into unshielded ILW vaults of a repository, reference case inventory



Implications for siting

The Generic Performance Assessment for the PGRC demonstrates that it is possible to locate such a repository concept in a range of geological environments and meet the regulatory risk target over all timescales.

Treatment of uncertainty

As described above the long-term safety and environmental assessment of the concept is based on an understanding of the general behaviour of the system focusing on the different ways in which radionuclides could leave the repository and enter the biosphere. This is represented in mathematical models that are used to calculate the safety and environmental impacts.

Some of the assessment models and associated parameters relate to processes on which there is little information or where information is difficult to obtain. This is a common problem in scientific and engineering analyses. Based on that experience, internationally accepted strategies for handling such data uncertainties in safety assessments have been developed, for example, NEA study groups have reached international consensus and published reports on establishing and communicating the long-term safety of deep disposal [69].

However, it is also important to recognise that there is substantial uncertainty associated with certain processes operating in a radioactive waste repository system on a timescale of a million years or more, and this uncertainty requires appropriate treatment in performance assessments in support of such a facility. In a repository system there are a number of different areas in which uncertainty may influence a performance assessment, including data uncertainty, model uncertainty, uncertainty about future states of the system and uncertainty about human behaviour.

There are various ways of handling uncertainty in data. These include using the most conservative possible values for uncertain data; and probabilistic approaches in which the range of uncertainty in parameter values is represented within probability density functions. A performance assessment may be relatively insensitive to some parameters, therefore poor data will be less important in some areas than others – sensitivity studies are very helpful in determining the significance of a particular parameter value to the overall repository performance.

Uncertainty in the formulation of conceptual models may be best handled by identifying and testing a range of different conceptual models. For example, in the Nirex 97 assessment [63] two conceptual models of the host rock structure were developed and carried through to the calculation stage where the different models could be calibrated and assessed for validity against independent data. The accuracy and correct functioning of the software itself can be verified by comparisons of results against those produced by other computer programs. It may also be possible to conduct test cases to reproduce answers from known analytical solutions.

For a post-closure performance assessment, there may be substantial uncertainty associated with the future of the repository system, and substantial variability. Nirex has developed a methodology for addressing this uncertainty in a systematic way, based on the analysis of FEPs and development of scenarios which can then be addressed in detail in a performance assessment.

For a given scenario, strategies for handling uncertainty tend to fall into the following broad categories:

- Demonstrating that the uncertainty is not important to safety because, for example, safety is dominated by other processes.

- Addressing the uncertainty explicitly, usually using probabilistic techniques, and showing that the expected situation is acceptable.

- Bounding the uncertainty and showing that even the bounding case gives acceptable safety.

- Ruling out the uncertainty, usually on the grounds of very low probability of occurrence, or because other consequences, if the uncertain event were to happen, would far outweigh concerns over the repository performance.

When assessing the performance of a radioactive waste repository over extremely long timescales, there are acknowledged to be uncertainties in many areas and some of these uncertainties will be large. However, not all of the uncertainties will be significant and there is international consensus [69] that, by using a combination of these strategies for treating such uncertainties, it is possible to develop a safety case for a repository.

A key driver for a deep geological repository as an option for the long-term management of radioactive waste, is to remove the large uncertainty associated with leaving the waste accessible to humans over very long timescales. This is because there is very much more uncertainty over the future of society than there is over whether the geosphere will perform its desired role of isolating the waste from such future societies. This is reflected in the relative timescales of geological change versus social change. A well-chosen geological site will be relatively stable for a long time into the future and provide effective containment of the radioactive material (see "Confidence in geological processes" below).

Status of Nirex performance assessment studies

A large amount of work has already been undertaken by Nirex and by similar organisations around the world to develop robust methodologies for the assessment of the long-term performance of geological repositories (see for example, [65]).

Nirex has a deliberate policy of seeking both preview (prior to implementation) and review of its scientific and technical work. The Nirex scenario development methodology and general assessment approach [59] and Nirex's most comprehensive performance assessment, the Nirex 97 assessment of a repository at the Sellafield site [63], have both been subjected to thorough formal peer review [61,64].

The current Nirex performance assessment studies are generic [19]. However, the assessment approach followed provides a link to earlier site-specific studies [70] and Nirex has published a report that describes the overall context for performance assessments and the ways in which they are expected to develop at the different stages of a repository development programme [65].

Nirex seeks continual improvement in its safety assessment work and is currently previewing proposals for its next safety assessment update. These proposals, which include more detailed modelling of the early post-closure timescales, will be scrutinised by the Nuclear Waste Assessment Team (NWAT) as part of the regulatory arrangements described in Section 4.3.

Confidence in geological processes

The safety of a geological repository is linked inevitably to time periods of at least tens or hundreds of thousands of years. It is hardly surprising that most people, non-scientists and scientists alike, find it difficult to come to terms with intervals such as these and to accept that they can be measured accurately. Yet it is vital that we understand the processes that will affect the repository and its surroundings over these immense time periods.

Central to the earth sciences are studies of the history of our planet. Underpinning this has been the development, over many years, of very precise methods for dating events and processes in geological history and, based on these, the establishment of an accurate record of geological time. The Earth is now believed to be slightly more than 4.5 thousand million years old – appreciably older than the periods we are concerned with here.

The discovery and systematic analysis of radioactivity provided the technical basis for a precise time scale against which to calibrate the geological record. A few natural chemical elements have unstable nuclei which decay, at characteristic and fixed rates, to produce different ("daughter") nuclei. Perhaps the most widely known and utilised is potassium 40 which decays to an isotope of Argon (argon-40). Potassium is a metal and very commonly found in rock-forming minerals such as feldspar and micas. Argon is a gas which is not incorporated into the minerals when they form. Once they are formed, however, the products of radioactive decay are trapped in the crystal lattice and, as time passes, argon builds up as potassium decays. Measuring the ratio of these two gives a direct estimate of age. On the basis of these and similar measurements, literally hundreds of thousands of "ages" have been measured in laboratories around the World with much research devoted to establishing uncertainties and precisions.

Other, independent, scientific techniques have been developed which allow the precision of the scale to be greatly refined and applied to many different rock types – not just those for which radiometric dating is possible. The Earth's magnetic field reverses relatively regularly and periods of "normal" and "reverse" magnetism have been calibrated and measured in different rocks. Equally, higher resolution biological dating has emerged from studies of fossil pollen and plankton – and utilised very successfully in the search for oil and gas. Finally, climate oscillations have been recorded in deep sea sediments (which give a continuous record going back many millions of years) by water temperature estimates from oxygen isotope ratios preserved in marine plankton. The painstaking research which led to this remarkably comprehensive understanding, including detailed descriptions of the methodologies employed, is described fully in [71].

On this foundation, earth scientists have built up a sound and quantitative understanding of the different kinds of process that cause the geosphere to be modified, including surface processes, and the time scales upon which they operate.

The long-term safety of the Nirex PGRC, in common with repository concepts adopted elsewhere, capitalises on the inherent stability of the geosphere compared with processes that occur at the Earth's surface. For its generic performance assessments Nirex has simplified the various rock mass characteristics that influence the transport of radionuclides in groundwaters into three parameters, Q, T and F (see above). These three parameters can be used to indicate how the return of many radionuclides to the surface environment would be prevented, and to what extent the concentrations of any radionuclides that might return would be affected by the processes of radioactive decay, retention on rock surfaces, or dilution in the groundwater system.

Any repository site that might be selected would have to demonstrate appropriate values for these parameters, that would be set in accord with regulatory safety requirements. However, the key issue to be addressed in any assessment of the suitability of a prospective site is how to provide credible evidence that the processes of groundwater movement and radionuclide transport are unlikely to be accelerated at repository depths at any time in the future.

Rocks are made up of a solid mineral framework and a network of groundwater-filled pores and fractures. The connectivity and dimensions of these pores and fractures determine the ease with which groundwater can flow through rock under an imposed driving force (the "permeability"). Driving forces and gradients in groundwater pressures are caused by spatial variations of water infiltration and land topography and by variations of water density due to salinity and/or thermal effects.

Potential changes that might alter Q, T and F in the long term are mainly those that might affect the volume and connectivity of pores and fractures in the rock mass and in the forces that drive groundwater movement. Examples of the changes that could affect the volume and connectivity of pores and fractures include the precipitation or dissolution of minerals due to chemical reactions and the closing or opening of fractures due to changes in imposed stress. Driving forces can similarly change with time, for example due to additional water pressure being exerted through the development of overlying ice sheets, groundwater infiltration decreasing in response to climate change, or density changes as groundwater compositions evolve or the thermal characteristics of a region change.

When considering more dramatic events that might change the rates of processes, we know, on the basis of radiometric dating of geological events, that some regions of the Earth's surface, located close to plate boundaries, are tectonically active. Frequent and massive earthquakes cause rock fracturing and may enhance permeability. Such regions remain susceptible to tectonic disruptions for many millions of years since the pattern of plate geometries only changes exceedingly slowly. Equally, there are large regions of the Earth's surface far away from plate boundaries where "quiet" conditions prevail – again for many millions of years. This is the case in the UK. Because these periods are very long, even compared with the longevity of artificially induced radioactivity, we can be confident that the characteristics of the deep subsurface will not change "suddenly" and site characteristics obtained by site investigation will be good indicators of future behaviour – even on a million year time frame.

Nirex is currently developing proposals for integrating the quantitative assessments and the other lines of reasoning, such as presented here, in an Environmental Safety Case (see Section 5.6).

Analysis of breakdown of PGRC multiple barrier system

The information presented above is intended to provide assurance of the long-term safety and environmental protection that will be provided as the repository system evolves with time. Further assurance of the intrinsic robustness of placing wastes in deep geological formations may be obtained from a separate type of analysis.

The post-closure performance assessments for the PGRC conducted by Nirex have attempted to take account of all identified uncertainties concerning the processes that may impact upon the calculated radiological risk. Safety of the concept is provided by multiple barriers avoiding undue reliance on any single safety function of one of the barriers. However the hypothetical extreme situation has been assessed, where no physical or chemical containment is assumed from the repository near field and all beneficial retardation processes in the geosphere are removed. Even under this scenario the results would not be catastrophic. Calculated annual doses are the same as those routinely received by members of the public in some locations of the UK from natural radiation [72]

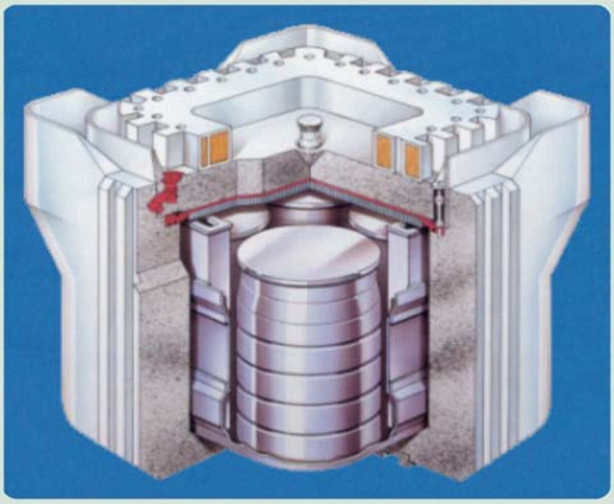
5.2 Safety of transport to the repository

ILW exists at 34 nuclear sites distributed around the UK. The PGRC assumes that all this ILW will require transport to a single destination. Any national waste management strategy based on one or more centralised sites would have a similar transport requirement.

Focus group exercises show that transport will be the aspect of radioactive waste management that is likely to affect the public most directly. Hence, the safety of transport is a key issue for public acceptability of the PGRC and it is extremely important that the transport system is developed in a way that addresses stakeholders' concerns. Nirex is developing a strategy for stakeholder engagement in relation to its transport safety programme to help achieve this [73]. For example, we are looking at sea transport as a possible means to reduce road and rail transport.

International standards and guidance for the safe transport of radioactive materials have been developed based on world-wide experience and best practice. This experience is distilled into the IAEA Transport Regulations [21], which apply to road, rail, sea and air transport of radioactive materials. These international regulations are enacted as EU Directives and by individual states, including the UK, and govern all transport of radioactive materials, including waste, through the public domain. A report has been produced annually by the National Radiological Protection Agency (NRPB) [74] which reviews the safety of radioactive materials transport within the UK. The reviews shows that radioactive materials have been transported safely to these standards for decades.

Figure 31
Standard transport package



Nirex has developed a concept for a national transport system to transport safely and efficiently all the UK's packaged ILW, and relevant LLW, from their sites of arising to a repository site [75]. This includes the specification of a range of transport packages (see Figure 31) and vehicle types, as well as the transport operation logistics. Key aspects are:

- development of designs and specifications for standard waste containers and specifications for their allowable contents (see Section 4.5);
- conceptual design of a range of reusable shielded transport containers for the transport of unshielded waste packages requiring shielding;
- development of realistic transport routes and logistics for a national transport system including all 34 nuclear sites and any one notional destination; and
- development of designs for rail wagons, road vehicles and associated transport hardware.

All individual elements are consistent with IAEA regulations, where applicable, and Nirex is working towards a formal demonstration of compliance with all the applicable safety standards. In addition to meeting international standards, Nirex has undertaken a detailed assessment of the safety of the transport operation which provides a basis for dialogue with stakeholders.

The assessments of transport safety are documented in the Generic Transport Safety Assessment (GTSA) [76]. The assessment uses probabilistic risk-based methodologies for safety assessment similar to those applied to repository operations (see Section 5.3). These are consistent with the Health and Safety Executive (HSE) requirements for operational safety assessments at nuclear sites [77]. The GTSA currently assumes a transport operation based on a combination of road and rail transport, with scenarios looking at different mixes of the two. The generic nature of the assessment is achieved by dividing the Great Britain mainland into 10 geographic zones and considering transport to a notional repository in each zone. The GTSA also includes an initial consideration of sea transport issues and this is to be expanded in the future. Initial stakeholder feedback indicates that this will be important.

Doses and risks are estimated for routine transport operations and also from transport accidents, taking account of significant features of the transport routes. The GTSA shows that the radiological risks from transport accidents will generally be small compared with the conventional accident risks. The estimated radiological risks are dominated by external radiation from the transport packages during routine operations.

The GTSA methodology is also applied to the assessment of individual waste packaging proposals, as part of the Letter of Compliance assessment process (see Section 4.6). Experience gained from this work provides feedback into the GTSA development programme.

Overall, the GTSA shows that a national programme for the transport of ILW and relevant LLW can be achieved within risk levels that are acceptable under Nirex safety policies and guidance from HSE. However, we are very conscious of stakeholder and public concerns in this area. Current work is focusing on:

- optimising areas of the transport system design where the GTSA has shown that, under some circumstances, risks could approach the Nirex design targets;

- enhancing the GTSA methodologies to deal better with the issues identified, to treat some additional scenarios, and to bring the methods used in assessments for transport operations more closely into line with those for repository operations; and

- identification of infrastructure, logistics and safety issues associated with a sea transport operation.

5.3 Safety of repository operations

The operation of any industrial facility carries risks that must be controlled so as to protect workers, members of the public and the environment. The key design feature of the repository system is the use of tried and tested technology, e.g. the lifting and handling systems are similar to those used routinely in existing nuclear facilities. For the PGRC, Nirex has developed safety standards and criteria consistent with international standards [78] and UK regulations and guidance [79]. Adherence to these standards and criteria is designed to ensure that all radiological risks are as low as reasonably practicable and within applicable regulatory limits. Conventional risks are also considered and judged against safety standards and best practice in conventional mining and construction operations.

The operational safety of the PGRC will be assured by good design and operational procedures, which are being developed through iterative design and safety assessment studies, as described in Section 4.4. The Generic Operational Safety Assessment (GOSA) [80] addresses the radiological and conventional safety of all phases of repository operation, i.e. waste package emplacement, monitored retrievable storage, vault backfilling, and repository sealing and closure.

The approach to assessing the design at each stage is to:

- identify faults and hazards that could be associated with repository operation;
- identify good engineering practice that can eliminate, reduce or mitigate hazards; and
- assess impacts of faults and hazards and routine operations in the generic safety assessment.

A HAZOP process is used to identify faults or hazards. This is a structured, critical examination of plant or processes that is undertaken by experienced designers, assessors and operators, aimed at identifying all potential hazards along with the consequent effects concerning safety, operability and the environment.

Faults and hazards are then addressed as follows:

- where practicable the potential hazards are eliminated by changes to the design, system, or process, which gives rise to the hazard;
- where the hazard cannot be removed or reduced to acceptable levels, protection or isolation from the hazard is provided to the workers and/or the public;
- where the hazard cannot be eliminated, its effects are mitigated by design, process changes and/or management control; and
- where faults and hazards cannot be eliminated the consequences are evaluated.

The consequences are evaluated by the following methods:

- Design Basis Accident (DBA) Analysis – is an assessment of the consequences from what are judged to be worst case accidents. The results of these calculations are used to judge whether there are sufficient safety features within the design and what safety status should be assigned to these features.
- Probabilistic Safety Assessment (PSA) – is an assessment of the annual radiological risk to workers and members of the public from operations (including accidents).
- Operational Dose Assessment – is an assessment of radiological doses to members of the public and workers both from direct radiation and discharges during normal operations.
- Conventional Safety Assessment – is an assessment of the consequences from conventional (non-radiological) faults and hazards.

Nirex has undertaken these evaluations based on its own experience of many years of research and development on geological repositories, and information from the operation of surface facilities for radioactive waste management in the UK. The evaluations take account of factors such as repository design features, the timing of the different operational phases, radionuclide and chemical inventories, package types, performance of different package types in accident scenarios, and the effect of external conditions.

The results of the assessments, which are presented in the GOSA show that the current design can meet the applicable regulatory and Nirex criteria, and operations would not present an undue risk to workers, members of the public or the environment.

The examination of operational safety issues will continue as the repository design becomes more specific and also will investigate safety implications of alternative designs and changes to the inventory of waste. Issues may also be raised through the ongoing assessments of operational safety in support of the LoC assessment process (see Section 4.6) and through Nirex's programmes of stakeholder dialogue. Nirex is also working to improve progressively the safety assessment methods and information base as the repository design and variants are developed.

5.4 Criticality safety

Criticality refers to a self-sustaining fission chain reaction, usually involving the fissile radionuclides U-235 or Pu-239. Such an event releases energy and, in a highly engineered special case, forms the basis for nuclear weapons. We find that this link between criticality and a nuclear explosion is a concern to many stakeholders.

The conditions required for a nuclear explosion would not be possible in a repository. In a weapon designed to produce a nuclear explosion, the fissile material must be brought together ("assembled") very quickly, usually by a conventional explosion, and neutron moderators, such as water, must not be present. In the repository environment, fissile radionuclides would migrate slowly through materials that would be saturated with water and they would be more likely to be dispersed than to be accumulated.

However, there is a theoretical possibility of a criticality event leading to a release of energy, although accumulating sufficient fissile material for a criticality event would be difficult. Nirex's specifications are designed to avoid the accumulation of sufficient material, but work is undertaken to understand the potential consequences of such an event if it were to occur.

During storage, transport and operational phases of the PGRC (up to vault backfilling), criticality could lead to damage to the waste packages, spread of contamination, exposure to workers during the event and during remediation of the damaged and contaminated areas. In these phases, the potential for criticality must be avoided. This is achieved by controlling the package design, including the level of fissile material, to avoid the potential for criticality in individual packages and assemblies of packages during storage, transport and repository operations. In addition, package designs are robust to accidents (impact and fire), which eliminates the possibility of criticality occurring as a result of an accident.

After repository closure, groundwater will cause gradual degradation of the waste packages and wasteform so that radionuclides may migrate within the vaults and surrounding rock. It could take several thousand years for this to occur. There is a possibility that migration could lead to the accumulation of fissile radionuclides from more than one package, with an associated, but low, probability of criticality. The consequences of such an event are less than in the transport or operational phases, as they would be contained by the geological barrier. Still, the potential for criticality after repository closure must be assessed.

In detail, calculations with very pessimistic assumptions, e.g. of geometry and neutron moderation indicate an amount as low as ~500g of Pu-239 could constitute a critical mass. Nirex modelling has shown that by setting a screening level of 50g Pu-239 equivalent per package the accumulation of a critical mass would be avoided. If a package contains less than the screening level, it can confidently be assumed that the possibility for criticality has been eliminated.

Analysis of inventory information indicates that 15-20% of ILW packages will contain more than the equivalent of 50g Pu-239. Packages containing levels of fissile material above this screening level can still be considered, and are currently assessed on a case-by-case basis, through the LoC assessment process, to determine the Safe Fissile Mass for these packages. A safe fissile mass above 50g could be accommodated in the presence of materials that inhibit the criticality chain reaction such as uranium-238 that may be present in the waste.

Recently the Nirex approach to setting waste package fissile levels has been reviewed by the Environment Agency [81]. The review recommended that Nirex should continue to develop the methodology underpinning the generic screening level, the objective being to:

- derive post-closure screening levels based upon an approach that considers both conservative and less pessimistic assumptions with regard to the likely evolution of the system after repository closure;

- align the approach for the criticality safety assessment of the operational phase with principles being developed by regulators and the industry; and

- develop waste transport safety criticality safety assessments through interactions with the Department for Transport.

The new approach is designed to enable a balance of risk arguments to be made, with the aim of ensuring that any agreed limits are proportionate and not unduly restrictive whilst being safe. The approach will identify general screening levels for waste packages containing four common categories of fissile material: low enriched uranium; highly enriched uranium; plutonium contaminated material; irradiated natural uranium.

After repository closure, the probability of criticality is minimised by limitation of individual package contents and operational constraints. The uniform chemical conditions created in the vault backfill (see Section 6.3) would severely restrict the migration and accumulation of fissile radionuclides. In addition to assessing and taking such steps to reduce the likelihood of a criticality occurring Nirex carries out research to assess the potential consequences of a criticality [82].

If a criticality did occur, some local mechanical damage and some heat-induced chemical changes might take place. Also there would be a change in the inventory (reduction of fissile radionuclide and production of fission products). The effects, however, would be confined within a small part of the repository and surrounding rock so that no immediate impacts would be experienced and any long-term impacts would be very minor. The study concluded that:

- the potential for a criticality is low, because a number of unlikely conditions and mechanisms would have to be met or act together for a criticality to occur; and

- even if a criticality did occur, its impact on repository performance would not be significant, because the criticality could only affect a small volume of a repository and a very small fraction of the inventory.

5.5 Non-radiological environmental assessment

In addition to the radiological assessments Nirex is planning to undertake a non-radiological environmental assessment of the PGRC. This has been in response to stakeholder feedback and a scope of work and methodology [83] have now been developed as a result of dialogue.

This envisages the following components:

- a non-radiological environmental assessment of the PGRC;
- a preliminary assessment of the impact of the repository on species other than humans;
- a report setting out issues that have emerged from ongoing stakeholder dialogue and describing how those issues are being addressed; and
- consideration of whether any of the criteria suggested or used by others for assessing waste management options should be used in the assessment of the PGRC.

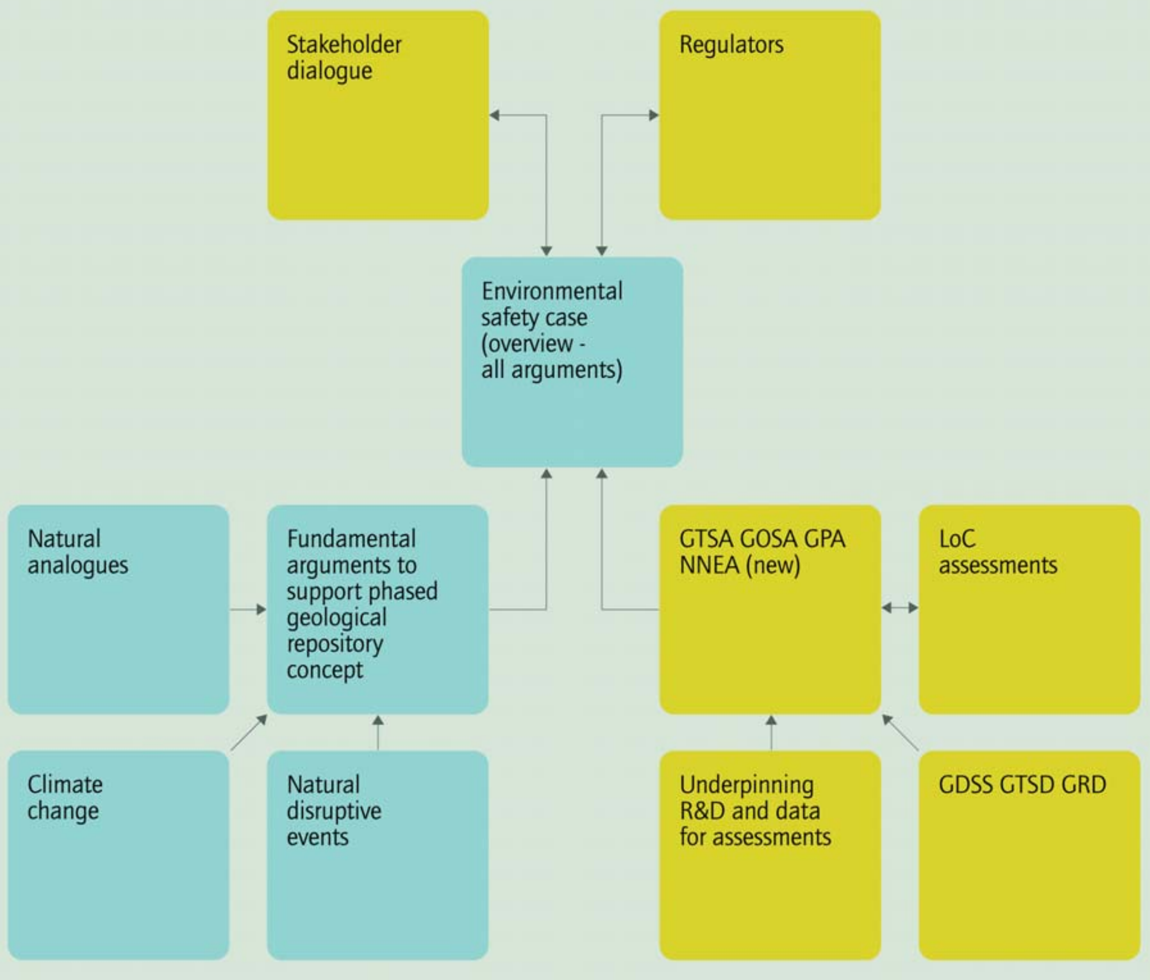
The strategy has been discussed at two workshops (in 2002 and 2005) to which Nirex invited a range of stakeholders including national and local Government representatives, regulators, NGOs, academics, members of the public, contractors and members of the nuclear industry. Feedback received is being used to guide the development of the non-radiological assessment. Progress to date has led to :

- a non-radiological environmental assessment scoping report;
- an assessment of the impacts of chemically toxic species; and
- a preliminary assessment of the impacts on species other than humans.

5.6 Environmental Safety Case

Nirex is currently developing proposals for an overall Environmental Safety Case that will present the case for the safety and environmental performance of the Phased Geological Repository Concept. It is envisaged that the Environmental Safety Case will use direct evidence from natural analogues (defined very widely) and other fundamental arguments. These arguments will be supported by the existing transport and operational safety assessments, the GPA and non-nuclear environmental assessment (see Figure 32).

Figure 32
Environmental safety case



6 RESEARCH PROGRAMME

A key component in demonstrating the viability of the concept is that it is underpinned by a credible research programme. Nirex has been carrying out research for over twenty years, covering a vast range of subjects and involving scientists from many organisations, both in the UK and abroad.

Key drivers for carrying out research are:

- Safety and environmental assessments of the Phased Geological Repository Concept. The assessments of the concept are underpinned by research, to ensure that the processes that are likely to affect the future safety and environmental performance of a repository are appropriately captured in the models.

- The Letter of Compliance process. In the process of giving packaging advice, we develop our understanding of specific wastes and their long-term behaviour and this can raise issues which need to be addressed by further research.

- Interaction with regulators. The Environment Agency has a programme for scrutinising our work, and this process may raise issues where further research is required.

- Stakeholder dialogue particularly within the scientific community. It is important to be able to show that we understand the key processes that would occur following closure of a repository. Research is required to establish whether these processes need to be represented explicitly in the concept safety and environmental assessments.

- Preview - a particular type of stakeholder interaction that involves dialogue about the future direction of research. This is a way of involving others, including external specialists, in defining our programme and setting the direction of particular research projects.

The research programme is extensive, covering a broad range of topics and it is not appropriate to give a full status report here. The current status of the key issues are described below by the main themes which are: wasteform research; gas generation; near-field research; geosphere research; biosphere research and criticality safety research. A comprehensive listing of reports from the research programme and other Nirex work can be obtained on the Nirex website www.nirex.co.uk.

6.1 Wasteform research

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

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

- The physical and chemical evolution of wasteforms [84].
- The integrity of the wasteform [e.g. 85].
- Generation of gas.
- The compatibility of wasteforms with the Phased Geological Repository Concept [86].

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

Both of these aspects have been the subject of extensive research programmes involving waste producers and external experts from contracting organisations. A methodology has been developed to take account of acid-generating material within wasteforms when calculating the amount of backfill needed in a repository [87] and this work can be used as a basis for considering the impact of non-cement based immobilisation matrices. The impact of complexants is discussed further under near-field research in Section 6.3.

To date, in performance assessment risk calculations, no credit has been taken for containment of radionuclides by the wasteform once the repository has been closed. However, we calculate [17, 18] that more than 90% of the initial radioactivity would decay inside the container in the thousand years following repository closure. This issue will be addressed in future modelling work, which will require further research to build on the current understanding of wasteform evolution.

A key aspect of the wasteform research programme relates to the potential for the wasteform to generate gas. This is discussed further in section 6.2 below.

The current status of wasteform research is sufficient to conclude that there are no issues that fundamentally threaten the viability of the concept. Through the Letter of Compliance process, Nirex will continue to address wasteform issues that may arise as each waste stream is packaged. Wasteform research will continue to be an important part of the Nirex research programme, particularly as post-closure performance assessment models are refined to model more explicitly the wasteform evolution.

6.2 Gas generation

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

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

The discharge of radioactive gases during repository operations can be reduced, for example by chemically scrubbing the gases before discharge. In the post-closure phase, the vault backfill has a relatively high porosity which will allow gas to disperse in the vault volume. The vault backfill and the grout within waste packages are cement-based and will react with carbon dioxide to form low solubility carbonates, limiting the release of gaseous carbon dioxide from the repository. Further work is required to demonstrate that the carbon dioxide would have sufficient access to backfill and that there would be sufficient time for the carbonation reaction to occur. However, scoping calculations presented in Volume 4 of Nirex 97 indicate that sufficient equilibration would be achieved and that therefore negligible gaseous carbon dioxide would be present in the repository.

Issues related to gas generation have been the subject of research over many years, both in the UK and internationally. Nirex has established an understanding of these issues sufficient to guide the design of the concept and to develop a model of gas generation within the repository, although some uncertainties remain about the amount of gaseous carbon-14 that would be generated from the waste. The possible impacts of gas generation have been reviewed in a recent EC-funded project [88]. An assessment of many of these impacts is included in the generic documents, although a more detailed assessment would be undertaken in support of a site-specific repository performance assessment.

A key issue for the Nirex Phased Geological Repository Concept is the potential radiological consequences of gases containing carbon-14. There are three potential sources of carbon-14 containing gases that are typically identified [19, 89]. These are irradiated graphite, irradiated metals and organic wastes.

The possibility of the release of gaseous carbon-14 from irradiated graphite and irradiated metals has not so far been included in gas pathway calculations in the generic documents, but simple models have now been developed to allow these possible sources to be subject to scoping calculations.

These scoping calculations show that, if it is assumed that the carbon in these materials reacts to form carbon-14 bearing methane and that this migrates as a free gas to the biosphere, there could be a significant impact on the calculated risk from this gas pathway. However, groundwater has the capacity to dissolve methane and work is underway to see if this capacity can be scoped in the absence of site-specific information. In some national programmes, dealing with broadly similar quantities of wastes with a potential for gas generation, it is calculated that all the methane generated will be dissolved in the groundwater systems overlying the repository. Once gas has dissolved, long groundwater travel times to the surface and release at the surface in solution both reduce the calculated impact of carbon-14 in methane to insignificant levels.

A key issue is the extent of the mixing between gas bubbles and groundwater, which depends on site-specific features, including the nature of the host rock. If there is considerable mixing, all of the gas can dissolve. Also, real, low-permeability rock-water systems, such as would be suitable for an ILW repository site, typically contain highly impermeable layers that could prevent the movement of free gas to the surface. Conversely, extended fracture systems could act as conduits for upward migration of free gas.

Such site-specific processes and features are not included in the geosphere description given in the generic documents and further work will be carried out to define better the range of conditions under which significant free gas release to the biosphere is unlikely to occur. In parallel, further research is required to determine the rates and quantities of gaseous carbon-14 generation.

6.3 Near-field research

The near field of the PGRC consists of the repository vaults and the immobilised waste within them, as well as the cement-based vault backfill. The near field provides two types of barrier functions to prevent the migration of radionuclides into the surrounding rock: physical barriers provided by the waste package, backfill and repository seals; and a chemical barrier provided by the cement-based materials in the repository.

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

- Wastes are immobilised in cement within a stainless steel container. This package provides passive safety during the operational period [90] and also contributes to the physical and chemical barriers after repository closure. Although no credit is taken in performance assessment risk calculations for package integrity after repository closure, calculations [17, 18] have shown that more than 90% of the initial radioactivity would decay inside the container in the first thousand years after repository closure.

- Once the vaults are backfilled and sealed, oxygen will be consumed (mainly by metal corrosion), so that anaerobic or reducing conditions are established [91]. Reducing conditions limit localised corrosion of stainless steel waste containers and maintain some radionuclides in low oxidation states, which have low solubility.

- Incoming groundwater will dissolve small quantities of the cement-based backfill, becoming alkaline (high pH) as it fills the vault [92]. The high pH environment ensures that the rate of corrosion of the stainless steel containers is very slow [16].

- The high pH of the cement porewater ensures that the chemistry of the near field is dominated by the hydroxyl ion (OH^-), which favours the formation of metal hydroxides. Hydroxides of many radionuclides have low solubility at high pH [50]. This effectively reduces the amount of radioactivity that can be dissolved in the groundwater.

- The backfill provides a high surface area for the sorption[9] of radionuclides from solution [92]. Radionuclides in solution in the backfill porewater can be removed from solution by "sorbing" to the backfill, reducing their ability to migrate out of the repository in groundwater.

[9] The generic term "sorption" covers the processes of absorption, physical adsorption and chemical adsorption. It is used here to include all processes that involve partitioning of a substance between solid and liquid phases, reducing the concentration in solution or retarding its migration.

- The backfill provides physical stability surrounding each container.

- At closure, the repository access routes would be backfilled and sealed to prevent these acting as preferential pathways for contaminated water [42].

The behaviour of a cementitious repository near field has been the subject of research programmes for more than twenty years. Nirex has established an extensive research base, which supports and underpins assessments of the long-term safety of the PGRC. The research programme has involved experts in universities and in contracting organisations, both in the UK and abroad, and draws on wide experience of the use of stainless steel and cement in a range of applications. The Nirex research base is supported by further research by other waste management organisations overseas and by co-operative international projects.

The near-field research programme can be described by the following key themes:

- Physical containment of radioactivity within the near field and the role that this plays in the PGRC.

- Chemical containment of radioactivity, particularly by the cement backfill over the long timescale for which the chemical barrier would have to operate.

- Chemicals or processes in the repository near field that could challenge the chemical containment of radionuclides by making certain radionuclides more mobile and whether these need to be explicitly represented in the long-term safety case.

The first of these themes relates to the role of physical containment and how this is modelled in the safety assessment. Corrosion of the waste container would be extremely slow and the waste immobilisation matrix would also provide physical containment for the radioactivity. To date, in performance assessment models, no credit has been taken for containment of radionuclides in waste packages once the repository has been closed, but in future modelling work, these features will be better represented.

The second theme relates to the requirements placed on the cement backfill, particularly given the long timescale over which the chemical barrier would have to operate. Chemical containment is an important safety function of the Nirex Phased Geological Repository Concept, providing a number of additional benefits over and above those provided by the waste package alone. Nirex has carried out a large programme of research in this area, including experimental and modelling work. However, demonstrating to stakeholders that the chemical barrier would indeed provide conditions in which the solubility of radionuclides would be low and that the high pH environment would last over the timescales required can be challenging. This is, therefore, considered to be a key issue and is the subject of ongoing research.

The third theme relates to chemicals and processes that could challenge the chemical containment of radionuclides. Under this theme the following topics have been considered:

- The effect of complexants

- The significance of backfill cracking

- Temperature and heating effects

- The effect of non-aqueous phase liquids (NAPLs), such as oils and greases

- The role of microbes
- The establishment of reducing conditions (see above) and the effect on radionuclide solubility
- Groundwater chemistry
- Colloids
- Radiolysis

Of these, two issues are particularly challenging, the effect of complexants and the effect of non-aqueous phase liquids (NAPLs), or more specifically light NAPLs, being substances that are less dense than water.

Complexants make radionuclides more mobile by increasing their solubility and reducing sorption. One of the most significant sources of complexants within the repository results when cellulose (present in the waste) degrades. The increases in solubility and decreases in sorption caused by the presence of cellulose degradation products have been measured in experiments and a methodology has been developed to include the effects in performance assessments. Other experimental and modelling work demonstrates that there are unlikely to be significant quantities of other materials within a repository that could have a similar magnitude effect on near-field solubility and sorption.

Light NAPLs are challenging because they have a known potential for uptake of some radionuclides and may migrate more rapidly through the geosphere than groundwater. The light NAPLs would only leave each repository vault if there was sufficient pooled in a reservoir in the roof space to overcome the forces that prevent such materials entering narrow fractures in the host rock. Once in the rock, further losses would be expected . Therefore the repository has a capacity for NAPLs at least up to the amount required to form the critical size of reservoir. Research has shown that the encapsulated wasteforms envisaged for wastes in which NAPLs such as oils and greases would be present at the time of emplacement would limit their rate of release into the repository, making the formation of a reservoir unlikely. Furthermore, materials such as oils are known to break down under radiolysis to give water-soluble or immobile products over timescales as short as 100 years, the timescales being subject to the precise conditions under which radiolysis occurs.

Given that the amounts of NAPLs such as oil and grease in wastes are controlled by the LoC process, this source does not represent a significant uncertainty. However, the possibility exists that further NAPLs could be created in the repository as breakdown products of the radiolysis of organic polymers in wastes. Work is underway to define the realistic potential yield of NAPLs from this source and the nature and rates of production of such NAPLs. Specific polymers in wastes are evaluated on a case-by-case basis through the LoC process.

Results from initial experimentation on the migration of NAPLs indicates that they would not have a significant secondary detrimental effect on beneficial processes such as sorption and confirm that they would access pores and fractures in rocks to become trapped.

The current status of near-field research is that:

- There is sufficient confidence in the behaviour of the repository near field to allow Nirex to give packaging advice to waste producers. In the process of giving packaging advice we develop our understanding of specific wastes and their behaviour in the repository near field and this helps to guide the research programme.

- Enough is known about the repository near field to begin a programme of site selection. When one or more potential sites have been selected, site specific research will be required.

- An ongoing programme of research will be required to ensure that the key issues continue to be addressed.

6.4 Geosphere research

The geosphere comprises the rocks in which the repository is constructed and those that surround them, extending to the surface. Managing radioactive waste within a geological environment which is several hundred metres underground provides advantages compared with leaving it on the surface, because a well chosen site can provide:

- A physical barrier that protects the repository from natural disruptive events such as weathering, glaciations, erosion, asteroid impacts and earthquakes.

- A mechanically stable environment for the repository.

- Long and slow groundwater return pathways from the repository to the surface environment, along which retardation processes, dilution and dispersion act to reduce the concentration of radionuclides in groundwater.

- A stable geochemical environment, which protects the engineered barriers.

- An environment which reduces the likelihood of inadvertent human intrusion.

- Protection from deliberate human interference.

Nirex has had a geosphere research programme since the 1980's. The programme has included research on the following themes, which relate to the safety features described above:

- Geosphere stability – includes consideration of natural processes such as volcanic activity, tectonic uplift, asteroid impacts and seismic events as well as the impact of the repository itself (the excavation disturbed zone and the alkaline disturbed zone).

- Spatial variability – includes developing methods for representing the natural variability of the geosphere in groundwater flow models. The nature of the rocks at Sellafield meant that Nirex was at the forefront in developing "state of the art" computer models capable of representing groundwater flow and radionuclide transport both in fractured and porous rocks [93]. Models of fracture flow were based respectively on knowledge gained from experiments of flow in individual fractures and at experimental sites at Reskajeage in Cornwall and Äspö in Sweden, while models of flow in porous rocks used experience from the water and oil industry. Since then, increases in computer power have meant that even more sophisticated and realistic models are routinely undertaken by the radioactive waste and oil industries.

- Retardation processes – naturally occurring processes that retard the transport of radionuclides in the geosphere. Of these the most important process is sorption of radionuclides to rock surfaces. A large number of laboratory measurements has been collected by Nirex and others, demonstrating that sorption is an effective way of retarding many radionuclides across a wide range of rock and groundwater types.

- Perturbing factors – the retardation described above could be affected by other factors, including complexants (either from the repository or present in the environment), colloids (present in groundwater) and microbial activity.

- Gas migration – processes involving two phase (gas-water) interactions that may impact on the migration of radionuclides in the gas and groundwater phases.

- Modelling – approaches to the development of and confirmation of mathematical models of the various processes noted above.

The research has been carried out using contractors at a number of UK universities as well as organisations such as the British Geological Survey and other specialist contracting organisations, for example, Serco Assurance. Much of the generic work has been carried out through EC part-funded or other international co-operative programmes, e.g. [94, 95], involving other waste management organisations abroad and their contractors.

During the 1990's, Nirex was investigating the geology of the Sellafield area, for its suitability to host a radioactive waste repository (see section 8.4). At that time, the geosphere research programme was closely integrated with the programme of site characterisation work, but since then research has been generic in nature and not linked to any specific site. Site-specific research will be required again if a site or sites are chosen for more detailed characterisation.

A key part of the work involves dialogue with stakeholders and this dialogue has identified a number of key issues, which either alone or in combination could influence the selection of a suitable site for implementation of the concept. For example demonstrating to stakeholders that the spatial variability of a site is appropriately understood and represented in models would be easier if the site were simple and easily characterised. Similarly it would be advantageous to choose a site with a low groundwater colloid population and a low concentration of naturally-occurring complexants. The choice of host rock would also strongly influence the research required on the migration of gas [88].

These issues have been recognised by all organisations investigating the disposal of radioactive wastes [96] and are not considered to be insurmountable. There is considerable experience of carrying out site-specific research, both within Nirex and internationally, where a range of host rock types have been studied.

The current status of work is sufficient to support packaging advice and to proceed with a site selection process in the UK. As part of any such site selection process, the geosphere will need to be characterised and a programme of site-specific research will be required. The choice of host rock and the geological setting would influence the nature of the research required. The geosphere represents a key aspect of the PGRC and geosphere research will continue to be a key component of the Nirex research programme.

6.5 Biosphere research

The biosphere is the near-surface and surface environment. It includes the atmosphere, rivers and lakes, the soil and the upper part of the bedrock. The biosphere is not considered as a barrier to radionuclide releases, rather it is a receptor for such releases. On the long timescales of relevance to performance assessment calculations, typically up to one million years, small quantities of long-lived radionuclides may be released from the repository system, migrate through the geosphere and reach the surface environment. Performance assessment calculations aim to assess the risk to humans and other biota from the subsequent radiological exposure. Biosphere research provides data and understanding about how radionuclides are dispersed or accumulated in the environment and how they enter the food chain.

The Nirex biosphere research programme has been at the forefront of biosphere research for radioactive waste management since the late 1980's and a large volume of information now exists to support assessments. The biosphere research programme has been divided into a number of project areas:

- Climatology (evolution of climate);
- Geomorphology (landform evolution);
- Ice sheet modelling;
- Near-surface hydrology and radionuclide transport;
- Soil-plant radionuclide transfer and uptake into the food chain;
- Description of potentially exposed groups (PEGs)[10].

The scope of the research work that Nirex has carried out to date includes literature reviews, laboratory and field experimentation, and numerical modelling studies of sub-system components.

Because of the long timescales involved, it is not possible to be certain about what a future biosphere might be like and how it might evolve over time. For example, human influence on climate is a topic of current scientific debate. In long-term safety assessments, the biosphere is represented by stylised scenarios, based on our understanding of current and past environments. The future biosphere conditions that are assumed are hypothetical and much of the ongoing work is to ensure that models encompass the range of conditions that could reasonably be expected to occur.

The use of stylised scenarios in long-term safety assessments is also the subject of work by the OECD Nuclear Energy Agency and advice on the formulation of biosphere scenarios has been developed through international co-operation during the IAEA BIOMASS programme [97] in which Nirex participated. Engaging stakeholders in dialogue about these scenarios will be a key part of the future programme.

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[10] In the glossary to the GRA [57], Exposed Group is defined in the following statement "For a given source, any group of members of the public within which the exposure to radiation is reasonably homogeneous; where the exposure is not certain to occur, the term potentially exposed group is used."

The biosphere research programme is guided by the need to conform to regulatory requirements and take due account of international best practice. In the UK, the most relevant regulatory guidance is that issued in 1997 by the Environment Agency, in conjunction with SEPA and the Department of the Environment for Northern Ireland [57].

The standards and data that Nirex uses to support its biosphere assessments take account of emerging national and international guidance, recognising that such guidance may ultimately influence the UK regulatory position and views on good assessment practice. Such guidance has been published by the National Radiological Protection Board –NRPB (now part of the Health Protection Agency) in the UK [98, 99] and overseas by the IAEA [97] and the ICRP [100]. Nirex has a watching brief to ensure that updated advice and guidance is incorporated into the planning of any future research work.

Dialogue with regulators is an important part of Nirex's work and recently the scrutiny of our work by the NWAT team has included review of our approach to the treatment of potentially exposed groups.

The Nirex biosphere research programme has close links with work carried out in overseas radioactive waste management organisations through jointly funded projects and EC supported programmes. Many of the biosphere-related issues are of general interest and several are being addressed in international fora, such as BIOCLIM (Modelling Sequential Biosphere Systems under Climate Change for Radioactive Waste Disposal) [101] and BIOPROTA (Biosphere Data Protocol Development for Assessments) [102]. Such international co-operation is cost effective and makes good use of scarce but internationally available resources. The degree of consensus that is achieved through such joint programmes lends support to the credibility of any conclusions reached. In the UK programme, much of the research is carried out in co-operation with universities, in particular Imperial College, the University of Newcastle and the University of East Anglia.

It is considered that there are no biosphere issues that represent threats to viability of the PGRC. However, it will be important to ensure that the research keeps up with developments in thinking for example about future climate change and to gain support for the modelling approach, which uses stylised scenarios to represent the biosphere. Research will also be required to address outstanding areas of uncertainty concerning the migration of radionuclides in the near-surface and to collate further data.

6.6 Criticality safety research

Section 5.4 summarises the topic of criticality safety with respect to the PGRC and describes Nirex's approach to the assessment of criticality safety. An important part of the Nirex criticality research programme is aimed at demonstrating an understanding of the repository system and the possibility and consequences of a criticality.

The criticality research programme is investigating the effects of possible criticalities arising from a wide range of hypothetical configurations of fissile materials. The consequences of these effects and their impact on subsequent repository performance are then being identified for configurations that could arise. Initial work [82] has concluded that even if a criticality did occur, it would only affect a small volume of the repository and the impact on the overall performance of the repository would not be significant. However, not all types of post-closure criticality event were considered in this initial work. Further work has been commissioned to improve our understanding of criticality in post-closure environments, to enable testing of the robustness of the initial conclusions, involving development of two different types of model to allow independent testing. This research involves criticality experts in universities and in contracting organisations and has been managed by a committee involving other experts in criticality research. The work is ongoing and will be subject to peer review.

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

6.7 Status of the research programme

- Nirex has established an extensive research base, which supports and underpins assessments of the long-term safety of the PGRC in the UK.

- Nirex commissions its research from experts in a wide range of fields, in universities and contracting organisations.

- The Nirex research base is complemented by further research by equivalent waste management organisations overseas, by co-operative international projects and by guidance material developed by regulators and international bodies such as the IAEA and the NEA. There is a general view that sufficient fundamental research has been done to show that geological disposal of radioactive waste is viable. The focus, for example of EC part-funded research into radioactive waste management, is now shifting towards demonstration that concepts can be implemented.

- There is sufficient confidence in the PGRC to use it as the basis for assessing waste packaging proposals under the LoC process. This process is embedded in UK regulatory arrangements for the packaging of ILW and is subject to scrutiny by regulators. Assessment of packaging proposals develops our understanding of specific wastes and their long term behaviour and this helps to guide the research programme. Recent submissions have highlighted carbon-14 containing wastes and NAPLs as requiring further research. Given sufficient resources, such issues typically take 1 to 5 years to address.

- Enough is known about the PGRC to begin a programme of site selection in the UK. Once a programme of site-selection begins, site-specific research will be required. The extent of the site-specific research programme will depend on the nature of the site, but is likely to require a programme of investigations which would continue through the early phases of construction.

- Ongoing dialogue with stakeholders, including the public and regulators, will be required to understand what further evidence is necessary to demonstrate the viability of the concept. This iterative process will identify requirements for further research.

7 HIGH-LEVEL WASTE / SPENT FUEL (HLW/SF) REPOSITORY CONCEPT

Historically, Nirex's remit has been focused on the long-term management of solid intermediate-level waste (ILW) and that low-level waste (LLW) that is unsuitable for disposal in near-surface facilities. The majority of Nirex's work has therefore been devoted to the long-term management of these wastes. Geological disposal is the preferred option for a range of long-lived radioactive wastes in most developed countries. Over the last three decades, the fundamental safety of this option has been illustrated in many national feasibility studies for geological disposal of a wide range of intermediate and high-level wastes (including spent nuclear fuel).

Nirex's remit is now to look at very long-term management options for all types of radioactive materials and not to simply focus on ILW as it did in the past. Nirex is therefore developing a comprehensive and coherent strategy for the management of all UK radioactive wastes and materials. Lessons learned from past experience have demonstrated the importance of a comprehensive and coherent approach which is flexible to the needs of stakeholders and enables them to be engaged in the debate.

With encouragement from Government, we are working with sister organisations (SKB (Sweden), Nagra (Switzerland) and NUMO (Japan)) to examine the extent to which the vast amount of work undertaken internationally on the long-term management of high-level waste (HLW) and spent nuclear fuel (SF) can be applied in the UK. Through a series of workshops we have developed a strategy, a reference concept for a geological repository for UK HLW/SF and a programme for developing the concept through an iterative process of design, assessment and research.

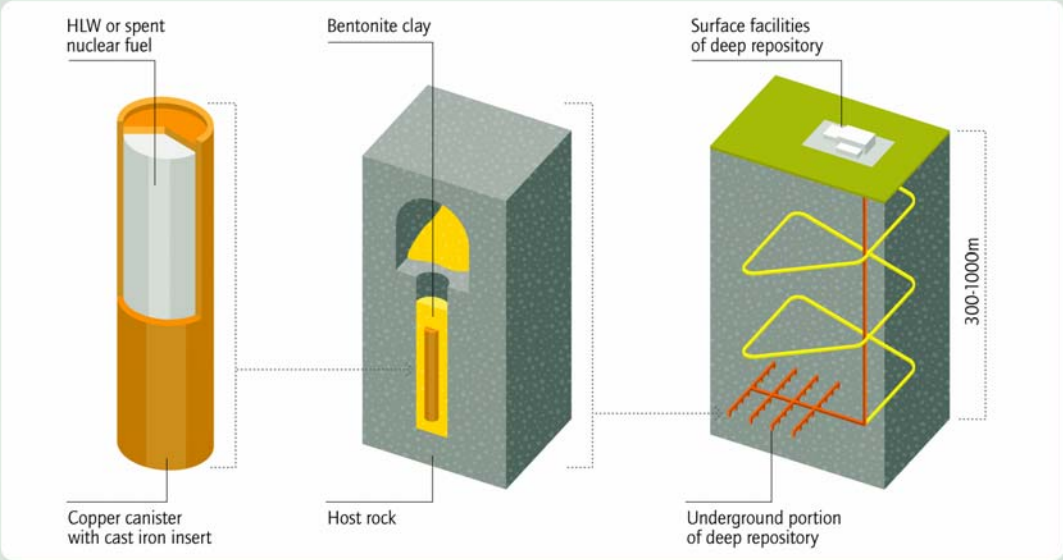
Internationally, a range of geological disposal concepts have been discussed and investigated for HLW and SF over a number of years. The concepts vary according to the nature and quantity of the waste and the different geological and social settings. Nirex has reviewed this range of concepts and has selected a concept to demonstrate the viability of HLW and SF disposal in the UK. Concepts were screened to select a concept that was at an advanced stage of development, based on well-established properties of the engineered and natural containment barrier systems, allowed for ease of retrieval and was supported by extensive R&D.

The UK Reference HLW/SF Repository Concept selected by Nirex for this 'viability demonstration' is based on the KBS-3 concept developed by SKB for spent fuel in Sweden. This concept has been extensively studied by the Swedish and Finnish national programmes for more than 20 years [103]. This selection also reflects the maturity of the Swedish and Finnish programmes, their involvement of stakeholders and their level of regulatory scrutiny and, in the case of Sweden, international peer review.

The KBS-3 repository concept is based on encapsulating spent fuel elements in a copper canister, that costs some £100k, with a cast iron insert. (Under suitable geochemical conditions, the corrosion of copper is extremely slow, and the copper canister is expected to maintain its integrity for an extremely long time). Each copper canister is placed in a vertical hole approximately 8 m deep, drilled along a series of access tunnels excavated at a depth of approximately 500m in water-saturated granitic rock. Within its deposition hole, the canister is surrounded by a bentonite clay that swells when contacted by water. The tunnels and rock caverns would be backfilled with a mixture of bentonite and crushed rock.

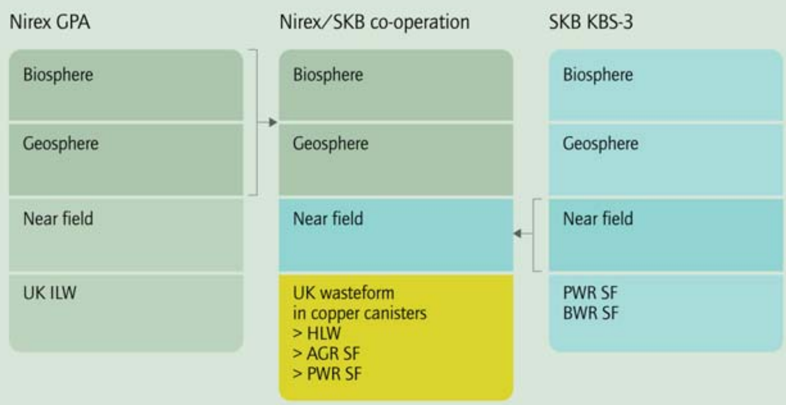
The UK Reference HLW/SF Geological Repository Concept (Figure 33) was developed [104] by adapting the KBS-3 concept in terms of canister length, diameter and structure of the insert to handle HLW and spent fuel from the UK's Advanced Gas Cooled Reactors (AGRs) and Pressurised Water Reactor (PWR).

Figure 33
Geological repository concept for HLW and spent fuel



A preliminary assessment of long-term safety of the UK Reference HLW/SF Repository Concept in a UK setting was performed recently with the help of SKB. In assessing the long-term safety, advantage has been taken of the large amount of assessment work on the safety of the KBS-3 concept already undertaken by SKB, as well as relevant Nirex work on the UK geosphere and biosphere conditions. To do this, SKB and Nirex have developed a model for the assessment of the UK's Reference HLW/SF Repository Concept (Figure 34). The model is underpinned by both Nirex and SKB R&D programmes.

Figure 34
Development of UK reference repository concept for HLW/SF



By carrying out a quantitative assessment of a concept based on SKB's KBS-3 design for spent fuel, it was confirmed that the long-term safety shown by SKB would also be assured for UK inventories and geological conditions that are identified as suitable for a geological repository. In addition to the groundwater flow characteristics, identified as the parameters Q,T and F, it is understood that the required geochemical conditions to ensure the long-term integrity of the copper canister are also available in a high proportion of the UK deep geology.

A probabilistic calculation of risk has been carried out using the model developed with SKB[11] [105]. The peak value of the mean annual individual radiological risk was found to be 10^{-11}, which is substantially below the radiological risk that defines the target applicable to ILW and LLW of 10^{-6} per year [57]. This means a risk to a person of 1 in 100,000 million per year of developing either a fatal cancer or a serious hereditary defect. The very low calculated risk is due to the combination of a long groundwater travel time for the UK geological characteristics used in the GPA and a robust engineered physical containment barrier (the copper canister). As part of the development of a safety assessment for the Reference HLW/SF Repository Concept, Nirex is performing further calculations to address the sensitivity of the system to key processes or components.

SKB's studies also illustrate the fundamental feasibility of reversal of key emplacement stages. Most countries with higher activity radioactive waste are also proposing a geological repository that incorporates retrievability and a phased approach to implementation and there are a range of methods that have been investigated and adopted to provide this. Nirex is taking a flexible approach to concept development that provides options for retrievability and phasing. The concept will continue to be developed through dialogue with stakeholders, including the public, to address their issues and concerns.

A basic cost study indicates a total project cost of around £5 billion for a repository to take the UK's HLW and spent fuel. This is comparable with estimates for repositories prepared in other countries.

In summary, the evidence for the viability of geological disposal for HLW and spent fuel in the UK comes from international experience, which covers a wide range of waste types in diverse geological environments. It is supported by a preliminary assessment by Nirex and SKB of the UK Reference HLW/SF Repository Concept - a provisional concept of what a UK repository for these wastes could look like.

Apart from this demonstration of fundamental concept viability, a further objective of developing a reference concept for a repository for UK HLW and SF was to provide guidance to waste producers on waste characterisation and packaging. Nirex is now developing packaging standards and specifications (WPS) for HLW and spent fuel. The need for such standards and specifications has been recognised by the Radioactive Waste Policy Group (RWPG). The work on the Reference HLW/SF Repository Concept has been used to inform the RWPG on "Initial Consideration of Waste Acceptance Criteria for the Long-term Management of Certain UK Radioactive Wastes and Potential Wastes" [106].

The HLW/SF repository concept is at an earlier stage of development than the Phased Geological Repository Concept for ILW. Our work on this concept is not currently subject

[11] On the basis of research and development performed by SKB on the evolution of copper canisters it was assumed that one canister each of UK HLW and PWR and AGR spent fuel has a defect that ultimately fails.

to the regulatory scrutiny applied to the ILW concept. However, the HLW/SF concept has been developed by combining the Swedish KBS-3 concept with UK waste data and the UK geosphere and biosphere characteristics used for the PGRC. The KBS-3 concept is underpinned by around twenty years of research, development and demonstration work. Its development has also been subject to continuous scrutiny by the Swedish regulator. Our work on the UK geosphere and biosphere is subject to regulatory scrutiny under our existing agreements for the ILW concept. In short, the HLW/SF repository concept is a well developed option underpinned by an extensive body of research and development all elements of which have been subject to scrutiny. Nirex is also discussing with UK regulators how the process of regulatory scrutiny for ILW can be extended to cover the HLW/SF concept.

Key challenges relating to the HLW/SF repository concept are retrievability and optimising the configuration of the underground openings.

The extent to which a HLW or spent fuel canister can be easily retrieved from an underground opening lined with swelling bentonite clay is an issue raised by some stakeholders. Further work is needed by Nirex to establish views on the degree of retrievability required for these types of waste. Retrievability is increasingly being addressed and incorporated by most countries in concept development. Nirex is seeking opportunities to participate in joint projects to examine technical approaches to HLW/SF retrievability.

Different countries have developed underground configurations based upon drivers such as the properties of the host rock and of the waste canisters. Nirex is working with other waste management organisations on research and demonstration projects that examine the options for configuring the underground openings such as vertical or horizontal emplacement openings. This work will be used together with site specific data to optimise the underground openings and layout for a HLW/SF repository concept for the UK.

Another area of work is the development of a combined repository concept whereby HLW/SF and ILW are located at the same site.

The technical implications of co-locating a HLW/SF facility at the same site as the Phased Geological Repository Concept for ILW is being investigated by Nirex as part of our ongoing work programme. This has potential cost savings compared to providing separate facilities and is also in effect the strategy that is being developed for the long-term management of high-activity and long-lived wastes in other countries such as France, Switzerland and Belgium.

To support discussion of the siting process, the generic work carried out to date is being extended to identify any specific requirements from a site due to the nature of the UK’s HLW and spent fuel or the concept for their long-term management.

Other materials

Nirex is using the PGRC and Reference HLW/SF Repository Concept, and associated developments of waste packaging standards and specifications, as a basis for investigating the waste management options and assessing the disposability of the other UK radioactive wastes and materials (if declared as wastes). This includes waste and materials such as separated stocks of plutonium and uranium, spent fuel from submarines and research reactors (as described in Nirex Report N/085 [1]).

8 PROJECT VIABILITY / IMPLEMENTATION

So far this report has set out why we are confident in the viability of the Nirex Phased Geological Repository Concept for the UK's ILW. It has also described why we are confident that a repository concept would be viable for the UK's HLW and Spent Fuel.

However viable concepts do not in themselves provide a long-term waste management solution. To move from a concept to a waste management solution it is necessary to address what would be required to allow the implementation of concepts.

Following the failure in 1997 to obtain planning permission for underground investigation of a potential repository site at Longlands Farm, near Sellafield, Nirex set out to learn lessons from that experience through extensive dialogue, both internally and externally. The aim was to gain an understanding of why previous attempts to solve this problem have failed. Those lessons could then be applied in the development of a new approach which could then lead to the successful implementation of a long-term radioactive waste management solution in the UK. Analysis revealed that Nirex had made many mistakes and that lessons could be grouped under the headings of structure, process and behaviour.

Structure

In terms of structure, one of the main lessons learned was the need for the organisation responsible for long-term waste management to be independent of the nuclear industry and for clear separation of long-term and short-term issues.

- Under nuclear industry ownership Nirex was seen by many as a front for the industry.

- The independence of its overall objectives, including decisions on packaging standards and specifications, was questioned because of its ownership.

- The need for separate organisations to address short-term and long-term issues is necessary to avoid the long-term issues being neglected due to short-term pressures. Separate organisations are also required so that tensions between the short-term and long-term issues are resolved in an open and accountable manner.

Process

We believe that Nirex itself was secretive and adversarial and was part of a secretive environment.

A key lesson was that the process for selection and implementation of a long-term waste management solution must be open, transparent and accountable at all stages. Specific issues included:

- The adversarial nature of the planning process in particular where a planning application is rejected and referred to a public inquiry.

- Recognition of the need to address local issues such as community benefits and veto rights for communities to allow a national policy to be implemented at a given site.

- The need to develop and gain broad acceptance for each step in the implementation process ahead of its application e.g. the approach and criteria to select suitable sites.

- Legitimacy of process. It must be seen to be fair and equitable.

Behaviour

We believe that Nirex's behaviour was unacceptable. It was marked by arrogance and a lack of weight attached to local concerns.

Lessons learned relating to behaviour include the need to:

- Work at stakeholders' speed, be responsive and allow for involvement of a wide range of stakeholder groups, i.e. allow access to and influence on our work programme.

- Have a wide-ranging transparency policy – Nirex's accountability in this regard is now overseen by an independent transparency review panel.

- Reflect stakeholder views in our work programme, e.g. retrievability.

Trying to apply these lessons has fundamentally changed our approach. The following sections describe how, by applying the lessons to the development and implementation of a viable concept, we think that a solution for the long-term management of the UK's radioactive waste can be provided.

8.1 Selection of a long-term waste management option

Past experience and legal advice have made it clear that all credible options need to be properly considered. The process for selecting the most suitable option(s) needs to be open, transparent and accountable. It needs to involve consultation with a wide range of stakeholders to encourage ownership and ensure a robust choice of option(s). The selected option(s) will then need to be reviewed and justified against other options at any stage in the future implementation.

To do this, the Government has established its Managing Radioactive Waste Safely (MRWS) process. As part of this process the Committee on Radioactive Waste Management (CoRWM) has been set up to recommend to Government a long-term management solution for the UK's radioactive waste.

The MRWS process and the work of CoRWM is based around public and stakeholder engagement. As such it addresses the issues of openness, transparency and involvement in the process for selection of a waste management option. The MRWS process effectively mirrors the requirements of Strategic Environmental Assessment (SEA) in aiming to provide a robust and auditable record of the basis for selection of the preferred waste management option.

To date CoRWM has short-listed four options, two of which are geological disposal and phased geological disposal (which Nirex proposes – the PGRC). The other two options on the current short-list are interim storage and near-surface disposal. However, neither of these are solutions in their own right that could be used for the long-term management of all the UK's higher activity radioactive waste. Rather they are options to be used in conjunction with deep geological disposal.

Interim storage by definition will require further actions to be taken after the storage period has expired. Given that some of the waste will remain hazardous for hundreds of thousands of years this on its own will not provide the long-term solution that is required. It could however form part of an overall strategy.

Near-surface disposal would only be appropriate for short-lived radioactive wastes as there is the very real potential for long-term environmental change at the surface disrupting the safety of a near-surface disposal facility (e.g. erosion due to glacial events). This option is therefore only suitable for a small proportion of the higher activity wastes being considered under MRWS.

The current timetable is for CoRWM to recommend an option to Government in July 2006. Following a Government decision to implement an option, work would need to proceed on setting the criteria on which selection of a suitable site would be based. This in turn would lead to the actual selection of a site (or sites) and investigations to evaluate suitability for a repository.

8.2 Selection of a suitable site for a geological repository

This section addresses why Nirex and others believe that a suitable site could be found in the UK for implementation of a repository. The rationale for this can be summarised in the following terms: there are areas of the UK where the geological conditions are potentially suitable for a repository and the technology exists with which to undertake the necessary safety and environmental assessments

The secrecy of the site selection process that identified Sellafield as a preferred site for an ILW/LLW repository was a significant reason for the RCF Local Planning Inquiry Inspector's recommendation, in 1997, that Nirex's appeal against the refusal of planning permission should be rejected.

A lack of public acceptance was also an important factor in the Government's decision to halt investigations related to geological disposal of HLW in 1981, the withdrawal of the proposal to use the Billingham anhydrite mine for disposal of long-lived ILW in 1985, and the cessation of investigations at four sites for near-surface disposal of short-lived ILW and LLW in 1987.

Experience overseas is that progress is being made where public involvement is actively encouraged and made a key feature of an open and transparent process. In Finland and Sweden site investigations are proceeding and repository concepts are being implemented. In Finland it has been suggested that for a site to be viewed as a legitimate choice there should be general support from at least 70% of the local population, around 40% support from the national population and 70% political support. The 40% can be characterised as a strong national feeling that the issue needs to be dealt with and that the option chosen is probably the way to do it.

In the UK, the siting criteria and the decision-making process will need to be established in an open and transparent manner through consultation. This should be done before the actual site selection process is started and should address issues such as whether it would allow local communities to volunteer or be granted a veto in respect of a site in their locality. This would need to be conducted in line with the European Commission Directive on Strategic Environmental Assessment [107]. An Environmental Impact Assessment would also need to be submitted and scrutinised through planning legislation.

By drawing upon the lessons from overseas and actively engaging in dialogue at both a national and local level, Nirex believes that it would be possible to demonstrate legitimacy of process. This could provide the necessary support for a new site selection process such that a phased geological repository could be implemented.

8.3 Site investigation and characterisation

The purpose of geological investigation and characterisation is to evaluate a site's suitability to host a radioactive waste repository that would conform with regulatory safety and environmental requirements. However, geological investigations integrate a variety of information from a diverse range of scientific and technical disciplines, including hydrogeology, chemistry, physics, rock mechanics etc.

To evaluate the potential suitability of a site, it is first necessary to understand what information is required to allow judgements to be made for hosting a repository. We believe that we have developed a viable concept through over twenty years of research that provides a good understanding of those requirements.

In general terms there are three purposes for the information that would need to be collected:

- to provide an understanding of the specific geological setting and the processes that would be involved in the evolution of the repository;

- to provide data that can be used in assessment models to investigate the long-term safety and environmental performance of the repository; and

- to provide data on rock properties to inform design and construction of the repository.

Nirex and its scientific and engineering colleagues have gained extensive experience of site characterisation from its programmes of investigations at Dounreay (1989-1991) and at Sellafield (1989-1997) and its involvement in overseas site investigation programmes before 1997. This experience coupled with a viable concept has enabled Nirex to establish a generic site characterisation programme. The starting point for the development of that programme is a comprehensive specification of all the information that will be needed from site investigations. From this it is possible to identify the properties that must be measured to derive that information and the techniques to undertake the measurements. This work is being currently refined in co-operation with RWMC of Japan and other European radioactive waste management agencies.

Site characterisation generally involves a programme of surface-based activities followed by underground measurements to test the suitability of a site. At Sellafield the surface based investigations included measurements taken from 29 deep boreholes drilled by Nirex (these have since been closed). To drill the boreholes, large oilfield-type drilling platforms were utilised. Feedback from the local community since then has led us to explore the use of different technologies in order to reduce the environmental impact of such operations.

Sweden and Finland have, in the past decade, developed their site investigation programmes based upon technology that uses mobile drilling rigs mounted on lorries. These mobile rigs are much smaller than those used previously by Nirex and have a much reduced impact on the local environment.   Nirex is currently evaluating the feasibility of using similar rigs in the UK or whether environmental impacts could be reduced in other ways.

The proposal at Sellafield was that underground investigations would be undertaken within a rock characterisation facility (RCF). Planning permission for the RCF was sought on the basis that it would be an underground experimental laboratory that for planning purposes was to be developed separately from the eventual repository. This view was never generally accepted and was considered by many to be simply the first stage in the development of a repository for radioactive waste.

Nirex's view now is that any future underground investigations should clearly be undertaken as part of repository construction. Any underground experiments or scientific monitoring activities that might be necessary to test the site suitability in detail would be co-ordinated with the repository construction activities.

In summary, Nirex believes that a potential repository site can be characterised to evaluate its suitability. This is a view shared by our 'sister' waste management organisations overseas and by the geoscience community. An open meeting arranged by the Geological Society of London and the British Geological Survey concluded:

> *"the geoscience community believes that it has the methodology and interpretive capability to characterise successfully a potential repository site"*

The full statement is available on the Geological Society's website [108].

8.4 Suitability of Sellafield as a potential repository site

It has been argued that the rejection of the RCF planning application indicates that Sellafield was unsuitable as a repository site. However, we believe that this was never a conclusion from the RCF Local Planning Inquiry Inspector's report.

Based on the reasons for rejection that were given in the Inspector's report Nirex now recognises that:

- The process that led to the selection of Sellafield for investigation as a potential repository site was flawed. The secrecy was a key issue. The lessons and requirements for any future site selection exercise are discussed above.

- Much more attention needs to be given to conventional planning and environmental issues such as visual intrusion and proximity of access ways to specially designated areas, such as the National Park in the case of Sellafield. Since then Nirex has developed a new Environmental Policy based upon stakeholder feedback and is now incorporating non-radiological environmental assessment into its PGRC.

- Nirex acknowledges that the planning application for an RCF was premature. The scientific information presented to support the application was based on data obtained from the first few years of surface investigations only. Much more data from the surface-based investigations was obtained up to and including 1996. This information was not presented to the Inquiry. It formed the basis for an overall assessment that was carried out in 1997 ("Nirex 97") and completed after the Inquiry result was known.

That post-closure safety assessment Nirex 97, [63] has been published and the evaluation of Sellafield 'Baseline Conditions' has been completed [109]. Both of these reports have been peer reviewed and the results of those reviews are also available [64, 110]. Based on the results of this work, we believe that Sellafield is a potentially suitable site for a repository. This view is shared by the British Geological Survey (BGS) and many other specialist consultants.

Based on data obtained from Sellafield investigations there would be scope to examine alternative repository locations within the rocks underlying the Sellafield area.

8.5 Repository development

Section 4.4 on the iterative development of the Phased Geological Repository Concept set out how the concept was based upon proven technology. To summarise:

Transport

Transport is one of the key issues to be addressed to ensure the acceptability of implementing a concept. Transport issues are particularly significant because they potentially affect all the communities on transport routes. Consequently appropriate consideration needs to be given to the transport of the radioactive waste and also to the movement of large construction plant and materials.

The PGRC provides for the transport of radioactive waste packages to a repository in its safety assessments, based upon internationally recognised IAEA standards. There is extensive worldwide experience of the safe transport of radioactive materials to such standards.

The movement of large construction plant and materials will be a key consideration in the non-nuclear environmental assessment of the concept. Any planning application for implementation of the facility would need to be supported by a full environmental impact assessment (EIA). Planning permission would be heavily dependent upon an acceptable EIA.

Sea transport – because of stakeholder and public concerns, we are examining the possibility of sea transport to minimise road/rail use.

Repository construction

The construction of the repository would be based entirely upon proven technology. Facilities at the surface for receipt and handling of transport packages would be similar to those used on existing nuclear sites and at conventional freight container ports around the world.

The excavations used for transferring and storing the waste deep underground would use conventional mining and construction technology.

Repository operation

The emplacement of radioactive waste packages into underground storage vaults is a relatively straightforward handling operation. Operations would be similar to those carried out routinely in existing surface waste stores.

Following the emplacement of all wastes in the repository over a period of about 50 years the option would be to:

- retrieve the waste;

- continue with monitored retrievable storage; or
- close and seal the repository.

Retrieval of the waste would involve a reversal of the emplacement operation to return waste packages to licensed storage facilities at the surface. This would be a similar operation to that envisaged for export of packages from existing stores.

Continuing with monitored retrievable storage would be relatively straightforward for a period of up to 100 years. Beyond then it would be necessary to gain access to the underground vaults for inspection and maintenance. This could be achieved through a rolling programme whereby vaults were emptied to enable refurbishment on a 50 – 100 year cycle. The inspection and maintenance activities would be similar to those that would be needed for continuing operation of surface stores.

Repository sealing and closure

Backfilling the ILW vaults with cement-based material would ensure the development of alkaline conditions as the repository resaturated. Such chemical conditioning would limit the solubility of the most radioactive radionuclides in the wastes and provide a medium to retard, through sorption mechanisms, the migration of any radionuclides that might be released from waste packages. Long-lasting repository seals would be constructed in boreholes and in the access ways to provide hydraulic isolation of the repository over the long term and provide further containment.

On-going work in the UK and abroad is examining materials and the engineering practices required to construct plugs, dams and other structures currently used in deep mine construction. Results from this work will be fed into the PGRC and into models used to assess the performance of repository seals.

Large-scale experiments in underground research laboratories have demonstrated that seals can be placed in tunnels or shafts and that they can provide the necessary barrier to the movement of groundwater. Typically the sealing systems that have been devised and tested employ a combination of concrete and swelling clay (usually bentonite) plugs, for example the Shaft Sealing Experiment conducted in the Stripa Mine laboratory in Sweden [111]. The concretes and clays selected are well-known materials which have been used in similar applications in other industries, and bentonite clay has the added advantage that it is a naturally-occurring material and as such shows stability over geological timescales.

Since the materials proposed for use in repository sealing systems have been studied extensively, the conditions under which their desirable properties might deteriorate are well understood. Therefore sealing materials and designs can be tailored to match the characteristics of a repository at a given site, within the overall repository design.

Evidence for the long-term structural integrity of concrete materials includes examinations of Roman concrete and comparisons with concrete structures made over the last century or so from Portland Cement [112]. More indirect evidence of greater longevity of the chemical make up of concretes comes from the study of cement-like rocks, which shows that this material can remain intact for many tens of thousands of years [113]. The longevity of the sealing properties of bentonite clay has been studied extensively for more than twenty years, yielding a detailed understanding of the mechanisms and rates of possibly deleterious chemical reactions. Even where an unfavourable groundwater composition is simulated, the deleterious reactions are limited in their extent and the results of experiments and modelling indicate that the sealing performance would not be impaired over the long timescales of interest [114]. The one known condition where it may be necessary to avoid the use of bentonite is in groundwaters that are very highly saline [115].

Post-closure monitoring

There are no regulatory requirements to monitor the repository after institutional control over the site has ended, although some monitoring is recognised as being required in a period of institutional control immediately following repository closure [57]. In fact there is a regulatory requirement that the long-term safety of the repository is not dependent upon monitoring or intervention.

However, feedback from dialogue on our proposed work programme suggests that some form of monitoring of repository post-closure performance would be highly desirable. Acting on that feedback we are examining options and techniques for post-closure monitoring [116].

Work on non-intrusive monitoring is now being taken forward in co-operation with a number of our equivalent organisations from overseas under the EC part-funded ESDRED (Engineering Studies and Demonstration of Repository Design) Project.

Programme and cost

Like any major project there are many interrelated activities which must be undertaken in an appropriate sequence in order to ensure successful implementation. The key to success is rigorous project management whereby the many different strands of work are integrated into a coherent programme. For implementation of the PGRC this requires a full understanding of:

- the nature and quantity of the radioactive waste;
- the scientific and technical basis of the concept;
- how the concept can be adapted to address stakeholders' views;
- the safety and environmental regulatory requirements;
- the planning framework including environmental assessments;
- the characteristics required from a site to achieve long-term safety;
- what is needed for public acceptance at a national and local level; and
- the resources needed.

Nirex has some twenty years' experience in the development of plans and programmes for approaching such a project in the UK. Based on previous attempts to implement such a project, both in the UK and overseas, lessons have been learned that must now be incorporated into future plans for implementation.

Nirex has developed a programme and cost estimate for this project which have been used by the producers of radioactive waste to make provisions for its long-term management. That programme has evolved in line with our increased understanding of all of the requirements for implementation of such a project.

The programme is based on repository availability in 2040. We are aware that the Nuclear Decommissioning Authority (NDA) has stated a preference for earlier (2025) availability of a repository.

Nirex is in favour of making progress with long-term radioactive waste management and implementing a deep geological repository in a timely manner. However, although we support the intention, successful implementation will only be possible with public acceptance.

One of the lessons learned from previous attempts to site a long-term waste management facility is that it is important to work at stakeholders' speed. The programme for implementing a facility needs to be flexible and able to incorporate ongoing interactions between the project and the local community. This may mean being able to accommodate longer discussion periods and more research to address stakeholders' concerns.

Figures 35, 36 and 37 illustrate the key activities, durations and costs for implementation of a repository for:

- ILW/LLW
- HLW/Spent Fuel
- Co-location of ILW/LLW and HLW/spent fuel disposal in the same facility

Figure 35
ILW/LLW repository programme and costs

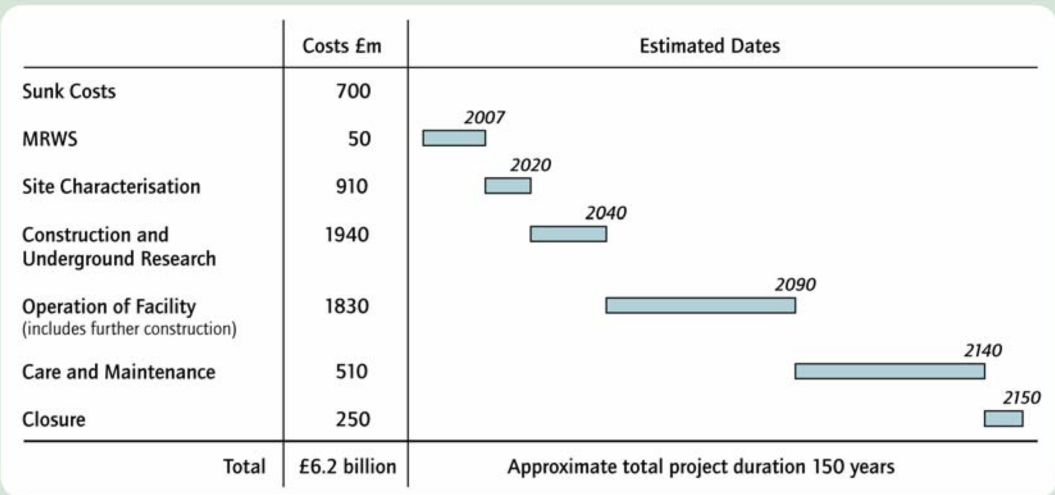


Figure 36
HLW/Spent fuel programme and cost estimate

	Costs £m	Estimated Dates
Site Characterisation	920	2007 2020
Construction and Underground Research	1600	2040
Operation of Facility (includes further construction)	2100	2090
Closure	315	2100
Total	£4.9 billion	Approximate total project duration 100 years

Includes HLW/SF canisters (£670m)

Figure 37
Co-location programme and cost estimate

	Costs £m	Estimated Dates
Sunk Costs	700	
MRWS	50	2007
Site Characterisation	1050	2020
Construction and Underground Research	2470	2040
Operation of Facility (includes further construction)	3040	2090
Care and Maintenance	530	2140
Closure	330	2150
Total	£8.2 billion	Approximate total project duration 150 years

Includes HLW/SF canisters (£670m)

It can be seen from Figure 37 that there is a significant cost benefit to be gained from co-location of HLW/spent fuel disposal in the same facility as ILW/LLW. Co-location of different types of high-activity and long-lived radioactive wastes in a modular repository design is a strategy for implementation that is being developed by radioactive waste management organisations in other countries such as Andra (France), Nagra (Switzerland), and ONDRAF/ NIRAS (Belgium).

Management arrangements (dependent on outcome of CoRWM)

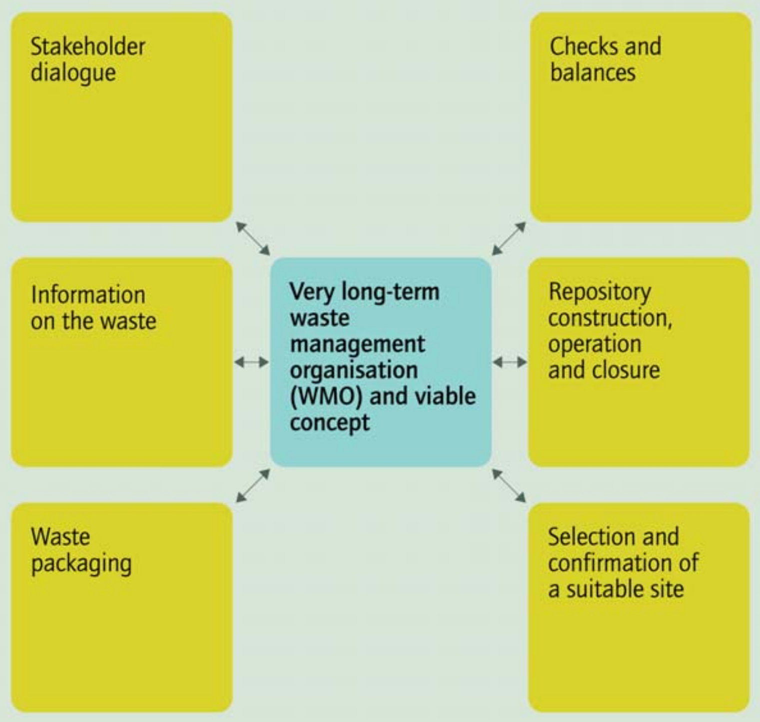
To put together a consistent, coherent implementation strategy, we believe that it is essential to have a single organisation responsible for planning, directing and co-ordinating all of the necessary activities that will be involved in implementing the very long-term management solution. The credibility of that organisation is of paramount importance to ensure the viability of the project. The Government has already taken such a view with decommissioning and clean-up, with the formulation of the NDA (April 2005). We believe that a similar but separate organisation needs to look after the very long-term.

There are important lessons that have been learned from previous experience in the UK and overseas relating to the requirements for such a long-term waste management organisation (WMO). We believe that the organisation:

- needs to be based on the Nirex role as the concept holder.
- must be separate from the nuclear industry creating the waste:
  - to provide independent standards and specifications to waste producers;
  - to act on behalf of society and not the nuclear industry; and
  - to divorce the issues of new build from the need to deal with existing waste.
- has to be separate from the NDA to avoid short-term prioritisation and to maintain the independence of packaging standards and specifications.
- needs a secure source of funding for the entire project, e.g. segregated account.

Since April 2005, Nirex has been made separate and independent from the nuclear industry and the NDA and is now wholly owned by Government. Funding is currently provided primarily through a contract with the NDA. This funding arrangement would need to be reviewed following the outcome of MRWS. The aim of the review would be to ensure that a secure source of funding was in place for the entire project.

Figure 38
Requirements for implementation



The WMO needs to engage in dialogue with a wide range of stakeholders allowing access to and influence on its work programme. The concept will require further development as exemplified by the introduction of retrievability, described in Section 4. The work of the WMO needs to continue to be subject to scrutiny by the regulators. That scrutiny will continue to provide independent checks and balances on the development of the concept and other work undertaken by the WMO.

Many organisations hold information on their own wastes. However, in our view, the WMO is the organisation that should continue to be responsible for providing a national radioactive waste inventory. As such, it needs to continue to have a thorough understanding of the nature, quantity and location of all radioactive waste in the UK. This knowledge, coupled with the concept, will enable it to continue to set standards and specifications for the packaging of the UK's radioactive waste. Assessment of specific packaging proposals in turn will improve its knowledge base on the wastes requiring long-term management.

Similarly, knowledge of the waste, its packaging and the concept for its long-term management will enable the WMO to establish what is required from a potential repository site. Evaluation and confirmation of a potential site's suitability would need to continue through repository construction, operation, up to and beyond the point of closure. The implementation of a repository would involve a number of organisations such as drilling companies, major construction companies etc. However, as noted above the activities of these various companies are inter-related and must be properly managed. This whole process will need to be overseen by a single organisation with a complete understanding of the concept and its requirements.

Nirex is currently developing its views on an implementation strategy for a PGRC. This is required as an input to the Government's Managing Radioactive Waste Safely review to show that the PGRC is a viable concept that could be implemented in the UK. If a phased geological repository is selected by Government as the long-term management option for the UK's radioactive waste then the implementation strategy will allow it to be progressed promptly.

Security arrangements

Nirex considers that integrated and well planned security measures are essential to counter a number of perceived threats which range from the malicious, through theft to irresponsible interference of radioactive waste at a planned radioactive waste repository. Security considerations are built into the design process and the operational planning, although specific details are not revealed since this would defeat their object. At each stage of security planning the Office for Civil Nuclear Security (OCNS) is consulted, for their approval and guidance, in their role as nuclear industry security regulator.

We believe that the PGRC provides robust protection against sabotage terrorism and mis-appropriation as well as being more secure in the event of societal breakdown. Nirex has a Security Plan for a Generic PGRC which has received interim approval from OCNS. However, any change to the PGRC concept will result in the requirement to revise the existing Security Plan or, if necessary, the writing of a new one.

9 SUMMARY AND CONCLUSIONS

In this report we have set out the reasons why we believe that the Phased Geological Repository Concept for ILW and certain LLW, coupled with the Reference HLW/ SF Repository Concept, provide viable technical options for the long-term management of the UK's higher activity radioactive waste. This section presents a summary of why we believe these options can and should be implemented in the UK without further delay.

9.1 Viability of the Concept

The evidence supporting concept viability is set out below against each of the following statements:

The long-term performance of the concept can be evaluated using well established assessment tools.

- The Nirex methodology for performance assessment has been developed in line with international best practice as established by the IAEA and the NEA;

- The Nirex methodology has been subject to international peer review from an OECD-NEA expert group [61];

- Similar assessment tools have been used by other countries to demonstrate the viability of their own geological repository concepts, many of which are at an advanced stage of development with plans for implementation.

The results of those assessments show that all relevant UK regulatory criteria can be met.

- Safety and environmental assessments have been carried out to show that regulatory principles and requirements can be met [19]. Those assessments cover the transport of waste to a repository, operations at a repository site and the long-term performance after the facility has been closed and sealed.

- Research is undertaken with one of its aims being to confirm values of key parameters that can affect the assessment results, for example [117, 118, 119].

- Where there is uncertainty in parameter values, internationally accepted strategies for handling such uncertainties have been adopted [120].

There is a high degree of confidence in the long-term performance of the concept.

- Safety of the concept is provided by multiple barriers avoiding undue reliance on any single safety function of one of the barriers.

- Although no credit is taken in performance assessment risk calculations for package integrity after repository closure, calculations [17, 18] show that more than 90% of the initial radioactivity would decay inside the container in the thousand years following repository closure. Containment and retardation in the engineered system ensures that no more than 1% of the initial radioactivity would be present in the rock around the repository, as a result of releases from the repository, at any time [19]. We calculate [19] that the geological barrier then prevents any more than 0.005% of the initial radioactivity from ever reaching the surface. This would meet the UK regulatory requirements.

- The predictable nature of the geological barrier provides stability for the very long timescales over which the waste remains hazardous. The earth sciences are the one area of science where such timescales are routinely considered. This emanates from an understanding of many common geological processes based on the ability to date geological materials and events precisely [71].

- Natural analogues have been identified and observed for important processes that contribute to repository performance. For example, at the Maqarin site in Jordan [113] a naturally occurring cement has undergone extensive interaction with groundwaters for many tens of thousands of years. Other evidence exists from analogues for the sorption and retardation of radioisotopes onto mineral phases, as observed for example at the 2 billion year old natural fission reactor at Oklo (Republic of Gabon) [121].

9.2 Remaining challenges to concept viability

The above section summarises the arguments that support our view that the Phased Geological Repository Concept for ILW and certain LLW, coupled with the HLW/spent fuel concept provide viable technical options for the long-term management of the UK's higher activity radioactive waste. This section presents a summary of the remaining challenges that need to be resolved to confirm viability and how these are being addressed.

Whilst the issues are significant, they are not considered to present a fundamental threat to concept viability. Such significant issues are given priority in our work programme and, with appropriate funds and resources, could be addressed within the next five years. Beyond then there will still be work required to provide detailed analysis of the concept and to evaluate the suitability of any potential site, including testing the compatibility of site conditions with the engineered system.

Key challenges to the PGRC

Carbon-14

C-14 has been identified as a key issue in the PGRC. Calculations have been carried out to scope the potential impact of C-14 for two alternative scenarios. In the first of these it is assumed that C-14 all dissolves in groundwater and is released to the biosphere in solution; in this case the calculated risk is well below the regulatory target. The second scenario assumes that carbon-14 is released as gas and all methane generated is released directly to the biosphere as gas, taking no account of any delay in the geosphere. In this case, the calculated risk is significantly over the regulatory target. In practice, some of the gas could dissolve in groundwater and the migration of gas in the geosphere would depend on the site geology. In many geological settings, some form of gas retardation may be expected.

Nirex has an ongoing programme of research on C-14, which is improving our understanding of these issues. Further work is still required, which includes: work to assess the extent to which gas would dissolve in groundwater; work to assess the extent to which different geological environments have the potential to retard gas migration; and work to reduce uncertainties in the rates and quantities of gaseous C-14 generated.

If, through further work, the calculated rates and quantities of gaseous C-14 generated were not to be significantly reduced, it could be necessary to establish siting criteria that would ensure that significant gaseous release to the biosphere would be unlikely. The implications of these criteria would need to be assessed and included within the requirements for the generic geology in the PGRC.

Although further work is planned which may include the identification of specific siting requirements, on balance Nirex believes that C-14 is not a threat to the viability of the phased geological repository concept.

Non Aqueous Phase Liquids (NAPLs) – such as oils and greases

NAPLs are challenging because they can have a greater capacity for uptake of some radionuclides and may migrate more rapidly through the geosphere than groundwater.

NAPLs would only leave a repository vault if there was sufficient pooled in the vault to overcome the forces that prevent such materials entering narrow fractures in the host rock. Therefore the repository safety case can accommodate NAPLs in each vault at least up to the amount required to form a large enough reservoir. This is estimated to be in the order of 10 tonnes [122]. Furthermore, NAPLs are known to break down under radiolysis to give water-soluble or immobile products over timescales as short as 100 years.

Given that the amounts of NAPLs such as oil and grease in wastes are controlled by the LoC process, this source does not represent a significant uncertainty. However, the possibility exists that further NAPLs could be created in the repository as breakdown products of the radiolysis of organic polymers in wastes. Work is underway to define the realistic potential yield of NAPLs from this source and the nature and rates of production of such NAPLs.

Key challenges to the High Level Waste and Spent Fuel (HLW/SF) concept

The HLW/SF concept is at an earlier stage of development than the Phased Geological Repository Concept for ILW. Our work on this concept is not currently subject to the regulatory scrutiny applied to the ILW concept. However, the HLW/SF concept has been developed by combining the Swedish KBS-3 concept with UK HLW/SF data and the UK geosphere and biosphere characteristics as used for the PGRC. The KBS-3 concept is underpinned by around twenty years of research, development and demonstration work. Its development has also been subject to continuous scrutiny by the Swedish regulator. Our work on the UK geosphere and biosphere is subject to regulatory scrutiny under our existing agreements for the ILW concept. In short, the HLW/SF concept is a well developed option underpinned by an extensive body of research and development all elements of which have been subject to scrutiny.

Key challenges relating to the HLW/SF concept are retrievability and optimising the configuration of the underground openings. Another area of work is the development of a combined repository concept whereby HLW/SF and ILW are located at the same site.

Retrievability

The extent to which a HLW or spent fuel canister can be easily retrieved from an underground opening lined with swelling bentonite clay is an issue raised by some stakeholders. Further work is needed by Nirex to establish views on the degree of retrievability required for these types of waste. Retrievability is increasingly being addressed and incorporated by most countries in concept development. Nirex is seeking opportunities to participate in co-operative projects to examine technical approaches to retrievability.

Optimisation

Different countries have developed underground configurations based upon drivers such as the properties of the host rock and of the waste canisters. Nirex is working with other waste management organisations on research and demonstration projects that examine options for configuring underground openings such as vertical or horizontal emplacement openings. This work will be used together with site specific data to optimise the canister designs, underground openings and layout for a HLW/SF repository concept for the UK.

Co-location

The technical implications of co-locating a HLW/SF facility at the same site as the Phased Geological Repository Concept for ILW is being investigated by Nirex as part of our ongoing work programme. This has potential cost savings compared to providing separate facilities and is also an approach being considered in other countries.

9.3 Implementation

Whilst technical solutions have been available for many years there has never been successful implementation of those solutions in the UK. This section summarises why Nirex believes that the concept can and should be implemented in the UK without further delay.

The geological characteristics required from a site are well understood and are afforded by a significant proportion of the deep geology in the UK.

- The British Geological Survey (BGS) working with Nirex has established geological criteria for deep repositories. Application of those criteria has shown that around 30% of the UK land mass is potentially suitable for a repository. Work is currently underway with the BGS to review the criteria based on current understanding. The geological criteria will be applied to the national geoscience database to update the estimate of the proportion of the UK potentially suitable for a repository.

- Nirex is confident that a potential repository site can be characterised to evaluate its suitability. This is a view shared by our equivalent organisations overseas and by the geoscience community. An open meeting arranged by the Geological Society of London and the British Geological Survey concluded: *"the geoscience community believes that it has the methodology and interpretive capability to characterise successfully a potential repository site"* The full statement is available on the Geological Society's website [108].

- It must be recognised that the selection of a suitable site would require consideration of a wide range of factors not just geological criteria. The establishment of any new siting process and criteria will be addressed as part of the current MRWS programme.

The concept is based on well developed science and technology in the UK and overseas.

- Similar concepts are being developed for the management of higher activity wastes in many other countries. [123]

- Repository concepts are supported by over twenty years of research and development both in the UK and overseas. There is a shared view amongst EU member states that enough fundamental research has been done and that the emphasis should now be on technology demonstration. [124]

- Technology demonstration is now the main focus of work being undertaken in underground research laboratories (URLs) such as Grimsel (Switzerland) and Äspö (Sweden). A major co-operation project currently making use of several URLs is the EC part-funded ESDRED (Engineering Studies and Demonstration of Repository Designs). The overall objective of ESDRED is to demonstrate the technical feasibility at an industrial scale of activities needed to construct, operate and close a deep geological repository in compliance with requirements on operational safety, retrievability and monitoring [125].

- The repository designs are based on the use of existing technology. Nirex has undertaken a review of all elements of the Phased Geological Repository Concept and identified examples to show that all elements utilise tried and tested technology. The HLW/SF concept is based on the Swedish KBS3 - V concept. In Europe this concept is the most advanced in terms of full scale demonstration. The Prototype Repository at the Äspö Hard Rock Laboratory in Sweden is a full scale demonstration of container, buffer and backfill emplacement, and of in-situ testing of its evolution.

- The geological isolation provided by 300 – 1000m of rock means that the concept is highly resilient to disruption by man-made [126] or natural events [127].

Provided that lessons from dialogue and past experience in the UK and overseas are taken into account we believe the UK can implement a long-term solution.

- Past experience shows it has not been possible to reach a consensus in support of implementation in the UK. Other countries are proceeding with implementation, such as Finland. Those countries have found that legitimacy is the key. A basic analysis of the elements of legitimacy would include equity (fairness), competence (the right science and technology) and efficiency (proper use of resources). All of this must be underpinned by transparency and accountability.

- Decisions relating to radioactive waste management must be viewed as 'fair'. This is particularly important when considering implementation because at that stage national decisions start to have an impact on local communities. A particular lesson from the past was that the siting process was carried out in secret and this, what we believe was poor behaviour by Nirex, led to conflict between the local community and Nirex as the body responsible for implementing national policy.

- Recent work (CARL, COWAM) has begun to look at community involvement in national decision making. Issues being considered include volunteerism, the right to veto, planning gain and the need for a 'contract' between the local community and national decision makers.

- For implementation to be possible it is essential that the underlying science and technology is seen as correct, robust and safe. Recent agreements between Nirex and regulators ensure that Nirex's work on ILW is now subject to independent scrutiny. The results of this are made publicly available. Future submissions in support of any planning application would also need to be subject to rigorous peer review. The scope of such reviews should be developed with the involvement of local affected communities.

- There needs to be a recognition that a solution is being provided by scientists and technologists on behalf of society This is different to the previous approach whereby specialists would develop a solution and then try to persuade society to accept it. An illustration of this change in approach is the incorporation of retrievability within the Nirex repository concept. Stakeholders had consistently demanded retrievability as a feature of the repository concept, but before 1997 Nirex challenged the need for this. This was a fundamental reason for opposition to Nirex's proposals. The difference in the approach is that Nirex now takes such demands as requirements to be met. The role of the technical specialists is to provide a means of meeting the requirements without compromising safety.

- For radioactive waste management, safety is paramount but it is necessary, at all stages of development and implementation, to ensure that value for money is obtained through efficient use of resources. To do this requires a sound knowledge of the nature and characteristics of the UK's radioactive waste, a thorough understanding of the concept and its performance over very long timescales and from this identification of the requirements from a specific site. Together this information allows the concept holder to focus resources on those elements that really matter thereby avoiding unnecessary cost.

It is the duty of this generation to implement a long-term solution.

- The UK has been generating radioactive waste in significant quantities since the 1940s. In 1976 a report by the Royal Commission on Environmental Pollution (the Flowers Report) highlighted the urgent need for a solution to deal with such waste. Yet here in 2005 the UK has still not implemented a long term solution for the management of its higher activity wastes. It cannot be right to continue passing this hazardous burden onto future generations.

- The ethical issues surrounding geological disposal have been debated on a national and international level. A workshop organised by NEA in 1994 on Environmental and Ethical Aspects of Radioactive Waste Disposal [25] agreed a number of points of relevance to this topic and summarised below.

- From an ethical standpoint including long term safety considerations our responsibilities to future generations are better discharged by a strategy of final disposal than by reliance on stores which require surveillance, long term responsibilities of care, and may in due course be neglected by future societies whose future should not be presumed.
    - *Those who generate the waste should take responsibility and provide resources for the management of those materials in a way which will not impose undue burdens on future generations.*
    - *If the present generation delays the construction of a repository to await advances in technology, or because storage is cheaper, it should not expect future generations to make a different decision. Such an approach in effect would always pass responsibility for real action to future generations and for this reason could be judged unethical.*

- Of particular importance in the above discussions was the participation of the OECD Environment Directorate, and of independent experts from academic and environmental policy centres.

9.4 Conclusions

Radioactive waste exists now and something needs to be done about its long-term management in the UK. Without such management the hazard and associated risks to people and the environment would be significant and unacceptable. Most other countries are planning to place long-lived radioactive wastes in a geological repository. Increasingly the concepts are being developed to incorporate retrievability and implementation in a phased, reversible manner.

After many years of research both in the UK and internationally we believe that the Phased Geological Repository Concept for ILW and certain LLW, coupled with the HLW/spent fuel concept developed with SKB of Sweden provide viable technical options. In this report we have also set out why we believe that the concept can and should be implemented in the UK without further delay.

We strongly support the need for an open and transparent process to select and implement a long-term waste management option for the UK. To that end we are making this report and supporting information available as an input to the Governments' MRWS consultation process.

Appendix 1 Concept review process

Objectives for the evaluation of issues

Nirex has conducted specific programmes of work to prepare for its participation in the MRWS consultation process, e.g. to provide information that may be needed by CoRWM. This has included an extensive collation of issues related to Nirex programmes of work and the Nirex Phased Geological Repository Concept (PGRC) identified from both external and internal sources (see Figure A1). These issues have been screened, categorised, evaluated and used:

- as an aid to making qualitative assessments and comparing various options that have been proposed in the past for the long-term management of radioactive waste;

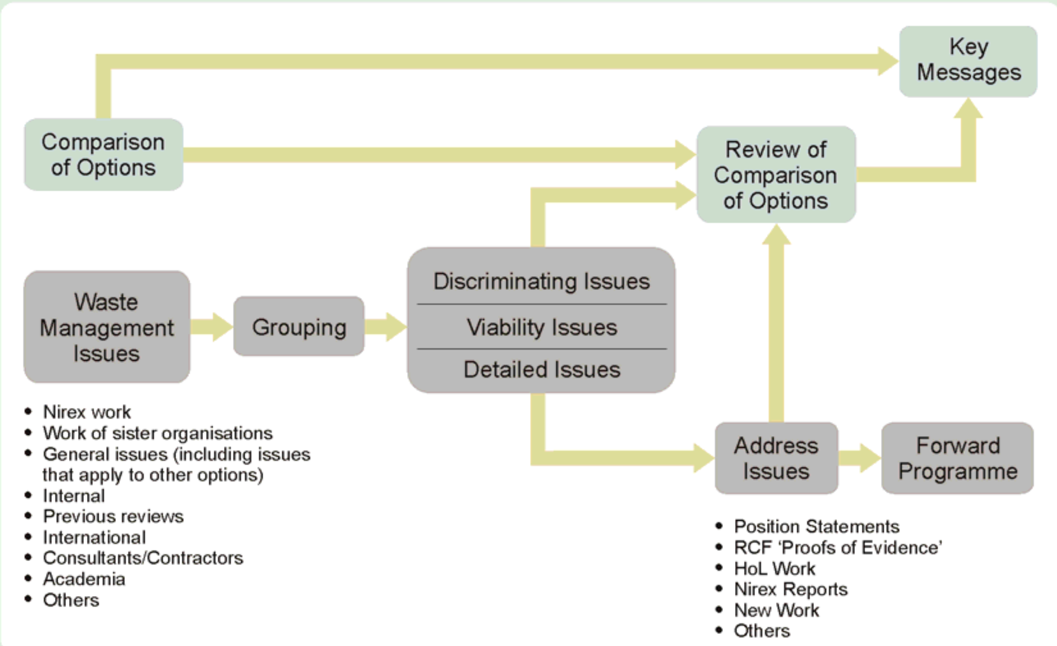
- as the basis for a detailed examination of the Nirex PGRC and assessment of its viability (this report); and

- as an aid to identifying any significant gaps in Nirex's ongoing and future research and information programmes.

This report is concerned only with the second point above – the detailed examination of the PGRC and assessment of its viability. In particular, this Appendix summarises how issues were identified, categorised and evaluated as input to this examination, and the results of the examination.

The process is described in more detail in a Technical Note [128], and the detailed evaluation of issues is documented in a series of 31 "Context Notes", each covering a topic area relevant to the PGRC.

Figure A1
Concept review



The identification of issues

Issues were identified from a range of external and internal sources (see Figure A2).

'External' sources included:

- Examination of selected independent and critical reviews of the Nirex proposals and work programmes since 1987. Initially over 50 reviews and critiques were examined and on this basis ten main sources (reports or sets of reports) were selected for detailed examination. These included review reports authored by The Royal Society, Friends of the Earth, Her Majesty's Inspectorate of Pollution, the Inspector overseeing the RCF Local Planning Inquiry, the OECD Nuclear Energy Agency and the RWMAC.

- Examination of additional, more recent, documents that would be likely to form a starting point for CoRWM's considerations – this included documents from Defra and the DETR related to the consultation process and strategy for radioactive waste management in the UK.

- Discussion with key scientific and technical advisors and academics – these were meetings held between October 2003 and January 2004 to elicit relevant issues and develop ways of obtaining continued input to Nirex's work to prepare for the MWRS process.

'Internal' sources included:

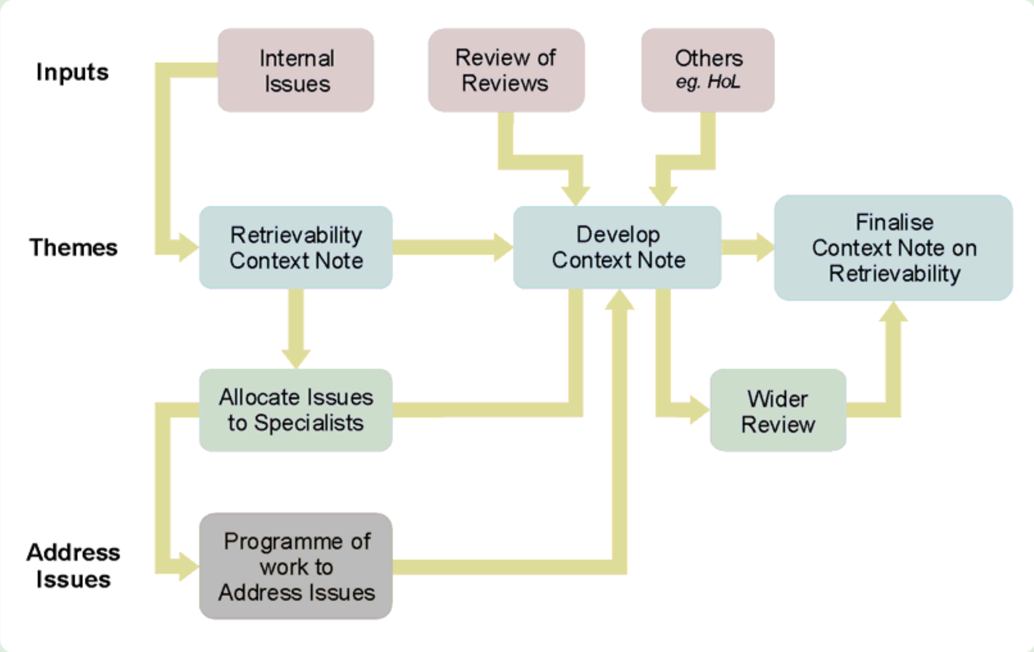
- Re-examination of an internal review held by Nirex following the RCF Local Planning Inquiry.

- An internal review of the current realisation of the PGRC as documented in the Nirex Generic Documents, including input from previews of the draft documents with waste producers and other stakeholders in 2000/1 and in 2003, and a review by a Nirex contractor.

- Input from experience with the Nirex waste package specification and advice process, i.e. the Letter of Compliance (LoC) assessment process.

- An internal workshop held to 'brainstorm' potential issues related to the PGRC, held in May 2003.

Figure A2
Identification, Grouping and Addressing Issues



The evaluation of issues

Inevitably, when drawing on such a variety of sources for relevant information, the quality of the documentation and level of detail in which issues were specified varies. The general approach, however, was as follows.

- Each issue was recorded together with its source and any available expansion on its motivation, implications or interpretation.
- Issues from each source were reviewed and assigned to one of about 30 topic areas concerning the PGRC.
- Nirex experts in each topic area examined the issues against the general background of the state of knowledge and experience in that topic area and made a qualitative ‘evaluation’ of each issue.
- Some issues were determined to be no longer relevant to the Nirex PGRC as now developed or a duplication of other issues, but, in principle, the aim was to assign each issue as either a ‘viability’, ‘discriminating’ or ‘detailed’ issue, see Box A.1.
- The assignment and evaluation of issues and associated arguments was then reviewed internally and some transfers of issues between topic areas and rationalisations of evaluations were made.

Box A.1: Issue evaluation terminology	
Term	Definition
Viability	An issue with the potential to threaten the viability of implementation of the Nirex PGRC. It may be solvable, however, either by setting site or design requirements so as to limit or avoid the problem, or by R&D which may better define the problem. The issue may be 'common' to, i.e. also undermine the viability of, other waste management options, and this should be noted.
Discriminating	An issue that only occurs for geological disposal or changes very significantly between waste management options, although not with the potential to undermine the technical viability of the Nirex PGRC. These issues can be used to help discriminate between the options.
Detailed	An issue related to geological disposal that can reasonably be taken account of in future R&D or assessment cycles for the PGRC. These issues would need to be addressed in order to develop and implement a waste management option. They do, however, not challenge the viability of the PGRC or serve to discriminate between options.

The aim of these evaluations was to sort issues as to whether they might be relevant to comparing various options for long-term management of radioactive waste (discriminating), relevant to assessing the viability of the Nirex PGRC (viability), or relevant to reviewing Nirex's ongoing and future research and information programmes (all three issue classes to be considered).

Documentation – the Context Notes

The detailed evaluation of issues in each topic area formed the basis for the development of a set of "Context Notes". These each describe the importance of a given topic area, the experience to date and future work planned by Nirex in the area, plus a summary evaluation of key issues in the topic area. Here, 'key issues' are issues that might have some potential to undermine or affect the viability of the Nirex PGRC. The work in hand or needed to confirm the viability in the light of the given issue is also identified.

The objective of the Context Notes is to provide a statement of the key issues and their status within the topical areas that are relevant to the development of the Nirex PGRC.

Each context note provides:

- a well-founded summary of the more important issues in each topical area;
- a traceable basis for this overview report, which provides a summary level understanding of the issues and their relative importance.

Issues identified as ‘viability’ have been distilled out from the Context Note to a summary table provided in each Context Note. Key issues may be expressed in a more generic form than that in which they were originally raised. Additional issues may also have been introduced over and above those coming from the various internal and external sources, if in the judgement of the Context Note author this is needed.

Box A.2: Summary evaluation method of issues used in the Context Notes		
Issue	Evaluation	Status
Concise statement of the issue. Issues can be grouped as far as possible and expressed generically.	Its implications. Its evaluation: viability or discriminating or detailed for the PGRC or all waste management options.	What needs to be done: comments on actions, work, discussion or what is needed (not necessarily by Nirex) to clarify or handle the issue. What is being done about it or planned to be done?

The Context Notes have been subjected to a formal review and QA process.

Product

The Context Notes, see Box A.3, provide a bank of information to establish the current status of the Nirex PGRC and to respond to questions regarding the Nirex PGRC that may be posed by CoRWM and others. The identification and evaluation of the issues has also been used to assist in defining research priorities and the forward programme of Nirex.

Whilst the approach used for the compilation of issues cannot be guaranteed as comprehensive, a wide variety of sources have been examined and analysed in a traceable manner. It is considered that the process has been sufficiently comprehensive to ensure that all of the important potential viability threats to the Nirex PGRC have been identified.

Box A.3: List of Context Notes

Nirex strategy, policies and management	
1.1	Radioactive waste management policy
1.2	Environmental and safety policies and strategy
1.4	Cost of the Nirex Phased Geological Repository Concept
1.5	Communication issues
1.6	Licensing and regulation
1.7	Social science
1.8	Additional radioactive wastes and materials
1.9	Other waste management options
Step-by-step development of the PGRC	
2.1	Waste packaging (WPS and LoC assessments)
2.2	Waste transport safety
2.3	Site selection
2.4	Site investigation
2.5	RCF role and functions
2.6	Repository design and construction
2.7	Repository operation and safety
2.8	Long-term and post-closure institutional arrangements
2.9	Environmental assessments
Long-term safety assessments and R&D programme	
3.1	Waste Inventory
3.2	Near-field research
3.3	Geosphere research
3.4	Biosphere research
3.5	Gas generation and its effects
3.6	Human intrusion
3.7	Post-closure performance assessment
3.8	Safety case arguments
Additional issues	
4.1	Retrievability
4.2	Monitoring
4.3	Criticality
4.4	Safeguards
4.5	Security

REFERENCES

1 United Kingdom Nirex Limited, *Identification and Description of UK Radioactive Wastes and Materials Potentially Requiring Long-term Management,* Nirex Report N/085, 2003.

2 Radioactive Waste Management Committee, *23rd Annual Report,* 2003.

3 United Kingdom Nirex Limited, *Options for Radioactive Management that have been Considered by Nirex,* Nirex Report N/049, 2002.

4 United Kingdom Nirex Limited, *Description of Long-term Management Options for Radioactive Waste Investigated Internationally,* Nirex Report N/050, 2002.

5 US National Academy of Sciences. *Management and Disposition of Excess Weapons Plutonium*, Washington DC, 1994.

6 International Maritime Organisation, *Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention 1972),* 1972.

7 C. Katkowski Q.C., *Legal Advice to Nirex on Sub Seabed Disposal*, A Legal Note for Nirex, 2005.

8 *The Antarctic Treaty*, 1959.

9 *The Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies*, 1967.

10 United Kingdom Nirex Limited, *A Survey of National Policies and Programmes Relating to Long-term Radioactive Waste Management Strategies,* Nirex Technical Note, 2004.

11 Health and Safety Executive, Nuclear Safety Directorate, *Guidance for Inspectors on the Management of Radioactive Materials and Radioactive Waste on Nuclear Licensed Sites,* 13 January 2001.

12 IAEA, *The Long Term Storage of Radioactive Waste: Safety and Sustainability – A Position Paper of International Experts,* IAEA, Vienna, 2003.

13 United Kingdom Nirex Limited, *Summary Note for CoRWM on the Impact of Rising Sea Level on Coastal Sites with Radioactive Waste Stores,* Nirex Technical Note, 2005.

14 H. Åhagen, P. Wretlund, K. Andersson, K. Hallberg and K. Nilsson, *Participation of the Municipality of Oskarshamn in the Site Selection Process for a Final Repository for Spent Nuclear Fuel – Motivation, Organization and Lessons Learned, ICEM05-,* 1438 Proceedings of the 10th International Conference on Environmental Remediationand Radioactive Waste Management, Glasgow, Scotland, 4 – 8 September 2005 (ASME, IMechE, BNES), 2005.

15 European Commission, *Concerted Action on the Retrievability of Long-lived Radioactive Waste in Deep Underground Repositories*, Project Report EUR 19145 EN, 2000.

16 United Kingdom Nirex Limited, *Corrosion Resistance of Stainless Steel Radioactive Waste Packages*, Nirex Report N/110, 2004.

17 F. M. Porter and A. V. Chambers, *The Development and Application of RARECAN*, Nirex Report NSS/R396, 1995.

18 United Kingdom Nirex Limited, *Why a Cementitious Repository*, Nirex Report N/034, 2001.

19 United Kingdom Nirex Limited, *Generic Post-closure Performance Assessment,* Nirex Report N/080, 2003.

20 United Kingdom Nirex Limited, *Waste Package Specification and Guidance Documentation – WPS/630: Guidance on Environmental Conditions during Storage of Waste Packages,* Nirex Document No. 485890, 2005.

21 IAEA, *Regulations for the Safe Transport of Radioactive Material, 2005 Edition,* Vienna, 2005.

22 United Kingdom Nirex Limited, *Retrievability of Radioactive Waste from a Deep Repository*, Nirex Report N/024, 2001.

23 United Kingdom Nirex Limited, *Generic Repository Studies, The Nirex Phased Disposal Concept,* Nirex Report N/074, 2003.

24 SKN, *Ethical aspects of nuclear waste. Some salient points discussed at a seminar on ethical action in the face of uncertainty in Stockholm, Sweden, September 1987,* SKN Report 29, 1987.

25 Nuclear Energy Agency, *The Environmental and Ethical Basis of Geological Disposal,* Paris, 1995.

26 House of Lords Select Committee on Science and Technology, *Management of Nuclear Waste,* Session 1998-99 Third Report, 1999.

27 UK CEED, *UK National Consensus Conference, 21-24 May 1999, London, Radioactive Waste Management – Citizens Panel Report,* 1999.

28 UK CEED, *Workshop on the Monitoring and Retrievability of Radioactive Waste, 2 December 2000, Manchester,* 2000.

29 UK CEED, *Workshop on the Monitoring and Retrievability of Radioactive Waste, 12 February 2001, Manchester,* 2001.

30 UK CEED, *Workshop on the Monitoring and Retrievability of Radioactive Waste*, *8 February 2002, Manchester,* 2002.

31 SAM, NNC and Nagra, *Technical Implications of Retrievability on the Nirex Phased Disposal Concept,* SAM Ltd. Report to Nirex, 2001.

32 SAM, NNC, Nagra and Lancaster University, *Options for Monitoring During the Phased Development of a Repository for Radioactive Waste,* SAM Ltd. Report to Nirex, 2002.

33 European Commission, *Thematic Network on the Role of Monitoring in a Phased Approach to Geological Disposal of Radioactive Waste,* Project Report EUR 21025 EN, 2004.

34 United Kingdom Nirex Limited, *Generic Repository Studies - Generic Waste Package Specification, Volume 1: Specification*, Nirex Report N/104, 2005.

35 United Kingdom Nirex Limited, *Generic Repository Studies – Generic Repository Design,* Nirex Report N/077, 2003.

36 United Kingdom Nirex Limited, *Implications of Deferred Backfilling on Repository Geosphere Performance*, Nirex Report N/056, 2002.

37 United Kingdom Nirex Limited, *Implications of Deferred Backfilling on Containment of Radionuclides in the Near Field Following Repository Closure,* Nirex Report N/059, 2002.

38 NNC Ltd., *Nirex: Demonstration of Waste Package Retrieval,* NNC Report PRSU/2524 to Nirex, 1997.

39 Environment Agency, HSE and SEPA, *Improved Regulatory Arrangements for the Conditioning of ILW on Nuclear Licensed Sites,* Regulators' Position Statement, 2004.

40 HM Government, *The Decommissioning of the UK Nuclear Industry's Facilities, Policy Statement*, 2004.

41 Health and Safety Executive, Environment Agency and Scottish Environment Protection Agency, *Conditioning of Intermediate Level Waste on Nuclear Licensed Sites – Guidance to Industry,* 2005.

42 NNC Ltd., *Nirex Generic Repository Design: Demonstration of Proven Technology*, NNC Report C6421/001 to Nirex Issue 4, 2003.

43 N. A. Chapman, T. J. McEwen and H. Beale, *Geological Environments for Deep Disposal of Intermediate-level Radioactive Waste in the UK. Proceedings of International Symposium on Siting, Design and Construction of Underground Repositories for Radioactive Waste, IAEA, Hanover 1986*, Paper IAEA-SM 289/37, 1986.

44 T. Sumerling and P. Smith, *Disposal of Nuclear Fuel Waste – Geological Alternatives, Designs, Implementation and Long-term Safety.* Interdisciplinary Science Reviews Vol. 23, No. 3, 1998.

45 United Kingdom Nirex Limited, *Generic Repository Studies – Design Assessment for Geological Repositories*, 2004.

46 Wardell Armstrong, *Generic Repository Studies – Assessment of Repository Designs in Clays and Evaporites*, Wardell Armstrong Report J01 to Nirex, 2004.

47 Nuclear Energy Agency, *Reversibility and Retrievability in Geological Disposal of Radioactive Waste – Reflection at the International Level*, Paris, 2001.

48 United Kingdom Nirex Limited, *Foundations of the Phased Disposal Concept, Waste Inventory and Packaging,* Nirex Report N/018, 2003.

49 IAEA, *Requirements and Methods for Low and Intermediate Level Waste Package Acceptability*, IAEA-TECDOC-864, Vienna, 1996.

50 R. M. Guppy, S.P. Vines and S.J. Wisbey, *The Benefits of Cementitious Encapsulation Matrices for the Conditioning of Intermediate-Level Waste, ICEM03 – Proceedings of the 9th International Conference on Radioactive Waste Management and Environmental Remediation, Oxford,* 2003.

51 S. Barlow and A. McCall, *The UK Process for Assessment of ILW Packaging Proposals*, *Waste Management 2005,* 2005 .

52 United Kingdom Nirex Limited, *Nirex Interactions with Waste Producers on Plans for Packaging of Radioactive Wastes – April 2003 to March 2004,* Nirex Report N/116, 2005.

53 United Kingdom Nirex Limited, *Compatibility of the Nirex Waste Package Specification with Long-term Waste Management Options*, Nirex Report N/057 v2, 2002.

54 Defra, *Report on RWPG Sponsored Compatibility Workshop, February 2004,* DEFRA RAS/04.007, 2004.

55 IAEA, *Safety Requirements for the Geological Disposal of Radioactive Waste,* IAEA Safety Standards Series WS-R-4, Vienna, 2005.

56 Nuclear Energy Agency, *The Post-closure Safety Case for Geological Repositories: Nature and Purpose*, Paris, 2004.

57 Environment Agency, Scottish Environment Protection Agency, Department of the Environment for Northern Ireland, *Disposal Facilities on Land for Low and Intermediate Level Radioactive Wastes: Guidance on Requirements for Authorisation,* 1997.

58 Nuclear Energy Agency, *Features, Events and Processes (FEPs) for Geologic Disposal of Radioactive waste: An International Database*, Paris, 2000

59 United Kingdom Nirex Limited, *Overview of the FEP Analysis Approach to Model Development,* Nirex Science Report S/98/009, 1998.

60 United Kingdom Nirex Limited, *Development and Application of a Methodology for Identifying and Characterising Scenarios*, Nirex Science Report S/98/013, 1998.

61 Nuclear Energy Agency, *Nirex Methodology for Scenario and Conceptual Model Development: An International Peer Review,* ISBN 92-64-17084-7, Paris, 1999.

62 United Kingdom Nirex Limited, *Nirex 95: A Preliminary Analysis of the Groundwater Pathway from a Deep Repository at Sellafield*, Nirex Science Report S/05/012, 1995.

63 United Kingdom Nirex Limited, *Nirex 97: An Assessment of the Post-closure Performance of a Deep Waste Repository at Sellafield,* Nirex Science Report S/97/012, 1997.

64 United Kingdom Nirex Limited, *Nirex 97: An Assessment of the Post-closure Performance of a Deep Waste Repository at Sellafield. Report on Peer Review by QuantiSci Ltd.*, Nirex Science Report S/98/014, 1998.

65 United Kingdom Nirex Limited, *Performance Assessment in Context*, Nirex Report N/117, 2005.

66 Nagra, *Effects of Post-Disposal Gas Generation in a Repository for Spent Fuel, High Level Waste and Long-lived Intermediate Level Waste Sited in Opalinus Clay*, Nagra Technical report 04-06, 2004.

67 SKB, *Template for Safety Reports with Descriptive Example*, SKB Technical Report 96-05, 2005.

68 Defra and United Kingdom Nirex Limited, *The 2001 United Kingdom Radioactive Waste Inventory: Main Report*, Defra Report DEFRA/RAS/02.004, Nirex Report N/042, ISBN 1 84029 287 3, 2002.

69 Nuclear Energy Agency, *Establishing and Communicating Confidence in the Safety of Deep Geologic Disposal: Approaches and Arguments*, Paris, 2002.

70 United Kingdom Nirex Limited, *The Nirex Repository Concept: Evaluating Performance*, Nirex Report N/011, 2000.

71 Harland et al, *A Geologic Timescale 1989*, Cambridge University Press, 1990.

72 National Radiological Protection Board, *Living with Radiation (Fifth Edition)*, NRPB, 1998.

73 Institute for Environment and Sustainability Research, Staffordshire University, *Strategy for Stakeholder Involvement in the Nirex Generic Transport Safety Assessment Development Programme*, Report to Nirex, 2004.

74 National Radiological Protection Board, *Survey into the Radiological Impact of the Normal Transport of Radioactive Material in the UK by Road and Rail,* NRPB-W66, 2005.

75 United Kingdom Nirex Limited, *Generic Transport System Design*, Nirex Report N/076, 2003.

76 United Kingdom Nirex Limited, *Generic Transport Safety Assessment*, Nirex Report N/078, 2003.

77 Health and Safety Executive, *Reducing Risks, Protecting People: HSE's Decision Making Process,* HSE, 2001.

78 Euratom, *Council Directive 96/29/ Euratom of 13 May 1996, laying down basic safety standards for the protection of the health of workers and the general public against the dangers arising from ionizing radiation*, Official Journal of the European Communities, L159, Vol. 39, 1996.

79 HSE, *Guidance on the purpose and content of nuclear safety cases*, HSE Technical Assessment Guide T/AST/051, 2002.

80 United Kingdom Nirex Limited, *Generic Operational Safety Assessment*, Nirex Report N/079, 2003.

81 Environment Agency, *NWAT Assessment of Nirex's Approach to the Setting of Fissile Limits for Waste Packages and Assessment of Possible Post-closure Criticality Events,* NWAT/Nirex/04/002, 2005.

82 United Kingdom Nirex Limited, *Topical Report on Post-closure Criticality Safety Assessment,* Nirex Science Report S/98/004, 1998.

83 United Kingdom Nirex Limited, *Environmental Assessment of the Nirex Phased Disposal Concept – Recommendations of the Environmental Assessment Task Team,* Nirex Technical Note, 2003.

84 R. P. Bush, A. Fenton, A. W. Harris and R. F. Simmons, *Mechanisms of Ageing for Cemented ILW Wasteforms*, AEAT/R/NS/0469, 2003.

85 M. Constable, A.W. Harris, D.J. Ilett, W.M. Tearle and A.T. Tuson, *Changes in Thermal Properties of Aged Wasteforms*, AEAT/R/NS/0689, 2004.

86 R M Consultants, *Comparison of Nirex Waste Package Specification with Waste Acceptance Criteria for Storage and Disposal Facilities in Other Countries*, R02-229(S), 2002.

87 L.J. Gould, A.W. Harris and A. Haworth, *Calculation of the Volume of Backfill Required in the Near Field of a Repository,* AEAT/ERRA-2270, 2001.

88 W. R. Rodwell et al, *A Thematic Network on Gas Issues in Safety Assessment of Deep Repositories for Radioactive Waste (GASNET)*, European Commission Report, EUR 20620, 2003.

89 T.W. Hicks, M.B. Crawford and D.G. Bennett, *Carbon-14 in Radioactive Wastes and Mechanisms for its Release from a Repository as a Gas*, Galson Sciences Ltd Report 0142-1, 2003.

90 N. Carr and C.F. Tso, *Waste Container Design – an Engineering Guide for Designers*, Nirex Report N/070, 2003.

91 A. Haworth and S.M. Sharland, *The Evolution of the Eh in the Pore Water of a Radioactive Waste Repository*, Nirex Report NSS/R308, 1995.

92 United Kingdom Nirex Limited, *Proceedings of the Royal Society of Chemistry / Nirex Symposium: The Chemistry of Deep Disposal of Radioactive Waste*, Nirex Science Report S/98/008, 1998.

93 C. P. Jackson and J.L. Knight, *Nirex's Approach to the Modelling of Groundwater Flow and Transport in Spatially Heterogeneous Rock Masses*, Nirex Report N/100, 2003.

94 O. Stephansson, J.A. Hudson and J. Andersson, *Guidance Document on THM Coupled Processes in Performance Assessment (Benchpar)*, European Commission report, EUR 21226, 2005.

95 M. Mazurek, F.J. Pearson, G. Volckaert and H. Bock, *Features, Events and Processes Evaluation Catalogue for Argillaceous Media,* OECD - NEA Report 4437, 2003.

96 SKB, *EC Concerted Action Project Report, Treatment of Geosphere Retention Phenomena in Safety Assessments,* SKB Report R-04-48, 2004.

97 IAEA, *"Reference Biospheres" for Solid Radioactive Waste Disposal, Report of BIOMASS Theme 1 of the BIOsphere Modelling and ASSessment (BIOMASS) Programme*, Vienna, 2003.

98 NRPB, *Board Statement on Radiological Protection for the Land-based Disposal of Solid Radioactive Wastes,* Documents of the NRPB, Vol. 3, No. 3, 1992.

99 NRPB, *Recommendations for the Practical Application of the Board's Statement*, Documents of the NRPB, Vol. 3, No. 3, 1992.

100 ICRP, *ICRP Publication 81*, *Radiation Protection Recommendations as applied to the Disposal of Long-lived Solid Radioactive Waste*, Annals of the ICRP, Volume 28, No. 4, 1998.

101 BIOCLIM (Modelling Sequential Biosphere Systems and Climate Change for Radioactive Waste Disposal). Background and documentation available at www.andra.fr/bioclim, 2005.

102 BIOPROTA (Biosphere Data Protocol Development for Assessments). Background and documentation available at www.bioprota.com, 2005.

103 SKB, *Interim Main Report of the Safety Assessment SR-Can*, SKB Report TR-04-11, 2004.

104 United Kingdom Nirex Limited, *Overview Report on Repository Concept and Programme Development for High Level Waste and Spent Nuclear Fuel in the United Kingdom*, Nirex Report N/125, 2005.

105 United Kingdom Nirex Limited, *Preliminary Post-closure Assessment of a Reference Repository Concept for UK High-level Waste/Spent Fuel,* Nirex Technical Note, 2005.

106 United Kingdom Nirex Limited, *Initial Consideration of Waste Acceptance Criteria for the Long-term Management of Certain UK Radioactive Wastes and Potential Wastes,* Nirex Report N/118, 2004.

107 OJEC, *Directive 2001/42/EC of the European Parliment and of the Council, On the Assessment of the Effects of Certain Plans and Programmes on the Environment, Directive 2001/42/EC,* 2001.

108 Geological Society, *Geoscience Verdict on Radioactive Waste Disposal,* News Release PR 26/99, http://www.geolsoc.org.uk/template.cfm?name=Radwaste, 1999.

109 United Kingdom Nirex Limited, *Sellafield Geological and Hydrogeological Investigations – Rock Characterisation Facility, Longlands Farm, West Cumbria: Report on Baseline Groundwater Pressures and Hydrochemistry,* Nirex Science Report SA/96/006, 1996.

110 United Kingdom Nirex Limited, *Review of Baseline Groundwater Pressures and Hydrochemistry Between November 1996 and October 1998: Report by an Independent International Review Group,* Nirex Report, 1998.

111 M. Gray, *International Stripa Project 1980-1992: Overview Volume III, Engineered Barriers*, SKB (Sweden), 1993.

112 United Kingdom Nirex Limited, *Excavating the Future: Archaeology and Radioactive Waste Management*, Nirex Report N/068, 2005.

113 United Kingdom Nirex Limited, *Nirex Safety Assessment Research Programme: A Natural Analogue Study of Cement Buffered, Hyperalkaline Groundwaters and their Interaction with a Repository Host Rock: Phase II,* Nirex Science Report S/98/003, 1998.

114 O. Karnland, *Cement-bentonite Interaction, Results from 16 Month Laboratory Tests,* SKB Technical Report TR-97-32, 1997.

115 R. Pusch, *The Buffer and Backfill Handbook, Part 1: Definitions, Basic Relationships and Laboratory Methods*, SKB Technical Report TR-02020, 2002.

116 Galson Sciences Ltd. and Golder Associates (UK) Ltd., *Techniques for Post-closure Monitoring: Summary Report,* GSL Report 0358-2 to Nirex, Version 1.1, 2004.

117 United Kingdom Nirex Limited, *Further Near-field Solubility Studies,* Nirex Report NSS/R357, 1997.

118 K. A. Bond and C. M. Linklater, *Sorption of Radionuclides onto Rock Samples from the Sellafield Area: Database of Distribution Ratios,* AEA Technology Report AEAT/R/ENV/0215 to Nirex, 2001.

119 M. C. Thorne, *Biosphere Factors for use in a Generic Performance Assessment: Comparison and Sensitivity Study,* Mike Thorne and Associates Report MTA/P0011d/2002-4 Issue 2 to Nirex, 2003.

120 Society for Risk Analysis and the European Safety and Reliability Association*, Proceedings of PSAM-II: An International Conference Devoted to the Advancement of System-based Methods for the Design and Operation of Technological Systems and Processes, San Diego, California (USA) 20-25 March 1994*, Plenum Publishing Corporation, 1994.

121 W. Miller, R. Alexander, N. Chapman, I. McKinley, and J. Smellie, *Geological Disposal of Radioactive Wastes and Natural Analogues*, Pergamon (Elsevier Science), Oxford: Waste Management Series, Volume 2, 2000.

122 M.M. Askarieh, A. W. Harris and S.J. Wisbey, *The Potential Impact of Oil and other Non-aqueous Phase Liquids (NAPLs) on the Long-term Management of Radioactive Wastes,* ICEM03-4887, Proceedings of the 9th International Conference on Radioactive Waste Management and Environmental Remediation, Oxford, England, September 21 – 25, 2003 (ASME, IMechE, BNES), 2003.

123 United Kingdom Nirex Limited, *The International RD&D Basis of Geological Repositories,* Nirex Report N/126, 2005.

124 European Commission, *DG-RTD Summary Report of the Meeting with Waste Agencies, Brussels, 16 June 2004*, EC (Brussels), 2004.

125 J. L. Gausson, *A European Project of Technological Demonstrators,* Presented at Waste Management 2005 (WM'05), Tucson, 2005.

126 IAEA, *Issues and Trends in Radioactive Waste Management*, Proceedings of an International Conference, Vienna, 9-13 December 2002, pp. 538-539, Vienna, 2003.

127 European Commission, *PADAMOT: Palaeohydrogeological Data Analysis and Model Testing – Overview,* EUR Report, 2005.

128 United Kingdom Nirex Limited, *The Identification and Evaluation of Issues Relevant to the Phased Geological Repository Concept (PGRC)*, Nirex Technical Note, 2005.

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