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UNITED KINGDOM NIREX LIMITED

Rock Characterisation Facility

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PROOF OF EVIDENCE

OF

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REPOSITORY PERFORMANCE

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DR. ALAN JAMES HOOPER will say;

1. PERSONAL DETAILS

1.1 I am Manager for Science for United Kingdom Nirex Limited ('Nirex') having joined the Company in September 1988 on secondment from the former Central Electricity Generating Board ('CEGB'). I am responsible for evaluations of long-term repository safety performance of the Sellafield site and for advising the Director for Science on co-ordination of the programmes of site characterisation, research and safety assessment.

1.2 I have been a UK delegate to the Co-ordinating Group for Site Evaluation and Design of Experiments for Radioactive Waste Disposal of the Radioactive Waste Management Committee of the Organisation for Economic Co-operation and Development Nuclear Energy Agency since its formation in 1990. I was elected its chairman in 1992.

1.3 I have been a member of the Scientific Advisory Committee to the Swedish Äspö Hard Rock Laboratory programme since 1992. This committee consists of senior scientists from academic institutions in Sweden and from the international waste agencies which are participating in the Äspö programme and is responsible for peer review of the results and planned experiments.

1.4 I hold a first-class honours degree in Chemistry from Nottingham University and a PhD in Inorganic Chemistry, also from Nottingham University.

1.5 Prior to my secondment and subsequent appointment at Nirex, I was employed by the CEGB. Between 1971 and 1980 I worked on projects to evaluate the transport of radioactive materials within power reactor circuits and the radiological consequences of such transport for workers and public. Between 1980 and 1985 I supported the CEGB Nuclear Decommissioning Project by contributing to evaluations of the radiological safety of alternative strategies for decommissioning CEGB Magnox Reactors. Between 1985 and 1988 I was responsible for the design and implementation of the research programme to support the strategy for the eventual disposal of the CEGB's intermediate-level radioactive wastes.

2. SUMMARY

Repository Performance at Sellafield

2.1 A preliminary assessment, based on results so far, of the post-closure performance of a repository located in the Potential Repository Zone ('PRZ') at Sellafield confirms the good promise of the Sellafield site as a potentially suitable location for a repository. The groundwater pathway is central to our considerations of repository safety and requires to be well understood. If resolution of identified uncertainties confirms our current understanding of the groundwater system at Sellafield, then a repository could be developed in the Borrowdale Volcanic Group of rocks ('BVG') of the PRZ which would meet regulatory requirements.

2.2 In particular, the predicted flow and composition of groundwater that would enter a repository located in the BVG of the PRZ at Sellafield would result in the physical and chemical containment in the repository of all but a small fraction of the radioactivity in the initial disposal inventory. Just three radionuclides: chlorine36, iodine-129 and uranium-238 are calculated to be released in quantities that result in significant contributions to the peak risk either from natural discharges or water abstraction in wells.

2.3 The assessment presented in my evidence emphasises the understanding that has been developed of the contribution of the various barriers in the repository system to the containment of radioactivity in a repository located in the PRZ at Sellafield. The evidence identifies the contribution to containment performance by the engineered and geological barriers.

2.4 Physical containment is afforded in particular by the waste containers which prevent ready access of groundwater to the wastes. The results obtained so far on the corrosion of steels under the conditions that would apply in a repository at Sellafield show that the rates of corrosion would be expected to be low and that the steel containers would remain sufficiently intact to result in containment within the repository of short-lived radionuclides accounting for the major part (about 99%) of radioactivity in the repository inventory.

2.5 In order to establish and maintain appropriate chemical conditions in a repository, the space in the vaults around the waste containers will be backfilled with a cement-based grout developed for the purpose, and known as Nirex Reference Vault Backfill. On the basis of results obtained so far of test work and modelling on the performance of this grout, concerning the suppression of the solubilities of radionuclides in groundwater and sorption of dissolved radionuclides onto cement surfaces, the chemical conditions established in a repository at Sellafield would result in the containment in the repository of most of the long-lived radionuclides in the disposal inventory. Over 99% of the residual 1% of long-lived radionuclides would decay during the period over which chemical containment, represented by conditioning the groundwater to a high pH, is maintained.

2.6 My evidence identifies three important radionuclides that because of their chemical properties or very long radioactive decay half-lives are not physically or chemically contained in the repository until they have decayed to insignificant levels. These are chlorine-36 and iodine-129, which are considered to be highly soluble and not subject to a high degree of sorption in the near field of the repository, and uranium-238 which has a half-life approaching 4,500 million years.

2.7 Groundwater flow models predict that the path taken by groundwater leaving the potential repository location leads to a discharge predominantly into the sediments currently off the coast below the Irish Sea. In this event the additional considerable dilution afforded by the sea leads to assessed risks to an individual at least three orders of magnitude below the target of 10^{-6} per year. However, the extended timescales of thousands of years before the groundwater returns to the surface may be sufficient for a change in climate to cause the sea level to drop and the discharge to be to a terrestrial environment.

2.8 The concentrations in which the radionuclides chlorine-36 and iodine-129 may reach the surface environment are determined by the flow of groundwater through the repository near field and by the extent of subsequent dilution of this volume of water by groundwater in the surrounding host rock and overlying sedimentary formations. It is shown that on the basis of results obtained so far the combination of low groundwater flow in the BVG at Sellafield and the dilution and dispersion afforded by the flow of groundwater in the overlying sedimentary formations is likely to give rise to concentrations of these radionuclides in the surface terrestrial environment consistent with meeting regulatory requirements.

2.9 In the case of uranium-238 the peak in risk from this radionuclide is considered to occur more than a million years after repository closure and to result from a daughter radionuclide, radium-226, produced by its radioactive decay. On the basis of the results obtained so far, both on the groundwater system and on the containment afforded to uranium-238 by the engineered barriers of the repository, the performance of the repository system is likely to give rise to concentrations of radium-226 in the surface environment consistent with meeting regulatory requirements.

2.10 On the basis of these results my evidence identifies the key uncertainties which remain and which need to be addressed to inform two key decision points in the development of a repository.

2.11 It is shown that the Rock Characterisation Facility ('RCF') is needed to provide information to address uncertainties in three main areas:

- groundwater flow and radionuclide transport;
- natural and induced changes to the geological barrier; and
- design and construction of the repository.

Groundwater Flow and Radionuclide Transport

2.12 The flow of groundwater into the near field of the repository is highly dependent upon the description of the networks of connected fractures in the BVG. My evidence describes how the integrated activities of observation, monitoring and testing over extended length scales and in three dimensions only afforded in the RCF are needed to build sufficient confidence in the calculation of the flow rate to meet regulatory requirements with respect to post-closure safety.

2.13 The calculated dilution of the radionuclides transported away from the repository in groundwater is dependent upon the properties of the flow channels in key geological formations. My evidence describes how these flow channels can be identified and characterised by the integrated activities over extended length scales and in three dimensions only afforded in the RCF.

2.14 Further key uncertainties are identified in relation to groundwater flow and radionuclide transport, namely:

- the nature and extent of rock matrix diffusion;
- colloid transport; and
- gas migration.

My evidence identifies the unique attributes of the RCF for addressing these matters.

Natural and Induced Changes

2.15 The key uncertainties that need to be addressed in respect of natural and induced changes to the geological barrier are identified as :

- validation of the stability of the hydrogeological system over extended timescales;
- the effect of excavation disturbance; and
- the effect of chemical disturbance (by alkaline near-field groundwater).

2.16 Detailed examination in the RCF of the fractures that are components of the networks of connected fractures should allow the geological history of flow patterns to be established, particularly by dating the mineralisation that has occurred in association with flows. This palaeohydrogeological record can then be compared with the present day flow patterns to test whether significant changes have occurred in the past and may therefore occur in the future.

2.17 The RCF is needed, in advance of the decision whether or not to propose development of a repository, to validate that the site characteristics are such that excavation disturbance would not significantly impair the containment performance of the natural geological barrier. Excavation of the RCF itself is the only means by which a measurable disturbance can be created to allow extrapolation in time and space of the consequences in the post-closure period of a repository.

2.18 The access to specific features in the rock in the RCF allows testing of the effects of alkaline near-field groundwater (derived from the cements in the repository) on groundwater flow and radionuclide transport in the surrounding host rock.

Design and Construction of the Repository

2.19 The way in which the RCF permits identification of geological and hydrogeological features that must be taken into account in refining the repository design in terms of depth, location, layout and orientation of vaults within the PRZ is described.

2.20 It is also described how the confidence that various underground features can be sealed adequately to satisfy regulatory requirements on post-closure safety is only obtainable by access to representative features and excavations in the rock mass as afforded by the RCF.

Impact of the RCF

2.21 Finally, my evidence notes that the performance of the geosphere barrier is unlikely to be impaired by the impact of the RCF and that this issue will require to be considered as an element of any application to the regulatory authorities for authorisation under RSA93.

3. SCOPE OF EVIDENCE

3.1 The purpose of my evidence is :

- to describe the Nirex approach to post-closure performance assessment (Section 4);
- to present a preliminary analysis of post-closure performance of a repository at Sellafield (Section 5);
- to describe the essential information required from the Rock Characterisation Facility ('RCF') to resolve remaining uncertainties in respect of that performance (Section 6); and
- to describe the impact that the RCF may have upon the containment performance of the geosphere (Section 7).

3.2 In Section 5, I describe the current understanding of the performance of a repository located at Sellafield. The role of the geosphere, both in ensuring the successful long-term containment properties of the engineered system and in diluting residual radionuclides dissolved in groundwater emerging from the engineered system, is described.

3.3 The evidence in Section 5 reflects the results obtained up to early 1994 on the geology and hydrogeology of the Sellafield site that are important to the movement of groundwater which could contain radionuclides released from the repository. The possible implications for repository performance of the results that have been obtained since early 1994, as presented in Dr. Chaplow's evidence (**PE/NRX/14**, Section 6), are also considered in Section 5. This evidence shows why Nirex considers the Sellafield site as offering good promise as a potentially suitable location for a repository and, therefore, why it is justified to secure further information on the site through investigations in the RCF.

3.4 My evidence shows that although the good promise of the site can be established, there remain key uncertainties which require to be addressed in the RCF to enable Nirex to decide whether or not to propose development of a repository at Sellafield.

3.5 The evidence in Section 6 specifies the further information required to address these key uncertainties which can only be acquired from the RCF. Dr. Mellor's evidence (**PE/NRX/16**, Sections 4 and 5) describes how the RCF needs to be developed and operated to deliver this information.

3.6 My evidence in Section 7 considers the potential for the excavation of the RCF, and of its shafts in particular, to impact upon the performance of a repository subsequently located within the Borrowdale Volcanic Group of rocks ('BVG') of the Potential Repository Zone ('PRZ') at Sellafield. It shows that there is a sound basis for the proposed location of the shafts and excavation methods.

4. APPROACH TO POST-CLOSURE PERFORMANCE ASSESSMENT

4.1 This Section describes the approach under development by Nirex to assess the post-closure performance of a deep geological repository at Sellafield. The term 'post-closure' refers to the period from the end of repository operations when, all the repository vaults having been filled with packaged wastes, the accesses to the repository are backfilled and sealed. 'Assessment' is the identification and modelling of the processes and pathways by which radionuclides from the repository may subsequently return to the biosphere and to people.

4.2 Performance assessment makes extensive use of models. Development of assessment models has been built around three major pathways for the possible return of radionuclides to the biosphere and to people :

- transport of radionuclides in groundwater;
- migration of radionuclides in gases; and
- return of radionuclides to the environment as a result of natural disruptive events or inadvertent human intrusion.

For a repository at Sellafield the most important pathway, in radiological terms, is the groundwater pathway. This is because each of the various radionuclides in the wastes might be transported in groundwater whereas only a small number could be transported as a gas. Also the transport of radionuclides by the groundwater pathway generally provides the framework for considering the effect of natural disruptive events or inadvertent human intrusion, except in the low probability scenarios of direct return of the contents of the repository by such means.

Groundwater Pathway

4.3 When the repository is first closed, it will contain air (for example in the pores of the cements used to immobilise the wastes, and in any unfilled spaces within the repository) which will, in time, be displaced by inflowing groundwater. Thereafter, subject to the performance of the engineered barriers of the repository, radionuclides will eventually dissolve or disperse in the water and be available to move into the surrounding rock. The extent to which the radionuclides come into contact with water, the extent to which they dissolve and their ability to move with the groundwater will each be controlled by the physical and chemical conditions in the engineered barriers of the repository.

4.4 The engineered barriers are designed to contain as much of the radioactivity as is reasonably practicable. This is achieved by providing physical containment barriers to movement of radionuclides, which are expected to operate for at least one thousand years after repository closure in respect of waste packages containing most of the radioactivity, and chemical containment, operating over a period of around one million years, which will limit the solubilities, and provide sorption, of radionuclides in groundwater moving through the repository.

4.5 The levels of the radiological effects of any radionuclides that are not contained by the engineered barriers and which reach the surface in groundwater will be determined largely by the concentrations of the radionuclides in solution. The limitation of radionuclide solubilities and the slow release of groundwater from the repository are of great importance because they determine the extent to which further reductions in concentrations must occur, through processes of retardation, spreading and dilution in the geosphere, for the repository system to be acceptably safe.

4.6 Once the radionuclides in the groundwater have passed from the repository into the successive layers of surrounding rocks, their rates of transport to the surface will be determined by the path taken by groundwater flow through the rocks, the time taken for water to travel along this path, and by various physical and chemical processes that lead to retardation and spreading. The groundwater from the repository will mix with groundwater in the surrounding rocks leading to dilution of the dissolved levels of radionuclides. The extent of dilution will not be determined solely by the amount of groundwater flowing through the overlying rocks, relative to that flowing through the repository. The spreading in space and time of the transport of repository-derived radionuclides in groundwater through each rock layer will increase the dilution afforded by their mixing with larger volumes of water in the succeeding rock layer.

4.7 Eventually groundwater containing repository-derived radionuclides will reach shallow regions of the rock, which may be considered to be at the boundary with the biosphere. On crossing this boundary and entering the biosphere further dilution, retardation or dispersion can occur by mixing with surface water (streams, lakes and the sea) or soils. Radionuclides could become available for uptake by people by their entering the food-chain, by their consumption in drinking water or by their inhalation in dust particles.

4.8 The concentrations of radionuclides, both in the groundwater pathway at its various stages of returning radionuclides to the surface and in the components of the biosphere, can be calculated on the basis of an understanding of the controlling physical, chemical and biological processes. The need is to calculate the potential uptake of radionuclides by people, living now or in the future, as a function of time. From a knowledge of the uptake of radionuclides through the various potential routes available, a total radiological annual 'dose' to hypothetical individuals can be calculated. This is subsequently converted to 'annual individual risk' using a dose to risk conversion factor of 0.06 per Sievert.

4.9 The times of the emergence of radionuclides in the biosphere and their concentrations will vary according to the controlling physical and chemical processes relevant to each radionuclide. The maximum concentrations of individual radionuclides returning to the biosphere will not coincide in time unless they have very similar physical and chemical properties. The total risk and the contributions of individual radionuclides are typically presented in graphs of annual radiological risk to an individual through time. The peak values shown on these graphs may be compared with the radiological risk target announced by the Government in its *Review of Radioactive Waste Management Policy, Final Conclusions, Cm 2919, July 1995* (*"the July 1995 White Paper")* (para 78, page 22) [GOV/208]. At the current stage of the project, calculations of risk are viewed as the best means of informing a judgment about the safety of a facility, in line with the statement in *the July 1995 White Paper*. However, it is recognised that in the future other technical factors, including ones of a more qualitative nature, will also need to be considered in arriving at the decision.

Assessment Models

4.10 The top-level tool used by Nirex for calculating radiological risk from the groundwater pathway is the computer program called MASCOT and its associated output processor MOP. MASCOT has been developed to carry out probabilistic safety assessments, in line with practice in other countries, for evaluating the safety of radioactive waste disposal systems. It takes proper account of the uncertainties associated with the values of important parameters which influence system performance. It employs the 'Monte Carlo' method in which repeated calculations of system behaviour are made using random sampling from specified probability density functions of the model parameters which are subject to uncertainty. The results provide estimates of the mean and distribution of calculated doses and associated risks.

4.11 MASCOT comprises sub-models describing the behaviour of the sub-systems of the overall repository system. These are designed to model the various processes involved in release of radionuclides from waste packages, their mobilisation and migration from repository vaults, transport through the geosphere and biosphere and consequent doses and risks to individuals. Input information for sub-models is derived from a variety of sources, including the output from more detailed models of the system, as described below.

Source Term Model

4.12 The "source term" model describes the behaviour of radionuclides in the repository vaults and calculates the rate of their release as solutes in flowing groundwater. Sub-models are used to represent different sections of the repository with different characteristics. The key processes considered are physical containment by the waste package, radioactive decay and ingrowth of decay products, solubility limitation, and sorption onto the vault backfill. The source term model is supported by a number of research models, such as RARECAN, CRACK 2, CHEQMATE and HARPHRQ, which address the key physical and chemical processes in more detail. The MASCOT source term model calculates the concentration of radionuclides in solution in the near-field groundwater as a function of time. (The near field of the repository is the part of the system comprising the waste packages, the backfill surrounding the packages and the seals used to close off the vaults. The near-field groundwater is the water within the porous structure of the backfill.) The near-field groundwater is available for transport into the geosphere at a rate dependent on the groundwater flow through the repository. (This is usually measured as the volume in m^3 per year of groundwater flowing through the repository volume.)

Groundwater Flow and Radionuclide Transport Through the Geosphere

4.13 The geosphere sub-models describe the behaviour of radionuclides as they are transported in groundwater flowing through the geosphere. The primary groundwater flow system through fractured rock, such as the BVG, comprises a network of connected fractures which can be represented on a number of scales. On the regional scale - tens of square kilometres - effective properties of the BVG and surrounding rocks are modelled using a continuum approximation to the flow system utilising the program NAMMU. At a repository local scale - of order ten square kilometres - a more detailed fracture flow model, NAPSAC, is employed.

4.14 Both NAMMU and NAPSAC permit multi-dimensional groundwater flow calculations and are used to provide values of the flow of groundwater through the repository, and of the groundwater flow path lengths and transit times across each of the hydrogeological units in the flow path. The groundwater flow through the repository is measured in cubic metres per year through the full volume of the engineered repository openings of approximately one million cubic metres. It must be assessed reliably because it is an important input to the source term sub-model in MASCOT. In addition, geosphere flow-path lengths and water transit times are required for the geosphere transport sub-models in MASCOT.

4.15 The transport sub-models within MASCOT calculate radionuclide transport through different parts of the geosphere taking account of radionuclide decay and ingrowth, advection, diffusion, hydrodynamic dispersion, and retardation by sorption. In addition, radionuclide transport can be retarded by diffusing into the pore space in the rock matrix.

Biosphere

4.16 The biosphere sub-models of MASCOT are essentially a series of flux-to-dose rate conversion factors which enable the geosphere calculations of time-dependent radionuclide fluxes into the biosphere to be converted into doses and risks to individuals. For most radionuclides a compartment model, BIOS, developed by the National Radiological Protection Board, is used to simulate the processes contributing to radionuclide transport and accumulation in terrestrial and marine environments. However, for some key radionuclides (chlorine-36, iodine-129 and uranium-238 and its daughters) a heterogeneous resource area model has been developed to permit a more detailed representation of the behaviour of the radionuclides in the biosphere. The development of this model has been guided by a more physically realistic catchment model generated by the computer code SHETRAN-UK which has been developed by Nirex, in conjunction with the Water Resources Systems Research Unit at the University of Newcastle. An integral part of the biosphere modelling is definition of critical groups. These are defined as being representative of those members of the assumed future communities that incur the largest annual Effective Dose from radionuclides present in the environment. The calculations of Effective Dose make use of models developed through the International Commission on Radiological Protection so that potential health risks to individuals can be calculated. Given the timescale over which releases are calculated to occur, significant changes in the climate are projected to arise as a result of glacial cycling: sea levels and human behaviour are predicted to change accordingly. Critical group behaviour is defined on the basis of the behaviour of existing communities in regions of the world which currently have analogous climate states. Many potential exposure routes are addressed, ranging from human consumption of contaminated water through to complex food-chain pathways.

Assessment Cycles

4.17 The key steps in assessment of the post-closure performance of a repository will be repeated several times before a decision is sought from the regulatory authorities to approve the start of disposal operations in a repository, following its construction and commissioning. This iterative process is known as the 'assessment cycle' as described in *Nirex Report 525, Scientific Update 1993, December 1993* (sub-section 5.2, pages 30 to 31) [COR/505].

4.18 One important function of an assessment is to calculate system performance for comparison with regulatory requirements to judge whether or not the system under assessment has the potential to meet them. A major, complementary output is a clearer understanding of the issues that are important to system performance. Identification of those issues helps to identify priorities for further data acquisition, on waste or site characteristics for example, for model development, and for refinement of repository design.

4.19 The presentation, in Section 5 of my evidence, of preliminary results on the post-closure performance of a repository located in the PRZ at Sellafield is intended to show our current understanding of the important issues. This understanding will develop and become more complete as assessment cycles are conducted in the future.

5. REPOSITORY PERFORMANCE AT SELLAFIELD

5.1 In this section of my Proof of Evidence I describe the calculated performance of the engineered and natural barriers to radionuclide transport afforded by a repository located in the BVG rocks in the PRZ at Sellafield. The natural barrier provided by the rocks surrounding the repository is of particular importance as this must ensure that the required chemical conditions can be maintained in the near field of the repository to contain most of the radioactivity, and that any residual long-lived radionuclides that are not contained in this way do not migrate to the surface environment in concentrations which would pose radiological risks exceeding regulatory requirements.

5.2 My evidence identifies the key characteristics of the Sellafield site which bear on assessment of the post-closure performance of the repository system. It is shown that the information and results from the Science Programme so far suggest the Sellafield site holds good promise as a potentially suitable location for a repository, but there are uncertainties which need to be addressed before a decision is taken on whether to propose development of a repository.

Disposal Inventory

5.3 The current planning basis for the repository is that it will receive for disposal 300,000 m^3 of solid, packaged intermediate-level radioactive wastes and 100,000 m^3 of solid, packaged low-level radioactive wastes up to the year 2060. The radionuclide content of this total volume of 400,000 m^3 of wastes is referred to as the "disposal inventory" and information on this content and the content of associated materials that may affect repository performance is taken from information compiled jointly by the Department of the Environment and Nirex on radioactive waste arising in the UK (*DOE/RAS/92.010, UK Nirex Report No. 284, The United Kingdom Radioactive Waste Inventory, November 1992 ("the 1991 National Inventory"*) [COR/520].) (See also: *DOE/RAS/92.011, UK Nirex Report No. 285, The Radionuclide Content of UK Radioactive Wastes, November 1992; and DOE/RAS/92.012, UK Nirex Report No. 286, The Physical and Chemical Characteristics of UK Radioactive Wastes, November 1992,* which are referred to as sources of information.)

5.4 The disposal inventory may be sub-divided into two broad categories of radionuclides according to their radioactive decay half-lives. Much of the disposal inventory is comprised of relatively short-lived 'fission products' such as strontium-90 and caesium-137 or 'neutron activation products' such as nickel-63, having radioactive decay half-lives of around 100 years or less. (Fission products are the result of the nuclear fission of elements such as uranium or plutonium, as used in the fuels of nuclear reactors. Neutron activation products result most commonly from the capture of neutrons by stable atomic nuclei, to create unstable nuclei which subsequently undergo radioactive decay).

5.5 The second category comprises radionuclides having radioactive decay half-lives from hundreds to millions of years. Many of these are heavy metal elements such as plutonium, which are very insoluble in the alkaline and chemically reducing ('low Eh') near-field conditions. These long-lived radionuclides include three having radioactive decay half-lives, of hundreds of thousands of years or more, which prove to be of great importance to the calculated performance of the deep repository. These are chlorine-36 with a half-life of 300,000 years; iodine-129 with a half-life of over 15 million years; and uranium-238 with a half-life approaching 4,500 million years. In order to understand the results of risk calculations reported in this Proof of Evidence, it is helpful to note that a 'daughter' radionuclide, radium-226, produced by the decay of the uranium-238 'parent' is of much greater radiological significance than the uranium-238 itself.

Key Radionuclides

5.6 The more important radionuclides in terms of their radioactivity content and relevance to the safety of disposal are listed in order of atomic number and according to radioactive decay half-life in Table 5.1. The sources of the three radionuclides found to be of greatest importance are outlined in rather more detail in the following paragraphs.

5.7 Chlorine-36 derives principally from neutron activation of naturally occurring chlorine, which is present as a trace impurity in various materials in nuclear reactors. Accordingly it is likely to be present in small quantities in many waste streams. Seven waste streams have been identified as the main sources of the radionuclide. They contribute about 65% of the total 16.6 TBq of chlorine-36 in the disposal inventory and have a volume of about 50,000 m^3. Because of the significance of this radionuclide in evaluations of repository post-closure performance, it is considered important to take account of uncertainties in the quantities present in the disposal inventory, as reported in *Nirex 95* (Volume 3, Table 6.3, page 6.25) [COR/522]. The value of 16.6 TBq is the central case determined for that exercise.

5.8 Iodine-129 derives from nuclear fission and it will be present in small quantities in a wide range of wastes. However, four waste streams contribute about 50% of the projected total of 0.92 TBq, having a total volume of about 500 m^3.

5.9 Uranium-238 is a major constituent of reactor fuel and will be present in small quantities in a wide range of wastes. Seven waste streams contribute about 55% of the total 36 TBq, having a total volume of about 37,000 m^3.

Packaging

5.10 Intermediate-level wastes intended for disposal will be immobilised within packages to produce the 'wasteform'. Most intermediate-level wastes will be packaged as unshielded wasteforms. Standard unshielded intermediate-level waste containers are predominantly drums or boxes fabricated from stainless steel, or in some cases carbon steel. The 0.5 m^3 capacity drum is the most commonly used container and larger drums or boxes typically have a capacity of 3 m^3. The waste is immobilised within the container, typically using a cement-based grout to produce a solid wasteform. The principal waste packages for shielded intermediate-level wasteforms are concrete boxes, having a length of approximately four metres, in which the waste is again immobilised in a cement-based grout.

5.11 Low-level wastes make a very small contribution to the radioactivity content in the disposal inventory (less than one part in 10,000). Typically they will be packaged into carbon steel boxes, having a length of approximately four metres. It is currently envisaged that the waste will not be immobilised within the container.

Physical Containment

5.12 Physical containment features include the initial prevention of access of groundwater to the radionuclides in the wastes and subsequent limitation of the movement of groundwater containing dissolved radionuclides away from them. The principal factor contributing to physical containment is the integrity of the waste containers. Other contributions are obtained from the inaccessibility of radionuclides in the wastes themselves, for example where their release requires the complete corrosion of large steel components, and from the limitation of movement of dissolved radionuclides by diffusion through the immobilising grout inside the containers.

5.13 More than 99% of the radioactivity in the disposal inventory will be present in the unshielded wasteforms contained in drums or boxes made of stainless or carbon steel. The resistance of these steel containers to corrosion under repository conditions is therefore important to the physical containment of radionuclides.

5.14 The general corrosion of steels is reduced by the presence of an alkaline water chemistry. This is an important benefit of surrounding the waste containers by Nirex Reference Vault Backfill which is designed to maintain water in its pores at a high pH (where high pH is an alkaline condition, low pH an acid condition). Corrosion is also very slow under the anaerobic conditions that will prevail in the repository after the initial volume of air has been displaced by inflowing groundwater and any residual oxygen in the water has been consumed by aerobic corrosion.

5.15 Under anaerobic conditions, steels are subject to corrosion which affects the entire surface of the metal, rather than at localised points. Typical results obtained from long-term research work carried out under deliberately extreme conditions of temperature (up to the maximum of 80C that might be reached for a short period of time in the repository) and representative conditions of water chemistry in the engineered barrier system of a repository at Sellafield show that the corrosion rate will be less than one micron per year. Using these and other data obtained from the research programme the average time for a metal container to be corroded through has been calculated to range from 9,000 to 16,000 years for the case of a stainless steel 0.5 m^3 drum, as reported in *Nirex Science Report S/95/011, Nirex Safety Assessment Research Programme, Nirex Near-Field Research: Report on Current Status in 1994, July 1995* (Sub-section "Container Lifetime Assessment", page 16) [NRX/15/1].

5.16 Research has been carried out to determine the effects on physical containment of the engineered gas vent in some designs of waste container and of localised corrosion which can affect carbon steels under the initially aerobic conditions in the repository. In these cases, there is no significant loss of containment even if saturation by water were established through the resulting small penetrations of the container. The release of radionuclides from the wasteform to the backfill outside the container is limited by the low rates of diffusion through the immobilising grout surrounding the waste.

5.17 The decay of the radioactivity in the disposal inventory is shown as a function of time in Figure 5.1. This shows that more than 95% of the radioactivity would be decayed after 300 years. It also shows that if physical containment is conservatively assumed to operate for one thousand years, the major part of the radioactivity (about 99%) would decay while contained within the physical barriers afforded by a repository under the conditions found at Sellafield. The major contribution to this containment is the corrosion resistance of the steel containers in the water chemistry of Sellafield groundwater conditioned to high pH in the pores of the Nirex Reference Vault Backfill.

Chemical Containment

5.18 The Nirex Reference Vault Backfill surrounding the emplaced waste containers in the disposal vaults has been carefully specified to fulfil a number of requirements, namely :

- long term maintenance of alkaline porewater chemistry in order to maintain low dissolved concentrations of key radionuclides under the prevailing conditions of groundwater flow and geochemistry;
- long-term maintenance of a high active-surface-area for sorption of key radionuclides; and
- relatively high permeability and porosity both to ensure homogeneous performance (so that localised concentrations of materials in wastes do not exhaust the desired chemical conditioning and thereby locally reduce the containment performance) and to permit the escape of gas generated by chemical reactions in the repository.

5.19 Two important effects to be taken into account in assessing the performance at Sellafield of the chemical barrier provided by the backfill are :

- leaching of reactive components by groundwater flow; and
- reactions with groundwater constituents

These are each discussed in the following paragraphs.

5.20 Under the chemically reducing ('low Eh') conditions of the repository, the solubilities in water of several important radioelements such as plutonium can be reduced to extremely low values (10^{-7} mols m^{-3} in the case of plutonium) at pH values of between 9 and 10. The solubilities typically remain at these low levels at any higher pH values that may be realised in the repository. Accordingly, the chemical conditioning performance sought from the

Nirex Reference Vault Backfill in respect of reduction of solubility is to maintain a pH above 10 for the period of time during which the relevant radionuclides will decay to insignificant levels.

5.21 The maintenance of the porewater of the Nirex Reference Vault Backfill at a pH value above 10 is achieved by the dissolving into the groundwater of calcium hydroxide which is present in the cement and lime constituents of the backfill. The required pH will be maintained until this supply of calcium hydroxide has been exhausted. For a given length of flow path through a repository vault, containing a given amount of backfill, the rate of removal of calcium hydroxide is determined by the groundwater flow. For the proposed volume of about 80,000 m^3 of backfill in a typical repository vault having dimensions 550 metres long, 23.5 metres wide and a waste stack height of 12 metres, and for a groundwater flow through the repository of 140 m^3 per year - as calculated in *Nirex 95* (Volume 3, Sub-Section 2.3, page 2.12) [COR/522] from the hydrogeological data for the Sellafield site - simple calculation shows that the pH would be maintained at a value of greater than 10 for many millions of years.

5.22 It is important to understand whether the pH could be reduced more rapidly than implied by this simple calculation. This could occur in parts of the repository by concentration of groundwater flows through localised conductive features in the rock, leaving other parts of the repository with a correspondingly longer period at high pH. From the information presented on groundwater compositions in *Nirex Report 524, The Geology and Hydrogeology of the Sellafield Area : Interim Assessment : December 1993* (Volume 3, Tables 3.4, 3.5 and 3.7) [COR/517], it is also possible to identify a number of dissolved chemicals present at depth in the PRZ at Sellafield which are reactive towards cements. All of these are taken into account, alongside similar reactive chemicals in the wastes themselves or which would result from their eventual breakdown, in calculating the period of time for which a high pH would be maintained. The results obtained so far allow us to assume conservatively that the required pH value of 10 or more would be maintained throughout the repository for one million years.

5.23 The Nirex Reference Vault Backfill was designed to afford a large surface area in its pore structure for the sorption of radionuclides from solution in the groundwater. The value measured for pore surface area of 2.8×10^4 m^2 per kilogram of material is highly favourable in this respect. It is recognised that some chemical reactions could block off parts of the porous structure of the backfill material or that cracks could develop in the backfill and the crack surfaces become altered to give less sorption. None of the experimental work carried out using synthesised Sellafield groundwater and related modelling work has indicated any significant adverse effects. However, in current safety assessment studies, the sorption capacity has been reduced from the high values observed in experiments, to take account of uncertainties in this respect.

5.24 A convenient way of reflecting the physical and chemical containment afforded by the engineered barriers in the repository concept is to draw a graph of the "fractional release" of a radionuclide of interest as a function of time. The fractional release is that fraction of the total amount of the radionuclide in the initial disposal inventory that would be found in the geosphere at a given time. Its calculation takes account of release of the radionuclide from the engineered system of the repository and also of depletion of the radionuclide by radioactive decay. Low values of fractional release indicate a good containment performance by the engineered barriers.

5.25 Figure 5.2 shows the benefit of chemical containment by reduction of solubility, by sorption and by the combination of the two processes in the near field in terms of the fractional release to the geosphere from the disposal inventory of plutonium-239. It can be seen that the chemical containment performance that would be afforded by the action of the Nirex Reference Vault Backfill within the groundwater system in the BVG of the PRZ at Sellafield is calculated to limit the fractional release of plutonium-239 to approximately one part in two thousand. This explains why, in assessment studies of the post-closure performance of the total repository system, plutonium-239 is found to return to the surface environment in such low concentrations as to make no significant contribution to radiological risk, as shown in *Nirex 95* (Volume 3, Table 6.18, page 6.36) [COR/522].

5.26 Calculations of fractional releases for longer-lived radionuclides than plutonium-239 show that the chemical containment significantly limits their fractional release for very long periods of time (beyond one million years in the case of uranium-238.) A period of one million years, conservatively taken as the duration for the operation of chemical containment in a repository located in the PRZ at Sellafield, is marked on Figure 5.1. This shows that over 99% of the residual 1% of radioactivity present in long-lived radionuclides would decay during the period over which chemical containment, represented by conditioning the groundwater to a high pH, is maintained.

Natural Barrier

5.27 On the basis of the evidence that I have presented thus far, the natural barrier afforded by the BVG rocks in the PRZ at Sellafield would ensure a low fractional release, that is radiologically insignificant, of all but a small number of the longest-lived radionuclides, as a result of the physical and chemical containment by the engineered barriers of the repository in that location. In the case of uranium-238, having a half-life approaching 4,500 million years, the release to the geosphere would be limited for over a million years by the low solubility in the high pH water in the repository and sorption onto cement phases. However, two long-lived radionuclides, chlorine-36 and iodine-129, do not have the metallic character in their solution behaviour that leads to reduction of solubility in alkali solution, and in experimental work to date have been found not to sorb strongly to cement phases or geological minerals. Accordingly the behaviour of these radionuclides is modelled by assuming high solubilities and no retardation by sorption in the flow of groundwater from depth to the surface.

5.28 The further important role of the natural barrier, identified at the start of this section of my Proof of Evidence is to ensure that residual long-lived radionuclides that are not physically and chemically contained by the engineered barriers, representing around 0.01% of the initial radioactivity, do not migrate to the surface environment in concentrations which would pose radiological risks exceeding regulatory requirements. This requires that the dissolved levels of radionuclides will be sufficiently diluted to low concentrations in the groundwater eventually carrying them to the surface.

5.29 The extent of dilution is determined by :

- the quantity of water flowing in the near-surface rocks, into which groundwater bearing radionuclides from the repository moves;
- the area of near-surface rocks into which groundwater bearing radionuclides moves : the greater the area the larger the volume of water for dilution (spreading in space); and
- the time over which the radionuclides are released into the near-surface groundwater system. The spreading in time arises from the rate at which they are released from the repository (determined by flow of groundwater through the repository and the repository porewater concentrations determined by the physical and chemical barriers) and spreading in time during passage through the geosphere due to processes such as dispersion, sorption and rock matrix diffusion.

5.30 A further dilution is afforded if the discharge of groundwater from the geosphere occurs into surface water in the biosphere - in the form of streams, lakes or the sea - before becoming accessible to people.

5.31 For a repository located in the BVG rocks in the PRZ at Sellafield, the release from the repository of radionuclides such as uranium-238 can extend to over a million years as a result of solubility and sorption control in the engineered barriers and of the relatively low groundwater flow through the repository of 140 m^3 per year, as given at paragraph 5.21 of my evidence. Even for those radionuclides such as chlorine-36 and iodine-129 that may not be subject to solubility and sorption control, it would take more than a thousand years to flush the radionuclides out of the repository in a flow of 140 m^3 per year.

5.32 The principal source of dilution by mixing of repository-derived groundwater with groundwater in overlying rocks is provided at Sellafield by the Calder Sandstone. A simple calculation is carried out in*Nirex 95* (Volume 3, Subsection 2.3, page 2.12) [COR/522]. It showsthat dilution by a factor of about 600 would be achieved by assuming direct mixing of the flow of groundwater through the repository with the flow of groundwater discharging through an area equivalent to the plan area of the repository to surface from the Calder Sandstone. For the radionuclides chlorine-36 and iodine-129 the spreading in time resulting from the short duration of the source term compared to the geosphere travel time gives a greater dilution factor of about 2,000.

5.33 As concluded in *Nirex 95* (Volume 3, Sub-section 9.1, page 9.2) [COR/522] the groundwater flow models used in the reported assessment studies predict that groundwater flow from a repository located in the PRZ to the surface environment will emerge predominantly at the bed of the eastern edge of the Irish Sea. If sea levels were to remain as at present, the discharge at this location would be subject to a further and considerable dilution by sea water. As a consequence of these successive dilutions, the annual radiological risk to an individual for discharge of all radionuclides to the marine environment is assessed to be at least three orders of magnitude below the target of 10^{-6}.

5.34 This annual risk to an individual is an output from the models that I described in Section 4 of my evidence. The computed mean value of risk is plotted on a graph as a function of time. It is a mean value because of the use of probabilistic safety assessment methods in which the calculations are repeated a number of times, corresponding to the sampling of the allowed ranges of values for input parameters, and an arithmetic mean is taken of the resulting values for risk. The appropriate graph showing the base-case calculation of risk from marine discharge in a Temperate (as current) climate is produced as Figure 5.3, after *Nirex 95* (Volume 3, Figure 6.6) [COR/522].

5.35 Under present conditions at Sellafield, a small proportion of the discharge might occur to the terrestrial environment in association with incised river beds. Furthermore, the time taken for emergence into the sea bed would be such that the sea level could possibly be lower as a consequence of climate change, possibly placing the whole of the discharge in a terrestrial environment.

5.36 Three further curves are presented in Figure 5.3 for a terrestrial discharge under three different biosphere states, corresponding to Temperate, Periglacial and Boreal climates. On the basis of current understanding of global climate patterns, Temperate or warmer conditions are expected to persist at Sellafield for several thousand years. Beyond that time period, colder Boreal or Periglacial conditions need to be considered. For the purpose of model calculations, each climate state is assumed to persist over the full period evaluated.

5.37 The Boreal climate state will be associated with a lower sea level than the current sea level. Discharge is therefore likely to be terrestrial. The peak annual individual risks in the Boreal terrestrial state are 1.1×10^{-7} at twenty thousand years after repository closure and 3.3×10^{-7} at four million years after closure. In all calculations for discharges to a terrestrial environment, the maximum of the risk curve occurring at about twenty thousand years is attributable mainly to chlorine-36 (with iodine-129 making a contribution of around 4%), and that after more than a million years is attributable to the daughter radionuclides of uranium-238, in particular radium-226. Chlorine-36 is effectively transported to the surface at the same rate as the water in which it is dissolved and the peak at about twenty thousand years corresponds to the most probable value of calculated groundwater return time. The most significant component of the calculated risk is from radionuclides entering the food chain, particularly through milk derived from pasture-grazing cows.

5.38 Simple scoping studies were carried out to allow calculations of risk for 'agricultural wells' in *Nirex 95* (Volume 3, Sub-section 6.7, pages 6.18 to 6.20) [COR/522]. The preliminary estimate of peak annual individual risk is 1.7×10^{-6} on the basis of an assessment for chlorine-36 and iodine-129 only : these radionuclides are expected to dominate risk in the period before 10^5 years. It is found that iodine-129 is the major contributor.

5.39 As noted in *Nirex 95* [COR/522], further refinement of the assessment methodology will produce a better view of risk from agricultural wells. As for all the results in *Nirex 95* [COR/522], the calculations for agricultural wells reflect a reference repository design rather than an optimised system. If necessary, there is scope for taking specific waste emplacement and repository design measures to reduce the risks as part of the optimisation process which ensures that releases are as low as reasonably practicable. In the case of iodine-129, which is the main contributor to the risk, 50% of the inventory is contained in a limited volume of waste, about 500 m^3, as stated in paragraph 5.8. For such relatively small volumes of waste, there is flexibility to develop specific measures, which might be impractical for larger volumes of waste.

5.40. A number of variant calculations were reported in *Nirex 95* (Volume 3, Section 7, pages 7.1 to 7.18) [COR/522]. These showed that the risks calculated to arise from a repository at Sellafield were not greatly changed as a result of changes in the spreading time for radionuclide transport in the geosphere if the duration of their release from the repository remains constant (that duration is inversely proportional to the groundwater flow through the repository.) Similarly, the system is robust to changes in the duration of the release if the spreading time in the geosphere remains constant. It is only if the duration of the release and the spreading time in the geosphere both have values significantly lower than currently calculated that annual individual radiological risks in excess of the target of 10^{-6} were calculated in *Nirex 95* (Volume 3, Figure 8.8) [COR/522] to arise from natural discharges to the surface.

Gas Pathway

5.41 The gas pathway refers to the migration of radionuclides in gaseous form from the repository to the surface environment. The most radiologically significant processes have been calculated to involve the incorporation of carbon-14 from the disposal inventory in methane generated from microbiological degradation of wastes in the repository and the subsequent entry of this methane into the food chain, as noted in *Nirex Science Report S/94/003, Post-closure Performance Assessment: Gas Generation and Migration, November 1994 ("Nirex Report S/94/003")* (Section 4.1, page 20) [COR/509].

5.42 The carbon-14 inventory of 2,600 TBq represents less than 0.1% of the total disposal inventory. Scoping calculations have been carried out making the following simplifications that are believed to be highly conservative :

- all the carbon-14 in wastes that contain biodegradable material is converted to gas;
- maximum rates of methane generation are achieved simultaneously in waste packages throughout the repository;
- all the gas generated in the repository is transported instantaneously from the repository to the surface and therefore no radioactive decay occurs; and
- the gas does not spread out in the geosphere to emerge in the surface soils over a larger area than the repository.

This leads to fluxes of carbon-14 in methane entering the biosphere that are equivalent to annual risks to an individual of about 10^{-7}.

5.43 Work is also under way in the Nirex Safety Assessment Research Programme ('NSARP') to study the possible significance of gas-water interactions on radionuclide transport. As noted in *Nirex Report S/94/003* (Sub-section 3.3, page 16) [COR/509] much of the required information is now available but the RCF is intended to enable some of the required site-specific data to be acquired.

Natural Disruptive Events and Inadvertent Human Intrusion

5.44 As discussed in *Nirex Science Report S/95/004, Post-closure Performance Assessment, Human Intrusion and Natural Disruptive Events, July 1995 ("Nirex Report S/95/004")* (Sub-section 3.2, pages 12 and 13; Section 5, page 16) [NRX/15/2], the location of a repository in the BVG at Sellafield is likelyto afford a high level of isolation of the wastes from the effects of natural disruptive events, such as erosion and seismicity, and inadvertent human intrusion.

5.45 The principal form of inadvertent human intrusion considered to date has involved the radiological exposure of geotechnical workers or surface inhabitants as a result of inadvertent drilling of boreholes into the repository at some time in the future, when records of its existence may no longer exist. In terms of the relevant characteristics - the dimensions of a repository vault cross-section and the inventory of heavy metal radionuclides - the current repository concept correlates quite closely with that assessed for the human intrusion scenario for a repository in the PRZ at Sellafield in *PERA* (paragraphs 5.6.11 to 5.6.14, pages 36 and 37) [COR/501]. A peak annual individual risk from intrusion of less than 10^{-8} was given in Table 5.2 of that report. *Nirex Report S/95/004* (Sub-section 3.1, pages 9 to 12) [NRX/15/2] updates the information on mineral resources in the Sellafield location on the basis of the extensive investigations carried out by Nirex. There has been no finding of a significant new resource that would suggest a higher incidence of drilling than assumed in *PERA* [COR/501].

Potential Suitability of Sellafield as a Location for a Repository

5.46 The analysis I have presented above confirms the good promise of Sellafield as a potentially suitable location for a repository. The groundwater pathway is central to our considerations of repository safety and therefore requires to be well understood. If resolution of uncertainties, as identified in Section 6 below, confirms our current understanding of the groundwater system at Sellafield, then a repository could be developed in the BVG rocks of the PRZ which would meet regulatory requirements.

5.47 In particular, the predicted flow and composition of groundwater that would enter a repository located in the BVG rocks in the PRZ at Sellafield are consistent with the physical and chemical containment of all but a small fraction of the radioactivity in the initial disposal inventory. Just three radionuclides, chlorine-36, iodine-129 and uranium-238, are calculated to be released in quantities that result in significant contributions to the peak risk either from natural discharges or water abstraction in wells.

5.48 If conditions at the Sellafield site were to remain as at present, resulting in predicted discharge predominantly to a marine environment, these releases would have small consequences when compared with the risk target. For release of chlorine-36 to a terrestrial environment - and of iodine-129 in the case of agricultural wells - the groundwater system needs to provide dilution of levels of radionuclides in repository-derived groundwater sufficient to lead to calculated risks consistent with regulatory requirements. On the basis of the calculations carried out, it is judged that such dilution will be afforded by the hydrogeological system at Sellafield.

5.49 The strong chemical containment that will be afforded to uranium by the Nirex repository concept ensures that any significant migration to the surface of uranium-238 and its daughter radionuclides only occurs at times beyond about one hundred thousand years after repository closure, as shown in *Nirex 95* (Volume 3, Section 6.4, pages 6.10 to 6.12) [COR/522]. The very long radioactive decay half-life of uranium-238, approaching 4,500 million years, means that it will return to the surface eventually unless a process of mineralisation leads to its permanent incorporation in the constituents of the cement-based backfill or the host rocks. There is evidence that this may happen but Nirex is not yet sufficiently confident in the evidence to incorporate the process in safety assessments. It is of course this long half-life that accounts for the abundant natural occurrence of uranium-238 on the planet. Given the considerable uncertainties associated with numerical assessments over timescales of the order of a million years, a comparison with naturally occurring radioactivity is considered to represent a more effective way of demonstrating the containment performance of the system with respect to this nuclide, This approach is under development for use in future assessment studies. Nevertheless, the extension of the numerical assessments to times beyond one million years has produced a calculated annual individual risk of 3.3×10^{-7} for a Boreal climate state.

5.50 The presentation in my evidence of the containment performance of the barriers in a repository located at Sellafield enables the identification of aspects of the site where Nirex must be confident that the underlying judgments are correct and that the range of uncertainty has been narrowed sufficiently. These are :

- the groundwater flow into the near field of the repository, which determines the duration of chemical containment and the rates of release of radionuclides; and
- the dilution, during transport in the geosphere, of the dissolved radionuclides in the groundwater released from the repository, which determines the concentrations of radionuclides in groundwater reaching the surface environment.

5.51 The most probable value for the groundwater flow into the near field of the repository is predicted to be 140 m^3 per year as stated in paragraph 5.21. This value is consistent with maintenance of chemical containment in the engineered barriers of the repository for a million years and limits the release of uranium-238 to levels consistent with risks meeting regulatory requirements. This value is also consistent with sufficient spreading in time of the release of chlorine-36 from the repository to ensure its subsequent dilution to levels that are also consistent with risks meeting regulatory requirements. However, groundwater flows greater than this cannot be ruled out. It is noted in *Nirex 95* (Volume 3, Section 2.3, page 2.13) [COR/522] that on the basis of the current judgments about the networks of connected fractures in the BVG used to calculate the flow, a small probability exists that the flow could be 150 times greater (or indeed smaller). If it were found that the description of the networks of connected fractures giving a flow 150 times greater is a better representation of the fractures in the BVG, then a repository would probably not meet regulatory requirements.

5.52 Similarly, the most probable value currently predicted for the dilution of radionuclides in the geosphere is consistent with a repository performance meeting regulatory requirements. This dilution is highly dependent upon the path taken by groundwater from the repository to the surface environment. The modelled path is determined by the judgments concerning networks of connected fractures in both the BVG and the overlying sedimentary formations and we must be confident that these are correct also.

5.53 The relevant information on the geology and hydrogeology of Sellafield, available in most part by early 1994, was used in the calculations of risk reported in Volume 3 of *Nirex 95* [COR/522]. Dr. Chaplow presents in his Proof of Evidence (**PE/NRX/14**, Sections 5 and 6) the further information which has become available since then.

5.54 This further information has added to confidence that the site at Sellafield offers a stable geological setting which will provide a low groundwater flow through a repository located in the BVG and high dilution in the overlying rocks for radionuclides released from repository vaults. It includes information on groundwater chemistry indicating long residence times for the groundwater in the BVG, and results from the cross-hole testing and Borehole RCF3 Pump Test. These tests have provided information on the limited nature of the connections over extended length scales in the fracture systems in the BVG and have indicated little connection between the BVG and overlying sandstones. While models of the groundwater system have not yet been updated and implications for risk calculated, I consider that this later information broadly supports the basis of *Nirex 95* [COR/522] with some indications that the modelling in *Nirex 95* [COR/522] may have been conservative in its representation of networks of connected fractures in the BVG and overlying sandstones.

5.55 In Section 6 of my evidence, I describe the information needed from the RCF to build further confidence in our judgments before key decisions can be made in the deep repository development programme.

6. INFORMATION REQUIRED FROM THE RCF

6.1 In his Proof of Evidence, Dr. Holmes (**PE/NRX/13**, paragraph 6.21) notes that for present purposes two key decision points can be identified in the development of a repository:

- a decision by Nirex to propose development of a repository, which will lead to an application for planning permission to develop the repository and possibly, at about the same time, to an application for authorisation under RSA93; and
- a decision by the regulatory authorities, after completion of repository construction and commissioning, to approve the start of disposal operations.

Nirex will prepare assessments of the post-closure safety performance of the repository for each of these decision points. That prepared for the first decision point will necessarily be preliminary and will be filled out and finalised to enable the regulatory authorities to take a decision on approval of the start of disposal operations.

6.2 As described by Dr. Holmes in his Proof of Evidence, (**PE/NRX/13**, paragraphs 6.22 to 6.24), the information requirements for the different stages of post-closure safety performance assessment are somewhat different in character. This leads to the identification of two separate categories of information required. These have different timescales for delivery that are related to the two decision points identified above.

6.3 The RCF programme, comprising 3 phases, has been developed to deliver the information that is needed in accordance with these timescales. It is expected that Phase 1 of the RCF programme could deliver the information required in relation to a decision to propose development of a repository. In particular, as will be explained in the following paragraphs in this Section of my evidence, we need to obtain sufficient information to build confidence in key models used in assessments of repository post-closure performance and to enable confident extrapolation of descriptions of the rock mass and groundwater system across the PRZ for use in developing the repository design.

6.4 The confidence achieved by the end of Phase 1 of the RCF programme will be dependent upon the amount and nature of information that has been obtained at that stage. The information available will determine the extent to which models and extrapolations can be put to the test. The adequacy of this testing will be subject to rigorous review as part of informing a decision on whether to propose development of a repository. In the event that it is found inadequate, further information will be sought from one or both of the subsequent phases of the RCF programme. A possible scenario is that more information will be required on geological and hydrogeological characteristics accessible to an extent that is too limited in Phase 1 as a result of their orientation or spacing in relation to the shafts and connecting galleries. In that case the subsequent extension of the horizontal galleries of the RCF, and drilling out from those galleries, will be designed to overcome this limitation.

6.5 The first category of information, required to inform a decision on whether to propose development of a repository, relates to those factors which are most important in determining the suitability of the site as a location for a repository. These factors are our predictions of groundwater flow and dilution, the potential for natural or induced changes to create significant new pathways for groundwater flow, and repository design. The position that the Company considers it necessary to achieve in respect of each of these factors for the first decision point is as follows :

- confidence in our ability to predict groundwater flow and dilution and that these predictions are consistent with meeting regulatory requirements;
- confidence that construction of a repository at the site, or future naturally induced changes, would not result in new pathways for water flow which would significantly impair repository performance; and
- confidence in the basis for optimisation of repository depth, location, layout and orientation, and consequent confidence in cost estimates for repository construction.

The safety assessment to be prepared in relation to this decision point will be required to take account of the alternative scenarios for long-term evolution of the repository system and information on naturally induced changes will be important to establish the appropriate framework for such an analysis.

6.6 In the second category of information, required in relation to a decision by the regulatory authorities on whether to approve the start of disposal operations, are those factors which will have been addressed in the laboratory or at other research sites, but where it is likely that the regulatory authorities will require an in situ demonstration that the results are applicable to the repository site. Such information requirements are currently considered to relate to the following :

- processes that can influence the transport of radionuclides in groundwater in the geosphere;
- quantifications of long-term effects of the interaction of the repository system with the localised flows in the surrounding rocks; and
- finalisation of detailed design, including repository sealing measures.

6.7 Our work has indicated that the factors for which information is sought in this second category are not likely to determine the basic suitability of a site as a location for a repository. Repository safety is calculated to be less sensitive to the ranges of assumptions that can reasonably be made about these factors. However, the demonstration that these factors have been taken into account in a realistic manner is considered to be a necessary element of a finalised assessment of post-closure safety performance needed to inform a decision by the regulatory authorities on approval of the start of disposal operations. It is also considered that the second category of information will include that required to fill out the information supplied in the safety assessment, prepared at the first key decision point, and that this will be achieved through a process of further systematic validation.

6.8 The safety assessment prepared for the first decision point will need to address all the factors influencing the post-closure safety performance of the repository, but will identify specific remaining uncertainties and the steps that will be taken to resolve them. If a robust evaluation can be achieved by the end of Phase 1 of the RCF programme, then the further work in Phase 2 and Phase 3 of the RCF programme would continue to address remaining uncertainties, probably within the framework of a plan, agreed with the regulatory authorities, for the progressive supply of information leading to a decision on approval to start disposal of wastes in the repository.

6.9 The calculations that we have carried out in *Nirex 95* (Volume 3, Section 9, pages 9.1 to 9.4) [COR/522] indicate that a repository located in the BVG rocks in the PRZ at Sellafield could be developed which would meet regulatory requirements. This is conditional on the basis that judgments about the rock characteristics, leading to predictions of groundwater flow, are correct. The risk calculations are based on a conceptual model which contains a particular description of the networks of connected fractures controlling flow in the BVG. Uncertainties in the values of parameters describing the networks have been recognised by ascribing a range of values having different probabilities about a central value for each parameter.

6.10 Limitations on surface-based observations mean that we cannot measure the parameters of interest directly. Expert judgment has been used in developing the conceptual model and associated ranges of parameter values. It is recognised by Nirex and the experts involved in this exercise that different judgments could be arrived at, leading to different conceptual models with different ranges of parameter values around different central values. Some of these alternative models, albeit improbable, could lead to the prediction of high values for the flow of groundwater into the repository or low values for its dilution in the overlying rocks that would not be consistent with meeting regulatory requirements for post-closure safety of a repository.

6.11 The remedy is to subject these conceptual models to a process of validation involving forward predictions, using the outputs of these models, and testing these predictions against field observations. This process of validation can be used to achieve the following objectives :

- discrimination between alternative conceptual models of the same system using tests to measure directly some aspect of the system for which different predictions are given by the alternative models;
- refinement of a conceptual model where there is some uncertainty about one or more components of the model, or about the parameters associated with the model, and the predictions can be compared with test results to reduce or remove the uncertainty; and
- confirmation of a conceptual model as fit for its intended purpose in post-closure performance assessment studies through testing of the adequacy of its predictions.

This process is intrinsic to the Nirex programme of hydrogeological investigations, where modelling has been carried out to design the more extensive hydrogeological tests and to establish criteria for their successful implementation, and will be developed further for application in the RCF.

6.12 In developing the approach to model validation for the RCF programme, it is recognised that predictions of the parameters that largely determine overall system performance, such as groundwater flow through the repository and dilution of levels of dissolved radionuclides in the geosphere, cannot be tested directly. The validation testing of the component conceptual models that are combined to create the description of the overall system performance must be sufficiently rigorous, therefore, to build confidence in their application. This implies requirements for testing over a range of length scales and for acquiring sufficient test data to satisfy scientific opinion as to the adequacy of the process.

6.13 The RCF overcomes limitations of surface-based or laboratory investigations for validation in the following ways :

- the RCF would permit tests and observations in three dimensions and at a scale more directly comparable to that of the repository;
- specialised tests could be performed in situ, directly on specific features of relevance to repository performance and under geotechnical and hydrogeotechnical conditions which are closely comparable to those of the repository; and
- the RCF would allow direct, in situ, observation and measurement of the response to excavation of the potential repository host rocks and groundwater system on a scale, at a depth, and in a location which would provide information which can be directly related to the performance of a repository within the PRZ.

6.14 In his Proof of Evidence, Dr. Holmes (**PE/NRX/13**, paragraph 6.6) has identified that the information that the RCF will provide can be considered to address uncertainties in three main areas :

- groundwater flow and radionuclide transport;
- natural and induced changes to the geological barrier; and
- design and construction of the repository.

The nature of the key uncertainties will be explained under these headings in the following paragraphs. The information required to address them will be identified in terms of its categorisation in relation to the future developments of post-closure performance assessments to support the two decision points as discussed above. It will be explained why the information required can only be obtained through the underground access to the rock mass which will be afforded by the RCF.

Groundwater Flow and Radionuclide Transport

6.15 The performance of the engineered barriers of the repository in affording physical and chemical containment is dependent upon the flow and composition of the groundwater in the repository. The overall performance will determine the rate of transfer of dissolved radionuclides in groundwater out of the near-field of the repository into the geosphere.

6.16 The transport of radionuclides by the groundwater in the geosphere is dependent upon the characteristics of the rock that control groundwater flow and the physical and chemical processes that operate within the rock. The combined characteristics of the repository host rock and overlying rocks will determine the pathways taken by radionuclides to return to the surface and the concentrations at which they will emerge in the biosphere.

6.17 The first category of information required before a decision is made to propose development of a repository is to test assumptions made about the characteristics of the site in relation to :

- the calculated flow of groundwater into the repository; and
- the spreading in the geosphere of residual mobile or long-lived radionuclides from the repository in groundwater that reaches the surface environment.

6.18 The second category of information, required to be provided to the regulatory authorities to enable them to take a decision on whether to approve the start of disposal operations is to test that evaluations of processes having the potential to affect the transport of radionuclides have realistically estimated the effects on post-closure performance. Currently, three potentially important processes are identified where information is needed from the RCF:

- rock matrix diffusion;
- colloid transport; and
- gas migration.

In addition, the second category of information will include that required to fill out the information supplied on groundwater flow and on spreading and dilution in the geosphere in the safety assessment prepared at the first key decision point.

6.19 The information required on each of the identified subjects is described under separate headings in the following paragraphs.

Calculation of Groundwater Flow through the Repository

6.20 The calculation of groundwater flow through the repository is carried out on the basis of descriptions of the networks of connected fractures in the BVG rocks in the PRZ at Sellafield, as given in *Nirex 95* (Volume 1, Sub-section 5.2, pages 5.6 to 5.10) [COR/522]. It is considered that groundwater flow occurs predominantly in fractures existing in hard rocks such as the BVG. Further, it is considered that fractures are not uniformly distributed through the rock but that, as a result of natural processes in the geological evolution of the rock formation, several individual fractures can have developed together in connected networks. These networks would extend over greater distances than their component individual fractures and are therefore likely to be more significant in controlling groundwater flow through the rock.

6.21 The flow of groundwater through such a network of connected fractures is controlled by factors such as its overall length, the aperture of the individual fractures in the network, the ways in which they are connected together and the variability of these characteristics within the overall network. The flow of groundwater through a repository will be determined by the properties of these networks of connected fractures, by the number of them intersected by the disposal vaults and by the hydraulic pressure gradients driving water along them. The locations of the networks and the spacings between them are therefore also important information, as is the distribution of hydraulic pressures within the networks.

6.22 As described in *Nirex 95* (Volume 1, Sub-section 5.1.2, pages 5.3 to 5.5) [COR/522], the results of hydrogeological tests carried out in boreholes have been interpreted in terms of assumed intersections of the networks of connected fractures by the boreholes. Where such an intersection is assumed, the properties of the fracture network are inferred from the hydrogeological measurements. The maximum lengths of these features are put at many hundreds of metres and so an individual borehole having a diameter of about 150 mm would be intersecting only a small part of the overall system. This introduces considerable uncertainties which are recognised by Nirex in assigning a wide range of possible descriptions to the network of connected fractures and an associated wide range of values for the important properties.

6.23 The networks of connected fractures can be investigated over a greater lengthscale by means of cross-hole testing between different boreholes. Nirex has carried out such tests, culminating in the Borehole RCF3 Pump Test, as described by Dr Chaplow in his Proof of Evidence (**PE/NRX/14**, paragraphs 6.36 to 6.40). These tests have involved the generation of different possible descriptions of the networks of connected fractures, in the forms of alternative conceptual models. By comparing the predictions of these models with the results of testing, uncertainties concerning groundwater flows can be resolved to some extent and as noted in paragraph 5.54 the outcomes appear encouraging. However, the principal uncertainty, concerning the range of possible descriptions of the networks of connected fractures, will remain in the absence of direct observations and complementary testing of the networks.

6.24 The information required from the RCF is a description of the networks of connected fractures as the main groundwater flow channels in the BVG, and the range of values that should be assigned to the key properties of these features, based upon physical observations. Furthermore, the information obtained must be capable of extrapolation both in space, throughout the volume of the BVG rocks in the PRZ, and also in time, to validate the application of the resulting models in assessments of repository post-closure performance at long times into the future.

6.25 The RCF will allow such information to be obtained because it will afford the opportunity to carry out complementary activities in parallel. Direct observations can be made on the way in which individual fractures are connected to form extended networks. The properties of the individual fractures can be measured in parallel with the measurement of the properties of the connected system as described by Dr. Holmes in his Proof of Evidence (**PE/NRX/13**, paragraph 6.11).

6.26 The access to a large volume of rock containing the networks of connected fractures will allow observations to be made of their locations and of any association with other geological features such as faults. Relationships with recognisable geological structures and information on trends in the orientation and spacing of the features would allow the testing of this information against further observations and would attach greater confidence to the extrapolation through the rock volume.

6.27 Our current groundwater flow models do not fully reproduce the hydraulic pressure field that is deduced from borehole measurements. A significant factor in the current differences between observation and prediction may be the way in which the descriptions of the networks of connected fractures are used to calculate hydrogeological properties on a regional scale. A further model development is planned, possibly incorporating relationships between the depth and location of the networks and their hydrogeological properties, to address this issue. Sinking of the RCF shafts will provide information to test the validity of such models.

Spreading in the Geosphere

6.28 As described in paragraphs 5.28 and 5.29 of my evidence, the concentrations at which radionuclides will be present in groundwater reaching the surface environment will be determined by a number of factors including their rate of release from the repository and their spreading in time and space during passage through the geosphere.

6.29 The rate of release from the repository is largely determined by the groundwater flow through the near field of the repository (taking account of the containment afforded by the engineered barriers), where the RCF is intended to provide essential information.

6.30 The RCF is intended to provide information for use in determining the spreading in time and space of the transport of radionuclides in the BVG rocks and the overlying sedimentary formations. The spreading of radionuclide transport will be highly dependent upon the properties of the main groundwater flow channels in the geological formation. Thus, the information on groundwater flow channels in the BVG rocks sought from the RCF in relation to calculations of groundwater flow through the repository would be required for this second purpose also.

6.31 The other geological formation which is important in this context is the St. Bees Sandstone. A wide range of conceptualisations of the flow channels in this formation remains possible on the basis of the results obtained so far. At one extreme, this range includes approximately vertical connected fracture networks extending over large distances and possibly connected with fracture networks in the BVG. At the other extreme of the range is the possibility that horizontal bedding structures, produced by the sedimentation processes that created the sandstones, would force the groundwater flow in a horizontal direction.

6.32 The RCF will afford the direct observation of the structural characteristics of the St. Bees Sandstone, as exposed in the RCF shafts. The correlation of the observed large scale geological structures with observations of groundwater flow and hydrogeological responses in the monitoring boreholes nearby should enable us to distinguish between the possible descriptions. A description based upon physical observations could then be used to calculate the spreading in time and space for radionuclide transport through this rock formation.

Rock Matrix Diffusion

6.33 Radionuclides transported in groundwater along flow channels in rocks, may diffuse into the surrounding bulk rock matrix. This would have the effect of retarding the transport of radionuclides and also result in some spreading in the geosphere of the initial radionuclide release from the repository. The consequent access to sorption sites in the surrounding bulk rock matrix affords additional retardation to radionuclide transport. The nature and extent of the operation of rock matrix diffusion and sorption affects the calculated radiological consequences of the release of metallic radionuclides such as uranium-238 in particular.

6.34 Particularly in the BVG there are uncertainties as to the extent to which this beneficial process will operate. The uncertainties arise from uncertainties about the networks of connected fractures, the internal structures of the fractures themselves and the in situ diffusivity of the rock matrix.

6.35 The requirement for this information is placed in the second category, to be provided to the regulatory authorities to enable them to take a decision on whether to approve the start of disposal operations. Information on the process of rock matrix diffusion has been obtained from laboratory measurements and experiments on rock core samples. However, for the results of this research to be used with confidence it must be ensured that the measurements were applicable to the main flow channels and that important properties of the rock were not modified by their removal from the bulk rock at depth to a laboratory. The RCF is required to give direct access to, and measurements in, fractures identified on the basis of their groundwater flow properties, and to make these measurements in situ with relatively little disturbance of the rocks.

Colloid Transport

6.36 Colloids are small particles of matter which remain suspended in groundwater because they do not settle under gravity. If colloidal particles are present in sufficiently large concentrations and remain stable for a sufficient length of time they have the potential to cause an increase in the effective transport of radionuclides in groundwater by incorporating radionuclides from the near field. No conclusive evidence has been found to suggest that colloids would exist at significant concentrations in a repository at Sellafield. However, because of the known difficulties of taking undisturbed samples of groundwater to analyse for colloids, robust arguments are not available to demonstrate that colloids will not be present. The key uncertainties relate to the quantities of colloids present in Sellafield groundwaters and the transport of colloids in fractures in the rocks at Sellafield.

6.37 Considerable efforts are being made to collect good groundwater samples from the boreholes at Sellafield for colloid analysis including the drilling of boreholes without the use of drilling muds. Whereas the practical difficulties have been overcome successfully for the analysis of species in solution in groundwater, the ability to obtain reliable samples and analyses of the colloid population is hampered by the introduction of relatively large quantities of particulate matter from the materials of the sampling equipment and the fluids necessarily used to drill, test and sample the boreholes. The immediate accessibility of the rocks at depth in the RCF affords the opportunity to take undisturbed samples of known origins. This is because more specialised sampling equipment, including provisions for stabilising existing conditions, can be located precisely within a feature of interest. This benefit of working within the RCF is extended to more general geochemical sampling where a higher spatial coverage of sampling can be achieved than through the use of boreholes drilled from the surface.

6.38 Nirex will seek to generate relatively simple empirically based models of colloid transport based on experiments conducted using flow rates and fracture properties of interest. Given the requirements for direct access to the fracture system in conjunction with the need for a high level of control of the experimental conditions there is a particular necessity to carry out such experiments in the RCF. It is envisaged that these experiments would characterise the transport of different colloids relative to a conservative tracer (a substance that is readily identified and remains dissolved in water as a trace on its movement) within a single fracture that had previously been characterised.

Gas Migration

6.39 Our current understanding of processes relevant to gas migration through the geosphere has been developed through the NSARP experimental programme at Reskajeage Quarry in Cornwall. The experimental results have been used to develop and refine the modelling approach described in *Nirex Report S/94/003* (Sub-section 3.3, pages 13 to 16) [COR/509]. There are two aspects of gas migration for which in situ testing is needed to confirm understanding and validate models in order to increase confidence both in the evaluation of the gas pathway itself and in the assessment of the effect of gas migration on groundwater flow :

- the entry of the gas into the water-saturated fracture network, since it is necessary to be able to predict the maximum overpressuring that will be generated in the repository as a result of gas production, in order to estimate the potential for gas-induced fracturing of the repository or the surrounding rock; and
- the migration of gas through the disturbed zone around the repository and through the geosphere where issues to be considered are the mechanisms for gas migration and the associated potential for coupled gas-water flow, the gas pathways through the fracture network and the time taken for the gas to return to the biosphere. (This information is needed to identify the period over which gas enters the biosphere and to assess whether enhanced migration of contaminated groundwater is likely to occur.)

6.40 The requisite experiments concerned with gas entry pressures and gas migration in the BVG can only be carried out in the RCF because horizontal boreholes are required to intersect identified and characterised fractures and to examine some of the issues relating to the transport of the buoyant gas through the water-filled fracture network.

Natural and Induced Changes to the Geological Barrier

6.41 It is recognised that the site characterisation programme carried out by Nirex yields information on the present day geology and hydrogeology. The current regulatory requirements for a repository apply at any time in the future. Consideration must therefore be given to future changes to the geosphere barrier as a result both of natural processes, including tectonic and climatic processes, and of repository construction itself. The information required from the RCF again falls into the two categories determined by the decision point against which it is generated.

6.42 In order to inform a decision whether to propose development of a repository, information is required on the type and extent of natural changes that could occur at the site to confirm that these will not significantly impair the performance of the geosphere barrier in respect of groundwater flow and radionuclide transport. Similar information is required on the disturbance to the rock that will be caused by excavating the repository itself, which is termed 'excavation disturbance'.

6.43 In order to inform a decision by the regulatory authorities on whether to approve the start of disposal operations, information is needed from testing underground of the chemical disturbance in rocks surrounding the repository caused by contact with alkaline pore water from the cement-based backfill. Every effort will have been made to assess the extent and nature of this change to the rocks surrounding the repository in a conservative manner, using information obtained from laboratory and field experiments and from desk-studies. However, the complex and site-specific nature of the interaction requires validation to be obtained that its treatment in assessment studies is appropriate and does not lead to underestimates of the transport of radionuclides.

Natural Changes

6.44 Dr. Chaplow presents evidence (**PE/NRX/14**, paragraphs 7.6 to 7.26) that the system of flowing fractures in the BVG has remained stable for a long period of time. In particular, no evidence has been obtained for the creation of new flow paths at depth as a result of any seismic activity during the last several million years and the groundwater system at depth shows evidence that there have been no extensive changes as a result of climate-related events such as glaciation for over a million years. However, the RCF will be needed to validate this evidence by means of direct observations of associations of groundwater flows, mineral formation and geological structures at depth. Detailed examination of the fractures that are components of the main flow channels should allow the geological history of flow patterns to be established, particularly by dating the mineralisation that has occurred in association with flows. This palaeohydrogeological record can then be compared with the present day flow patterns to test whether significant changes have occurred in the past and may therefore occur in the future. On the basis of information obtained from borehole testing, this does not appear to be the case, but such a conclusion would only be reliable when greater confidence is obtained in the descriptions of the networks of connected fractures themselves through observations and measurements in the RCF.

Excavation Disturbance

6.45 The information that can only be obtained from carrying out work underground in the RCF relates to the disturbance of the geology and hydrogeology that will result from excavation itself.

6.46 Creating an excavation in rock at depth by any method removes material which was previously bearing some of the load of the adjacent and overlying rocks. Removal of this material therefore causes a redistribution of the stresses around the excavation. This redistribution may be accompanied by some physical movement of the rocks around the excavation, including movements on existing fractures and the creation of new fractures. This phenomenon is termed excavation disturbance. The excavation disturbance is confined to a volume, or zone, of rock which surrounds the excavation. This disturbed zone of rock surrounding shafts and drifts might provide additional paths for transport in groundwater of radionuclides from the repository. The issues are the hydraulic conductivity of the excavation disturbed zone and how far the zone extends from the excavation.

6.47 Currently, views as to the extent and nature of the excavation disturbed zone are based on past precedent of excavation projects at other sites and a knowledge of the in situ stresses and rock quality measured in Boreholes. On this basis, it is assumed that the hydraulic conductivity of the rock surrounding an excavation may increase by a factor of up to a hundred over a distance equivalent to twice the diameter of the excavation. This is believed to be a conservative description of the hydraulic characteristics and extent of the excavation disturbed zone. Scoping studies have shown that disturbance on this scale is unlikely to impair the performance of the repository and the effects of disturbance have not been included in assessment models on this basis. The information which is needed from the RCF is measurement of the hydraulic and mechanical characteristics of the excavation disturbed zone in the sandstones, Brockram and BVG to test the validity of this assumption.

6.48 It is found that the potentially important effects of excavation disturbance on groundwater flow characteristics are specific to the geological and hydrogeological setting and to the nature of the excavation itself. They are likely to vary as a function of depth and location because of the different mechanical loadings that will exist through the rock mass in three dimensions. Furthermore the effects, particularly in the long-term, are dependent upon a number of interacting processes.

6.49 The benefit of the RCF is that it will allow direct measurement and monitoring of excavation disturbance in the sandstones, Brockram and the potential repository host rock. In particular the important geological and hydrogeological properties of the rock surrounding the excavation can be determined before and after the excavation has been carried out and can be observed as a function of time in the post-excavation period. The monitoring is particularly important to build confidence in our understanding of the evolution of the excavation disturbed zone over time. To enable extrapolation over timescales of interest, the trends in further development of the disturbance will be determined. The response of the disturbed rock to mechanical loading such as borehole testing will be particularly helpful in this respect.

6.50 The disturbance caused by the excavation will provide a significant test of the understanding of changes that might result from natural processes. The stress redistribution that will occur during shaft sinking will be a useful analogue for natural events such as glaciation that might place a cycle of mechanical loading on the rock mass. The response of the groundwater flow system can be monitored to test the effects on the hydrogeological system of such an event.

Chemical Disturbance

6.51 A chemical disturbance will be produced in a volume of rock, or zone, around the repository by the alkaline fluid emanating from the Nirex Reference Vault Backfill. This chemical disturbance has the potential to modify the surfaces of fractures in the rock.

6.52 Information on this subject is currently obtained by conducting laboratory experiments on rock samples from Sellafield, by constructing mathematical models that couple groundwater flow and chemical reaction and by building confidence in the results of this work from comparison with observations on naturally occurring alkaline groundwater systems.

6.53 The essential role of the RCF is to provide the opportunity for calibration and validation of the mathematical models developed from the current programme to give the information required on the key issues listed. The RCF allows the detailed characterisation of identified flowing fractures to determine their structure and mineralogy, the variability of these properties and the precise compositions of groundwater in contact with the flow-wetted surfaces in the fractures. Once the fractures were characterised in this way, their accessibility in the RCF would allow the conduct of well-controlled validation experiments. The principal reactions involved are believed to be relatively slow and the experiments would build confidence in the trends of changes to the rock properties rather than determining the long-term characteristics of the disturbed zone by direct measurement.

Design and Construction of the Repository

6.54 The information required from the RCF on design and construction of the repository can again be placed in two categories determined by the decision point against which it is generated. In this area in particular, the information acquired for the decision to propose development of a repository will be refined for subsequent development of a finalised safety assessment.

6.55 In order to take a decision to propose development of a repository, the repository design must be developed sufficiently to provide a basis for the optimisation of repository depth. location, layout and orientation. This would allow decisions to be taken on these parameters, albeit allowing for finalisation of details in light of further investigations underground, including those associated with repository construction.

6.56 There is little doubt that a repository could be constructed and operated safely: the key issue is whether it will provide the long-term isolation and containment of radionuclides in radioactive wastes once it is closed. A sound basis for assessment of the post-closure performance requires that key aspects of the design related to transport of radionuclides can be defined. This responds to the requirement most recently restated in *the July 1995 White Paper* (para 78, page 22) [GOV/208] that best practicable means should be adopted to limit risk. For a deep geological repository this is taken to mean that, where there are options concerning the depth, location, layout and orientation of the disposal vaults within the host rock, the decisions taken must be justified.

6.57 It will be important to work within a framework, which has been discussed with the regulatory authorities, that establishes the basis for making these decisions and does not foreclose options by inappropriate developments.

6.58 The RCF is particularly valuable in allowing us to proceed in a step-wise fashion of investigation in the potential host rock to finalise the repository design. Dr. Chaplow describes in his Proof of Evidence (**PE/NRX/14**, paragraphs 8.13 to 8.16) a three-dimensional representational model of the PRZ rock mass that is currently under development. This will provide the framework of testing our understanding by each successive step of excavation and associated investigations represented by the phases of the RCF programme. Each step in developing the RCF and investigating the surrounding rock mass will be designed to create the minimum site disturbance required to gain the required justification for fixing an aspect of design through testing the rock mass model against the resulting observations. Thus any exploration by development of galleries in a horizontal direction out from the shafts will only be undertaken when there is sound justification for the depth at which this will occur from confirmation of the modelled rock characteristics. Further extensions of investigations away from the shafts will only be undertaken when there is sound justification for the eventual location and orientation of a repository. Care will also be taken that the nature of the investigations to fix these aspects of repository design would not compromise our ability to fine tune these aspects at the final stages of development of a repository itself.

6.59 Before seeking the approval of the regulatory authorities for the start of disposal operations, information must be obtained, for use in a finalised safety assessment, with respect to the methods of placing engineered seals, developed in laboratory facilities, in the required settings.

Repository Depth, Location, Layout and Orientation

6.60 Currently judgments concerning repository design are based upon interpretations of the rock mass and hydrogeology of the PRZ from information obtained from the programme of site characterisation. These interpretations do not yet enable us to take a firm view on the benefits to be obtained from particular depths, locations, layouts or orientations of the repository vaults within the PRZ.

6.61 Repository design (in particular depth, location, layout and orientation) would affect factors identified previously :

- the calculated flow of groundwater into the repository;
- the calculated spreading time for radionuclide transport in the BVG; and
- the mechanical and hydraulic characteristics of the excavation disturbed zone.

The information required is to develop an understanding of how these factors will vary as a function of interactions of different processes at different locations throughout the PRZ. In particular information is required that enables the extrapolation throughout the BVG rocks in the PRZ of the distribution of networks of connected fractures.

6.62 It might be envisaged, for example, that the repository could be located at a depth at which there were relatively few or even no networks of connected fractures sufficiently long to act as groundwater flow channels from the repository depth to the overlying sedimentary formations. Alternatively, the spacing and orientation of the networks of connected fractures might allow a layout of the repository vaults that minimised or wholly avoided intersections with them.

6.63 It is intended that the main RCF galleries will be created at the same horizon as the repository vaults. The RCF shafts are required to give access to these galleries and their depth will be determined by consideration of the following factors :

- the sufficiency of information available on taking the shaft to a certain depth through its intersections with an adequate number and type of geological and hydrogeological features of interest; and
- confidence that, taking remaining uncertainties into account, a repository could be developed at the selected horizon that would meet regulatory requirements.

6.64 The RCF shaft sinking provides for the validation of the prior understanding and associated models which will be developed to underpin the preliminary view on repository depth, currently put at 650 metres below Ordnance Datum ('bOD'). Those models will predict the information that will become available to test this view. The shaft sinking phase will have programmed into it a decision point at which the results to date will be evaluated to establish whether the understanding and models are confirmed. If so, the RCF galleries will be developed at the depth previously identified.

6.65 That decision point will provide for an updating of the understanding and modelling. The updating could indicate that further information is required to meet the scientific objectives of adequately validating the models or that a greater depth is appropriate for the optimisation of the repository. If so, the RCF shafts will be developed to the necessary depths. The maximum depth currently under consideration for the repository is 900 metres bOD and the shafts of the RCF would have to be sunk to a depth of 935 metres bOD (to provide for a sump) if this were found to be the optimised depth of the repository. The shafts might also be sunk to investigate depths of up to 900 metres bOD to provide sufficient information for model validation and a decision on repository (and hence gallery) horizon which could be at a lesser depth.

6.66 Given the intention to minimise the disturbance of the rock in making these investigations, it will not be practicable to carry out detailed investigations from the RCF throughout the PRZ. Instead, the investigations must be sufficient, in terms of the representative sampling of the rock mass, to give a firm understanding of the variability of key geological and hydrogeological characteristics of the rock mass. The understanding that is sought of the variations within the rock mass is to enable the variable characteristics to be predicted throughout the PRZ on the basis of other measurements from boreholes and various surveys. This will allow the required extrapolation across the rock mass to inform decisions on repository depth, location, layout and orientation.

6.67 An essential role of the RCF in providing this information is to allow the testing of our ability to carry out the required extrapolation. This would involve making predictions of the expected geological and hydrogeological characteristics on the basis both of previous investigations from the surface and of targeted drilling underground and then carrying out excavations to test these predictions. The finalised location of the repository vaults in the rock mass would be determined by interpreting the results of targeted drilling from the RCF. It is essential to gain confidence from such work in the RCF that, in any subsequent excavation of a repository, the information from prior investigations could be utilised successfully to confirm the important properties of the blocks of rock selected.

Sealing

6.68 The sealing requirements for the repository will be established in an iterative manner by assessment studies. This process allows the long-term performance requirement to be established for seals placed in various features of the repository system. This in turn translates to the required properties such as fluidity, durability or hydraulic conductivity (in set condition) at the time of placing seals. The achievement of the required properties relates strongly to the interaction between the materials and the precise geological setting specific to the site and location. The features that are currently considered are as follows:

- flowing fractures intersecting repository vaults (which are assumed not to be sealed in current models);
- large openings such as vaults, tunnels, drifts and shafts;
- disturbed zones surrounding excavated openings; and
- underground boreholes drilled from the proposed RCF itself.

6.69 The requirement is that this work should be carried out in representative geological settings, and in particular in the BVG at depth where the levels of in situ stress and rock quality will be appropriate. Furthermore the requirement is to allow a long lead-time for the seals to set and to establish an initial equilibrium in advance of using the results in support of a performance assessment. Therefore the validation that sealing requirements can be met can only be achieved by carrying out work underground in the RCF.

7. IMPACT OF THE RCF

7.1 In taking the decision to apply to develop the RCF, Nirex has given careful consideration to the potential of the RCF shafts in particular to affect the post-closure performance of a repository subsequently located within the PRZ because this is clearly a matter on which Nirex will have to satisfy the regulators at the appropriate stage of an authorisation procedure under RSA 93. Two issues are of particular relevance to these considerations:

- the location of the shafts relative to the eventual development of the repository vaults and accesses; and
- the method of excavation and the associated disturbance of the surrounding rock and hence of its hydrogeological properties.

7.2 For both these issues, the potential for effects on post-closure performance only exists if sealing materials cannot be placed in the openings and disturbances caused by the excavations to restrict groundwater flow and to maintain this barrier over long timescales. This is believed to be achievable but, because of the site-specific nature of sealing requirements, it is intended that suitable designs and specifications of seals will be demonstrated at a later stage of the programme. In order to progress to that stage, information will be used from a number of sources, including work that is currently under way in the Nirex Science Programme, relevant work previously carried out in other international programmes, and work that is proposed to be undertaken in the RCF. In the absence of this information the shafts have been evaluated in scoping studies as if sealed against the flow of groundwater to only a very low standard, equivalent to a compacted aggregate material. The results of these studies have shown no detrimental effect on transport of radionuclides and on this basis seals have to date not been included in assessment models.

Location of the Shafts

7.3 The key concern in respect of the location of the shafts is the possibility that they would provide a preferential pathway for groundwater flow that compromises the containment performance of the geosphere. Consideration has been given to various issues in this respect :

	i.	the potential for the shafts to intersect a major channel for groundwater flow from depth and to connect this to the surface environment;
	ii.	the potential for a driving force for groundwater flow from the vaults of the repository into the shafts;
	iii.	the potential for a driving force for vertical upward flow of groundwater in the shafts; and
	iv.	the potential for a U-tube groundwater flow system with the shafts conducting water into the repository and this subsequently being discharged into the inclined drift tunnels envisaged as the principal accesses to a repository at Sellafield.

7.4 Consideration of the hydrogeological conditions in the PRZ showed that the consequences of realising ii. or iii. would not be significantly affected by the choice of shaft locations. A pragmatic design solution is available to address iv. whereby there is sufficient flexibility in the routing of the inclined drifts that these could be arranged to arrive at the repository in close proximity to the shaft locations.

7.5 When the RCF was proposed in 1992, a good database was available for conditions at depth in the vicinity of the cluster of the boreholes into the PRZ, represented by Boreholes 2, 4 and 5. This gave no indications of a major flow channel that might connect with a shaft located at Longlands Farm and therefore gave confidence that the possibility at i. above was unlikely. The drilling of several further boreholes in this location and the interpretation of more detailed geophysical surveys, as reported by Dr Chaplow in his evidence (**PE/NRX/14**, paragraphs 4.6), have confirmed this prognosis.

7.6 The location of the shafts was determined to be in the north-eastern quadrant of the PRZ because this was interpreted to be upstream in relation to the overall direction of flow in that location, as reflected by the choice of cross-section for groundwater flow modelling reported in *Nirex 95* (Volume 3, Section 2.1.1, pages 2.2 to 2.3) [COR/522]. The location of the shafts at Longlands Farm, within the north-eastern quadrant of the PRZ, would allow sufficient horizontal distance between that location and the north-eastern boundary of the PRZ, for the inclined drift access envisaged for a repository to be brought around the shaft location to approach from upstream without going outside the PRZ.

Excavation Methods

7.7 The main concern in respect of the excavation methods chosen to develop the RCF is that these will disturb the rock in such a way as to develop preferential pathways for groundwater flow. The effect of excavation disturbance on groundwater flows is an important area of study proposed for the RCF. At this stage pragmatic assumptions have been made as to the effects, whereby the hydraulic conductivity of the rock is increased by two orders of magnitude to a distance into the rock surrounding the excavation equivalent to twice the diameter of the excavation. These are thought to be conservative assumptions. Moreover, as I noted in paragraph 6.47 of my evidence, scoping studies have shown that disturbance on this scale would be unlikely to impair the performance of the repository and the effects of disturbance have not been included in assessment models on this basis.

7.8 There is a good body of evidence from previous practice concerning the extent of excavation disturbance of rocks of different qualities as a function of key variables such as the diameter of the excavation and the excavation methods chosen on which to base these assumptions. When the assumed extent of the disturbance is combined with the chosen values for the increased hydraulic conductivity of the BVG within this disturbed zone there is calculated to be no significant effect on the movement of groundwater from depth to the surface. This analysis takes no benefit from any measures that might be taken to reduce excavation disturbance effects or to seal the disturbed zone subsequently.

7.9 It was originally envisaged that the shaft excavation would require the freezing of some part or all of the sandstone formations overlying the BVG. This would have required the introduction of a large number of drill holes around the shaft and possible disruption of the rock by freeze-thaw cycling. The replacement of this method by one where groundwater control is achieved by the preferred method of grouting would introduce a major reduction in the mechanical disturbance that would be caused, albeit that no significant impact upon groundwater flow was calculated to result.

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NRX/15/2
Nirex Science Report S/95/004, Post-closure Performance Assessment, Human Intrusion and Natural Disruptive Events, July 1995.

TABLE 5.1: INVENTORY OF RADIONUCLIDES IMPORTANT TO SAFETY OF DISPOSAL

I. Short-lived radionuclides with half-lives less than 100 years

Radionuclide	Half-life (years)	Radioactivity (TBq)
Hydrogen-3	12.35	52,000
Nickel-63	96.00	1,130,000
Strontium-90	29.12	151,000
Caesium-137	30.00	547,000
Plutonium-238	87.74	9,670
Plutonium-241	14.40	123,000

II. Long-lived radionuclides with half-lives less than 100,000 years

Radionuclide	Half-life (years)	Radioactivity (TBq)
Carbon-14	5,730	2,570.0
Nickel-59	75,000	14,100.0
Selenium-79	65,000	5.99
Niobium-94	20,300	1,020.0
Radium-226	1,600	11.1
Thorium-230	77,000	0.115
Protoactinium-231	32,760	0.0192
Plutonium-239	24,065	11.700.0
Plutonium-240	6,537	13,100.0
Americium-241	432	43,500.0
Americium-242m	152	35.5
Americium-243	7,380	21.7

III. Long-lived radionuclides with half-lives greater than or equal to 100,000 years

Radionuclide	Half-life (millions of years)	Radioactivity (TBq)
Chlorine-36	0.301	16.6
Zirconium-93	1.53	339.0
Technetium-99	0.213	318.0
Tin-126	0.10	4.16
Iodine-129	15.7	0.919
Caesium-135	2.3	8.72
Thorium-232	14,050	0.0784
Uranium-234	0.2445	62.4
Uranium-235	703.8	1.33
Uranium-238	4,468	35.8
Neptunium-237	2.14	61.0
Plutonium-242	0.3763	12.8

Footnotes

i.	Radioactivity given in TBq at time of repository closure (assumed 2060)
ii.	Total Inventory in 2060 is 14.17 x 10^6TBq. (The table does not list radionuclides that are so short-lived that they are not important for post-closure safety.)
iii.	Disposal inventory is derived from *the 1991 National Inventory* [COR/520].

FIGURE 5.1: RADIOACTIVE DECAY OF DISPOSAL - INVENTORY WITH TIME
(Click on image to see in full size)

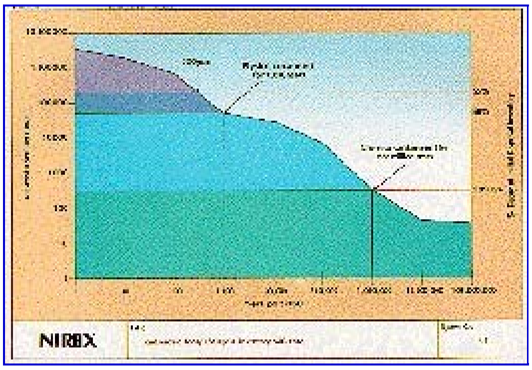


FIGURE 5.2: FRACTIONAL RELEASE OF PLUTONIUM-239 AS A FUNCTION OF BARRIER OPERATION
(Click on image to see in full size)

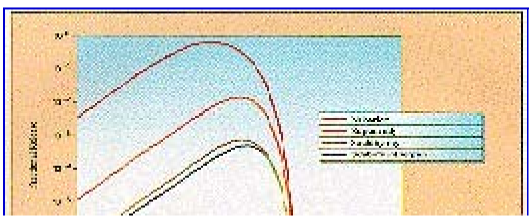
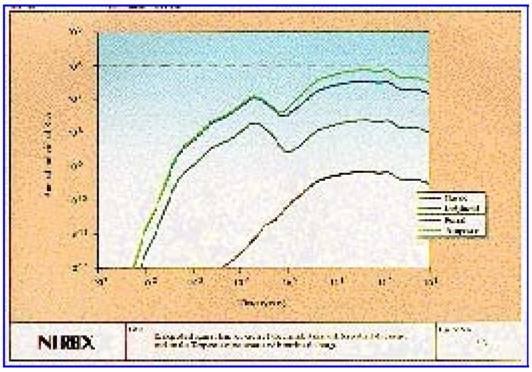


FIGURE 5.3: RISK PLOTTED AGAINST TIME FOR EACH OF THE CLIMATE STATES WITH TERRESTRIAL DISCHARGE, AND FOR THE TEMPERATE CLIMATE STATE WITH MARINE DISCHARGE
(Click on image to see in full size)



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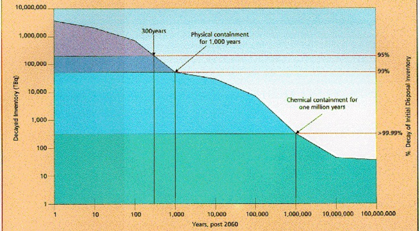
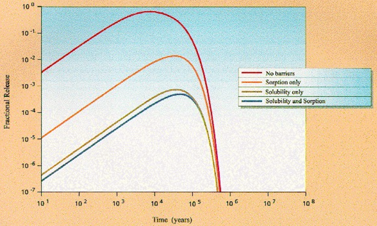
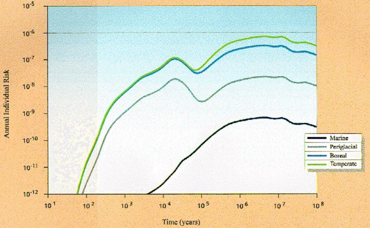


NIREX	Title Radioactive decay of disposal inventory with time	Figure No. 5.1



NIREX	Title Fractional release of plutonium-239 as a function of barrier operation	Figure No. 5.2



NIREX	Title	Figure No.
	Risk plotted against time for each of the climate states with terrestrial discharge, and for the Temperate climate state with marine discharge.	5.3