TECHNICAL REPORTS SERIES No. 413

Scientific and Technical Basis for the Geological Disposal of Radioactive Wastes

INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA, 2003

SCIENTIFIC AND TECHNICAL BASIS
FOR GEOLOGICAL DISPOSAL
OF RADIOACTIVE WASTES

The following States are Members of the International Atomic Energy Agency:

AFGHANISTAN
ALBANIA
ALGERIA
ANGOLA
ARGENTINA
ARMENIA
AUSTRALIA
AUSTRIA
AZERBAIJAN
BANGLADESH
BELARUS
BELGIUM
BENIN
BOLIVIA
BOSNIA AND HERZEGOVINA
BOTSWANA
BRAZIL
BULGARIA
BURKINA FASO
CAMBODIA
CAMEROON
CANADA
CENTRAL AFRICAN REPUBLIC
CHILE
CHINA
COLOMBIA
COSTA RICA
CÔTE D'IVOIRE
CROATIA
CUBA
CYPRUS
CZECH REPUBLIC
DEMOCRATIC REPUBLIC OF THE CONGO
DENMARK
DOMINICAN REPUBLIC
ECUADOR
EGYPT
EL SALVADOR
ESTONIA
ETHIOPIA
FINLAND
FRANCE
GABON
GEORGIA
GERMANY
GHANA
GREECE
GUATEMALA
HAITI
HOLY SEE
HUNGARY
ICELAND
INDIA
INDONESIA
IRAN, ISLAMIC REPUBLIC OF
IRAQ
IRELAND
ISRAEL
ITALY
JAMAICA
JAPAN
JORDAN
KAZAKHSTAN
KENYA
KOREA, REPUBLIC OF
KUWAIT
LATVIA
LEBANON
LIBERIA
LIBYAN ARAB JAMAHIRIYA
LIECHTENSTEIN
LITHUANIA
LUXEMBOURG
MADAGASCAR
MALAYSIA
MALI
MALTA
MARSHALL ISLANDS
MAURITIUS
MEXICO
MONACO
MONGOLIA
MOROCCO
MYANMAR
NAMIBIA
NETHERLANDS
NEW ZEALAND
NICARAGUA
NIGER
NIGERIA
NORWAY
PAKISTAN
PANAMA
PARAGUAY
PERU
PHILIPPINES
POLAND
PORTUGAL
QATAR
REPUBLIC OF MOLDOVA
ROMANIA
RUSSIAN FEDERATION
SAUDI ARABIA
SENEGAL
SIERRA LEONE
SINGAPORE
SLOVAKIA
SLOVENIA
SOUTH AFRICA
SPAIN
SRI LANKA
SUDAN
SWEDEN
SWITZERLAND
SYRIAN ARAB REPUBLIC
TAJIKISTAN
THAILAND
THE FORMER YUGOSLAV REPUBLIC OF MACEDONIA
TUNISIA
TURKEY
UGANDA
UKRAINE
UNITED ARAB EMIRATES
UNITED KINGDOM OF GREAT BRITAIN AND NORTHERN IRELAND
UNITED REPUBLIC OF TANZANIA
UNITED STATES OF AMERICA
URUGUAY
UZBEKISTAN
VENEZUELA
VIET NAM
YEMEN
YUGOSLAVIA, FEDERAL REPUBLIC OF
ZAMBIA
ZIMBABWE

The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world".

Printed by the IAEA in Austria
February 2003
STI/DOC/010/413

TECHNICAL REPORTS SERIES No. 413

SCIENTIFIC AND TECHNICAL BASIS FOR GEOLOGICAL DISPOSAL OF RADIOACTIVE WASTES

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2003

IAEA Library Cataloguing in Publication Data

Scientific and technical basis for geological disposal of radioactive wastes. —
Vienna : International Atomic Energy Agency, 2003.
p. ; 24 cm. — (Technical reports series, ISSN 0074–1914 ; no. 413)
STI/DOC/010/413
ISBN 92–0–100103–7
Includes bibliographical references.

1. Radioactive waste disposal in the ground. I. International Atomic Energy Agency. II. Series: Technical reports series (International Atomic Energy Agency) ; 413.

IAEAL 02–00310

FOREWORD

It has been the technical consensus of most waste management specialists for several decades that geological disposal, using a system of engineered and natural barriers, is the preferred means of disposal for high level and long lived radioactive wastes. However, geological disposal of these types of radioactive wastes has not yet been realized in any country, unlike disposal of low and intermediate level wastes, which has been practised for over fifty years. Most geological disposal programmes are the subject of debate and suffer delays as some sectors of society do not have confidence in this option.

While the debate is not yet closed on the issue, the progress which has been made in the scientific and technical aspects of geological disposal over the last decade provides assurance to the waste management community that sound technical solutions underpinned by good scientific investigation are available. Therefore, the importance of reporting at the international level on the scientific understanding and adequacy of knowledge related to the geological disposal concept convinced the IAEA to undertake the development of a technical report to provide Member States with the rationale and guidance that support the development of safe geological disposal systems.

This report focuses on the different functions that a repository is expected to assume in different periods of its life cycle and describes the processes relevant to the containment of the radionuclides in the repository and other processes which might affect the long term integrity of the different barriers. Building, operating and decommissioning a geological repository for long lived radioactive waste, including closure of all underground excavations, require considerable technical and scientific information to be used in every aspect of the conceptual approach, design, engineering and safety assessment of such a facility. This publication highlights in particular the central role of the safety case and discusses the use of safety/performance assessments in the decision making process during repository development.

Although a large part of existing knowledge is generic in nature and is derived from the earth sciences and from underground engineering work, much specific knowledge has been derived from the characterization of potential repository sites and from studies in underground research laboratories. The types and quality of results that have already been acquired are more specifically discussed in a companion document of this report, The Use of Scientific and Technical Results from Underground Research Laboratory Investigations for the Geological Disposal of Radioactive Waste (IAEA-TECDOC-1243).

This report was produced as a result of a number of Consultants Meetings and an Advisory Group Meeting. A list of the participants at these meetings appears at the end of the publication. The IAEA officers responsible for the report were J. Heinonen and M. Raynal.

EDITORIAL NOTE

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Radioactive wastes of all types need to be managed responsibly in facilities under institutional control to provide public safety, protection of the environment and security from accidental or deliberate intrusion [1, 2]. However, in the long run, long lived radioactive wastes need to be disposed of in a way that does not require continued institutional control. The concept of isolating long lived radioactive wastes from the human environment by placing them deep underground in repositories located in host rocks characterized by high stability and low or no groundwater flow, i.e. geological disposal, was proposed over 40 years ago [3]. Geological disposal concepts have been developed to the present level after considerable thought, R&D and debate, including societal and ethical considerations [4–11]. Alternative disposal options, such as disposal in subduction zones along the boundaries of the Earth's tectonic plates, in polar ice caps or even in space, have been rejected on the basis of generic assessments. Geological disposal of waste packages in the clay-rich sediments underlying the ocean floor, despite the extremely promising results of international studies carried out in the 1980s [12], is presently not considered a realistic disposal option owing to being prohibited by the London Convention [13].

Geological disposal is nearing implementation in several Member States and at least one geological repository located in bedded salt and destined to receive long lived waste with insignificant heat generation (WIPP in New Mexico, USA) is currently in operation [14]. Nevertheless, support is being voiced by some sectors of society for postponement of disposal and for more review of different waste management strategies, including long term storage and partitioning and transmutation. Requirements for and implementation of the reversibility of radioactive waste disposal in geological repositories are also being considered in various Member States [15]. While the debate is not yet closed on these issues, the progress which has been made in the scientific and technical aspects of geological disposal over recent decades gives assurance to the waste management community that this is a sound technical solution which is supported by good scientific understanding. This is a consequence of many years of scientific work carried out by numerous professional institutions around the world which have created the international basis for the demonstration and confirmation of the soundness of the geological disposal concept [16–26].

1.2. OBJECTIVE

The objective of this report is to review and discuss the scientific and technical knowledge which supports the development of geological disposal systems. It is expected that the report will provide Member States with an impartial view on the scientific basis and rationale of the geological disposal concept and the mechanisms to realize disposal and assess its safety. It should also provide some indication of the R&D requirements regarding some of the open issues mentioned in Section 1.1.

A large part of existing knowledge is generic in nature and is derived from the earth sciences and from underground engineering work. However, much specific knowledge has been derived from the characterization of potential repository sites, from studies in underground research laboratories and from the operation of underground repositories for the disposal of various types of waste, including hazardous wastes and low and intermediate level radioactive wastes (LILWs). Examples of LILW disposal facilities include those at Asse and Morsleben in Germany. Relevant knowledge has also been derived from natural analogue studies, from deep excavations and from hydrogeological and geochemical investigations carried out for a variety of purposes.

1.3. SCOPE

This report focuses on the identification of, and practical means to obtain and use, the necessary information at each stage of the development of a geological repository for solid radioactive wastes. The emplacement of the wastes can be carried out in different ways and various repository designs are possible. The different types of geological environment that have been considered for the disposal of radioactive wastes can contribute in different ways to the overall objective of ensuring containment of the radionuclides for the necessary period of time.

Geological repositories have the greatest potential for ensuring the highest level of waste isolation, and are considered applicable to the disposal of the most demanding categories of radioactive waste, including high level waste, spent nuclear fuel and other long lived radioactive wastes. Building, operating and closing a geological repository for long lived radioactive wastes, including closure of all underground excavations, require that considerable technical and scientific information be used in every aspect of the conceptual approach, design, engineering and safety assessment of such a facility.

Some Member States have made the decision that practically all radioactive waste containing non-negligible quantities of radionuclides, regardless of their half-lives, should be placed in geological repositories. Such repositories specifically designed for the disposal of LILW, for example the proposed Konrad facility in

Germany, are also within the scope of this report. Historic programmes in some countries, notably the former Soviet Union and the United States of America (USA), have involved the injection of liquid wastes or sludge into deep geological formations. These practices are not dealt with in this report.

1.4. STRUCTURE

The status of the scientific understanding and adequacy of knowledge in regard to the disposal of radioactive wastes in geological repositories is described in four sections.

The second section deals with the geological disposal concept and the different functions that a repository is expected to assume in different periods of its life cycle.

The third and fourth sections describe the processes relevant to the containment of the radionuclides in the repository and other processes which might affect the long term integrity of the different barriers. They also address the site or concept specific aspects of several important issues and indicate the areas which are likely to require further work within particular geological disposal programmes.

The fifth section highlights the central role of the safety case and discusses the use of safety/performance assessments (SA/PAs) in the decision making process during repository development. This section emphasizes the need to build a consensus on the conclusions of the safety case.

The final section includes short statements and a discussion of important general issues. These are put in the perspective of what has been learned, and what scientific and technical knowledge would need to be acquired at a proposed site and for a specific disposal concept in order to achieve a reasonable assurance of safety.

2. THE GEOLOGICAL DISPOSAL CONCEPT

2.1. INTRODUCTION

Several terms related to geological disposal and underground investigations are used in this report in accordance with the following definitions.

Geological disposal. Emplacement of wastes in an appropriate facility at a depth of at least several hundreds metres without the intention of retrieval. While geological disposal is generally associated with the disposal of solid long lived radioactive wastes, some Member States plan to place all types of radioactive waste in geological repositories.

Geological repository. A facility for radioactive waste disposal located underground (usually several hundred metres below the surface) in a stable host rock to provide long term isolation of radionuclides from the accessible environment (biosphere).

Underground repository. Generic term no longer used formally in IAEA documents in relation to the disposal of radioactive wastes. The term refers to any disposal facility located in a geological environment at a depth greater than some tens of metres. It includes repositories for LILW in engineered rock cavities, boreholes and other underground facilities for the disposal of hazardous wastes.

Underground research laboratory. As defined in IAEA-TECDOC-1243 [27], an underground research laboratory (URL) or facility is any underground facility (purpose built or existing) used to carry out experiments and other in situ R&D work needed in the development of a geological disposal system.

Disposal of radioactive wastes in a deep stable geological environment is intended to provide sufficient isolation, both from human activity and from dynamic natural processes, that eventual releases of radionuclides will be in such low concentrations that they do not pose a hazard to human health and the natural environment.

A geological disposal system can be defined as a combination of conditioned and packaged solid wastes and other engineered barriers within an excavated or drilled repository located at a depth of some hundreds of metres in a stable geological environment. The geological formation in which the waste is emplaced, referred to as the 'host rock', generally constitutes the most important isolation barrier. The various barriers act in concert, initially to contain the radionuclides, therefore allowing them to decay, and then to limit their releases to the accessible environment. A combination of engineered and geological barriers is generally known as a 'multibarrier' system [6]. It is obvious that multibarrier systems are fully effective only after closure of the repository. Closure is defined as the series of operations required to emplace all barriers foreseen by the repository design and to backfill underground openings and seal any connections between the disposal zone and the surrounding formations or the surface.

A key precept of geological disposal is that the combination of natural and engineered barriers should contain the short lived, highly active radionuclide content of the wastes completely, i.e. until their radioactivity has decayed to insignificant levels. This period is generally of the order of a few hundreds to a few thousands of years. There is broad agreement, however, that the majority of repository concepts cannot be relied on to contain completely all the long lived radionuclides present in the wastes. Long lived radioactive wastes are defined by the IAEA Radioactive Waste Management Glossary as those containing significant amounts of radionuclides with half-lives greater than thirty years [28], but usually containing radionuclides with much longer half-lives. In order to achieve complete containment of such radionuclides, the containment system would have to function for extremely long periods, and this is difficult to demonstrate for many disposal systems.

Consequently, a geological disposal system, after closure, can be seen to have different functions at different times in the future:

(a) Isolation from near surface processes: by removing the wastes from the near surface environment they are protected from the active processes occurring there.
(b) Protection of the biosphere: the biosphere is shielded and protected from the radioactivity of the wastes, which is at its peak in the first few hundred years after disposal.
(c) Isolation from human activities: deep disposal of wastes makes it less likely that future human activities will result in exposure to radioactivity, either directly (by digging up the wastes) or indirectly (by some means of mobilizing components of the waste).
(d) Early containment: substantially complete containment of short lived radionuclides for some hundreds or thousands of years, perhaps largely within the engineered barriers of the repository.
(e) Limitation of releases: delaying and limiting the rate and the consequent concentrations in which radionuclides will be released from the progressively degrading engineered barrier system (EBS) into the geological environment and eventually transported to the biosphere. This is achieved by a combination of physical and chemical mechanisms which, among other functions, may limit the access and flux of groundwater to the wastes and from the repository to the biosphere, and may limit the solubility of radionuclides, or sorb or precipitate them reversibly or permanently onto surfaces in the rocks and the EBS. In addition, the process of radioactive decay progressively reduces the amount of radionuclides present in the disposal system.
(f) Dispersion and dilution: the flux of long lived radionuclides through the rocks of the geological barriers implies three dimensional dispersion and may take place in widely different groundwater environments. In some concepts and at some specific proposed repository sites, releases would encounter major bodies of groundwater at depth or closer to the surface, or similar large bodies of surface water. This will result in an additional function, i.e. an overall dilution of released radionuclides such that concentrations on initial return to the biosphere are lowered.

The overall safety and acceptability of a proposed disposal system will be achieved by a balance of these functions, which will vary from site to site and from concept to concept. The balance of these functions is often called the 'safety concept'.

The functions themselves are achieved by selecting suitable geological environments for disposal and matching them with repository designs and EBS concepts which take advantage of the main features of the environment. Typically, a suitable environment for deep disposal [29–31] would display properties such as:

- Long term (millions of years) geological stability, in terms of major earth movements and deformation, faulting, seismicity and heat flow;
- Low groundwater content and flow at repository depths, which can be shown to have been stable for periods of at least tens of thousands of years;
- Stable geochemical or hydrochemical conditions at depth, mainly described by a reducing environment and a composition controlled by equilibrium between water and rock forming minerals;
- Good engineering properties which readily allow construction of a repository, as well as operation for periods which may be measured in decades.

A well chosen geological environment will act as a cocoon for the repository EBS, protecting it from gross fluctuations in physical stress, water flow and hydrochemistry. Large fluctuations in these properties generally arise from the conditions in dynamic regions of the lithosphere, such as tectonically active regions and moderately deep rocks and groundwater systems which are easily and rapidly affected by unavoidable changes in climate and unpredictable changes in land use. Deeper rocks are generally sheltered from these latter effects; increasing depth acting as a buffer against, and smoothing out in time the magnitude of, near surface perturbations. This is an extremely important function of the geological barrier, as long term stability in the 'boundary conditions' enables the only part of the disposal system which can actually be designed and optimized (i.e. the EBS) to function predictably for long periods of time.

Suitable geological environments for disposal of long lived radioactive wastes exist widely throughout the world. They can vary considerably in their nature and, thus, provide the desirable features mentioned above in different combinations and to different extents. Typically, suitable environments can be found in:

(1) Extremely low permeability rocks in which advective groundwater flow is essentially precluded. These include massive evaporite deposits, such as salt domes and large formations of bedded salt, and some plastic clay and mudrock formations. In such host rocks, provided geological stability is maintained, there is no natural mechanism for water-borne radionuclide release to surrounding geological formations other than extremely slow diffusion through

pore waters and along crystal boundaries, unless the presence of the repository itself adversely affects host rock stability. However, because such possibilities exist, the evaluation of such host rocks at potential repository sites also involves consideration of the surrounding wider geological environment, in which advective flow may occur (e.g. in overlying and/or adjacent aquifers).

(2) Deep groundwater systems which have displayed stable extremely low natural advective fluxes for periods of hundreds of thousands of years or longer. Typically, the groundwater in such systems would be saline, and possibly even dense brine, as a result of the largely stagnant nature of the groundwater system, isolated from significant fresh water recharge. It would also be chemically reducing, which minimizes the mobilization and transport potential of many radionuclides.

(3) Groundwater systems which have low fluxes combined with long transport paths away from the disposal zone to potentially accessible groundwater systems or to the biosphere. Such environments might display thick (hundreds of metres) stable unsaturated zones (the region above the water table) and slow long distance migration pathways in deep groundwater bodies. They may also occur in saturated rocks in some coastal regions or in massive sedimentary basins, where infiltrating groundwater moves slowly to great depths before eventual discharge, perhaps with considerable mixing and extensive dilution in near surface waters.

In such environments, provided repository construction is feasible both practically and economically, and provided that safety standards can be met, the exact nature of the host rock is not a controlling factor in the choice of a site. Experience in many countries over the last twenty or thirty years [32] has shown that acceptable conditions can be found in such diverse rock types as granites, metamorphic basement rocks, plastic clays, more indurated claystones, bedded evaporites, salt domes, porous volcanic tuffs, highly compacted volcanic tuffs and various well lithified sedimentary or volcano sedimentary formations. It has been common practice for many years to categorize these rather loosely into ‘crystalline rocks’, ‘argillaceous rocks’, ‘rock salts’ and volcanic rock. Whilst this historic categorization is retained in some later parts of the present report (as it is a convenient way of describing general groups of rock properties when considering near and far field processes), it is emphasized that suitable disposal environments may occur in a wide variety of rocks. This range of geological environments is illustrated by the various host rock types listed in Table I.

TABLE I. HOST ROCK TYPES CONSIDERED BY MEMBER STATES FOR THE GEOLOGICAL DISPOSAL OF SOLID RADIOACTIVE WASTE

Host rock types	Examples
Crystalline rocks	
Granite	Canada, China, Finland,
Gneiss	Sweden
Argillaceous formations	
Strongly consolidated clays:	Hungary
claystone, mudstone	
Consolidated clays:	France, Switzerland
shale, marl	
Plastic clay	Belgium
Rock salt	
Bedded salt	USA
Salt domes	Germany
Volcanic tuffs	
Above water table	USA

2.2. DISPOSAL SYSTEMS

2.2.1. Basic system concepts

The majority of geological disposal systems under investigation involve the excavation of a repository at a depth of several hundred metres in an appropriate host rock in a suitable geological environment. In the most common approach, vertical shafts or an access tunnel, or a combination of these, are then excavated to the planned depth. At this depth, horizontal disposal galleries are excavated where the waste packages are emplaced so as to be surrounded by the selected buffer material. Even after backfilling and sealing of the repository the waste still remains technically retrievable for long periods of time, basically depending on the length of the waste package integrity.

Although the main effort has gone into assessing this type of excavated repository, disposal in deep boreholes drilled from the surface could be considered as a viable option for geological disposal. However, much less effort has been spent on the controlled emplacement of waste packages in deep boreholes. Consequently, at present it may be more difficult to produce a comprehensive safety case for a deep borehole system. However, a few generic assessments have indicated that, in favourable geological environments, disposal in deep boreholes might show beneficial aspects. In addition, when small quantities of waste are involved (e.g.

disused medical and industrial radiation sources), the concept of emplacement in a few deep boreholes certainly deserves the most careful consideration. For the purposes of this report, however, attention is focused on the excavated repository concept as the principal alternative.

2.2.2. Repository design

Detailed repository design is clearly highly specific to waste type and to geological environment. Large volumes of long lived waste with negligible heat generation are usually conditioned in relatively bulky (~1–10 m^3) packages. Repository concepts for their emplacement normally involve the construction of caverns with height and width dimensions of ~5–20 m, provided the geotechnical properties of the host rock permit the excavation of such large openings. Disposal of high level waste (HLW) or spent fuel (SF) normally involves smaller waste packages (with waste volumes of the order of 1 m^3) emplaced in tunnels, or boreholes from tunnels, with diameters from ~1 m to a few metres only. Regardless of the waste type and even for small quantities of waste, construction of the access and emplacement shafts and tunnels will involve the excavation of a substantial underground facility involving the removal of some hundreds of thousands of cubic metres of rock, to millions of cubic metres for larger waste disposal programmes. Geological repositories presently being considered have underground dimensions varying from a few square kilometres to as much as about twenty square kilometres depending on the inventory of waste, on its thermal output and on the repository design.

The major natural and engineered components of a geological disposal system can conveniently be thought of in the following groups [6, 33–39]:

(a) The waste form, i.e. the waste in whatever form it is at the time of emplacement in the containers. Some low level wastes can be packaged without any treatment or conditioning, or simply after compaction to reduce their volume, while other wastes, generally characterized by higher levels of activity, are conditioned by dispersion in a stable matrix such as cement, bitumen or glass.

(b) The waste package, i.e. the combination of the waste form and any surrounding containment components. The purpose of the container can vary from short term containment during transport and/or storage to shielding and longer term containment. Depending on management requirements, packages can consist of untreated or of treated and conditioned waste in steel drums, simple concrete containers and casks or of more sophisticated stainless steel or other metal containers, such as vessels for vitrified wastes.

(c) The engineered barriers also include any overpack on the waste container (e.g. steel or concrete multipackage containers for some LILWs, and copper or titanium outer canisters for SF in some disposal concepts), the backfill/buffer material emplaced immediately around the waste packages (such as cement for some LILW concepts and highly compacted bentonite for several HLW and SF concepts) and the repository mass backfill in and around the region used for waste emplacement (often a mixture of crushed rock and clay).

(d) The repository, including, for performance assessment (PA) purposes, the rock immediately adjacent to the excavations and the backfilling and sealing systems back to the surface.

(e) The natural barrier system, including the geological formations surrounding and protecting the repository, between the disposal zone and the geosphere–biosphere interface; various processes act to retard released radionuclides as they pass through the natural barriers.

(f) The biosphere, in which radionuclides released from the geosphere move through various regions, being subject to dilution and reconcentration processes, although at very dilute conditions, simultaneously causing radiological impacts to humans and other species.

Among these components, the choice of natural barriers is within the control of repository designers only during the site selection phase. The repository, including the various EBS designs, can be controlled and optimized at all stages up to operation and closure [40–42]. The biosphere is not only outside the designer's control but, being quite variable with time in the future, is also difficult to incorporate into safety assessments (SAs) in its full complexity and detail. As a consequence, many long term SAs have considered the biosphere only as a simple dose receptor and a means of converting releases of radionuclides from the rock into radiation doses to humans. However, most assessors have developed and used different hypothetical biosphere models. Current thinking, as promoted in the recent international BIOMOVS and BIOMASS projects, is towards treating the biosphere more consistently, applying the concept of 'stylized' or 'reference' biospheres to SAs of geological repositories [43, 44]. An alternative approach presently under consideration is to reduce the uncertainty associated with future biosphere conditions by using as safety indicators estimated impacts of the repository on near surface geological compartments, such as radionuclide concentrations in shallow groundwater or radionuclide fluxes through the geosphere–biosphere interface [45].

The EBS and other repository structures fall within what is commonly termed the near field for PA purposes, i.e. the parts of the system which are significantly affected by the presence and emplacement of the wastes. The natural barriers lie within the far field, while the biosphere is generally treated separately again, as discussed above.

The role of the various isolation barriers may differ significantly in different disposal concepts, as the essential requirement is the overall safety of disposal and not the performance of single barriers. However, some redundancy in isolation capacity among the various isolation barriers may be beneficial for the presentation of the safety case, by increasing the confidence that the isolation system is actually capable of meeting the safety related constraints.

2.2.3. Design and construction constraints

The previous section mentions how the types of waste and their packaging will affect the overall repository design. This aside, the principal constraint will arise as a result of the host rock properties and the geological environment selected [31, 46]. The range of rock mechanical characteristics and repository construction constraints for various host rock types is illustrated in Table II.

2.2.3.1. Consolidated hard rocks

Excavation and construction of self-supporting underground openings in consolidated hard rocks at the depths generally considered for disposal (up to about 1000 m) generally does not represent a technical problem. There is much experience worldwide in this type of engineering. Clearly, each site will present its own special challenges, perhaps in terms of in situ stresses, localized ingress of water at shallow depths, thermal gradients or water chemistry, which at depth is controlled by known processes. Owing to the frequent presence of major subvertical fracture zones in

TABLE II. ROCK MECHANICAL CHARACTERISTICS AND REPOSITORY CONSTRUCTION CONSTRAINTS FOR A VARIETY OF POTENTIAL HOST ROCKS

Host rock	Rock mechanics	Repository construction requirements
Crystalline rocks		
Granite	High strength	No lining required
Gneiss		
Argillaceous formations		
Strongly consolidated clays: claystone, mudstone		
Consolidated clays: shale, marl	Low to medium strength	Lining required
Plastic clay	Plastic	Strong lining required
Rock salt		
Bedded salt	Hard plastic	No lining required
Salt domes		
Volcanic tuffs	Medium strength	No or light lining required

many hard rocks, special attention needs to be paid to the avoidance of these structures in repository rooms. The lateral extent of a repository may be constrained because of these structures. One way to compensate for such a limitation could be to develop multilevel repositories to take advantage of the greater vertical extent of good quality rock. It is widely accepted that construction can be carried out without undue difficulty in hard rocks, and the main effort at present is on characterizing the effect of the excavation technique on the near field rock in the waste disposal zones.

The potential for affecting rock properties by excavation such that the rock behaves differently in the immediate surroundings of the waste to the way in which it would behave in its intact form, is known as excavation damage or disturbance. The volume of rock potentially affected is termed the excavation disturbed zone (EDZ). This has been extensively investigated in underground research laboratories to optimize excavation techniques. Excavation damage is a permanent change in the rock properties. The drill and blast techniques of excavation are known to cause a larger EDZ than excavation by tunnel boring machines, causing the latter technique to be favoured for some regions of the repository in certain national programmes. The excavation disturbance is commonly caused by readjustment of the rock stress, for example, in the vicinity of a tunnel. The effects of the disturbance may be reversible as opposed to excavation damage which is irreversible. Characterization of the EDZ, including estimating how permanent it may be, is an important aspect of site specific investigations for some concepts, as the information will be required in order to evaluate groundwater flow around waste package locations.

Although hard rock environments do not need heavy supports or lining there is a need for local support, for example, by using grout or shotcrete. The materials for these purposes are commonly cement based, and therefore it may be important to study the possible impacts of these materials on the chemical conditions of the repository near field and to consider them in the PA.

2.2.3.2. Low to medium strength rocks

In rocks which have less strength, such as many less consolidated argillaceous and other sedimentary rocks, a key issue is the requirement for support of the excavations by some form of tunnel and shaft lining, designed to prevent spalling, caving or creep. This requirement may limit the depth at which disposal can take place without incurring unacceptable difficulties or costs. The greater the depth, the greater the thickness and strength of any lining structure. In addition, the lining may need to have some form of grout or backfill inserted around it, to fill any void between lining and rock. The EDZ in such formations would be of a different nature to that in hard rocks and would be expected to evolve with time as stresses within the repository zone readjust by strain, creep and swelling of some clay minerals.

The presence of the lining and the possible need for its dismantling before repository closure has to be assessed and its long term properties need to be accounted for in PAs, as they can affect near field water flow and chemistry. There are results of generic R&D available on these issues, but site specific research needs to be carried out based on the properties of candidate host rocks.

Sedimentary formations are often characterized by greater lateral than vertical extent. In geologically less complex regions, where major faulting is not encountered, this can allow repository designs to extend greater distances on a single level than in consolidated hard rocks such as basement granites and gneisses.

2.2.3.3. Plastic rocks

At one extreme of low strength host rocks, some candidate disposal formations display the potentially advantageous features of plasticity and creep. Over long periods of time any opening constructed in them will close as the rock deforms in a plastic fashion, assuming there is no lining remaining. Whilst some clays display plastic behaviour, the best example of this type of rock is halite (rock salt).

Repository concepts in bedded salt or salt domes, which are also characterized by zero advective flux of groundwater, generally do not envisage any kind of support (as the openings remain undeformed for an adequate period for emplacement of the wastes) and involve reuse of excavated salt as the backfill. Backfilling is anticipated to take place soon after waste emplacement. The near field will deform and readjust, reducing progressively the void space. The engineered barriers in salt are comprised of the waste package and any additional conditioning materials. The backfill will eventually become an integral part of the near field rock.

Construction in massive salt formations involves few technical problems as there is considerable mining experience in these types of formation. Owing to the high thermal conductivity of halite, salt domes generally display relatively high internal temperatures, which need to be accounted for in both design and performance assessments. Owing to their considerable vertical extent, salt domes generally allow the designer to consider multilevel repositories.

There is less experience in excavation work in plastic clays at typical repository depths. Experience from the underground research laboratory at Mol (Belgium) over many years, using various excavation and support techniques, indicates that there may be less difficulty than originally envisaged, although this is likely to be a highly site specific matter. As in other low strength rocks, plastic clays require tunnel support; the impact of lining materials, if left in place, on near field evolution will have to be assessed and accounted for in PA work.

2.2.4. Additional constraints

The design, construction and operation of a geological repository need to be constrained in such a way that favourable conditions for safe isolation are maintained. Before a repository is constructed, a 'baseline' of the site is required. Defining the baseline conditions includes a description of the geological environment, a characterization of its conditions and a definition of the processes to be used in the SA. This baseline description will act as a reference against which changes that take place during the construction and operation of the repository are compared and evaluated.

The disturbance caused to the geological environment depends on the properties of the different host rocks and hydrogeological environments. For example, at candidate sites consisting of hard fractured rock with groundwater flow, special attention should be paid to the inflow of groundwater to underground excavations. The inflow may cause a lowering of the water table which may perturb hydrogeochemical conditions and, in the case of dense saline waters at lower horizons, may cause upwelling of these waters. The control of water inflow, however, may lead to extensive use of grouts, which are mostly cement based materials. This, then, may have impacts on the performance of the isolation barriers and needs to be considered in the long term SA of the disposal system. On the basis of the results of the PAs, a set of technical constraints may have to be developed — in the example mentioned above, a requirement to use low alkaline cement instead of ordinary cement.

In the case of a repository located in rock salt, consideration needs to be given to the high solubility of halite. The existence of ancient deposits of rock salt is proof that they have been effectively isolated from circulating groundwater. The safety assessment of a repository in rock salt will have to consider scenarios incorporating enhanced contact with groundwater as a result either of natural processes or of human actions.

2.3. DEVELOPING A GEOLOGICAL REPOSITORY

Building and operating a geological repository for long lived radioactive waste is a unique endeavour for which there are almost no precedents on which to base many of the decisions which will be required. At the time of writing only one such repository has been commissioned, the Waste Isolation Pilot Plant (WIPP), and the waste to be emplaced in this facility has negligible heat generation. Nevertheless, despite the lack of practical experience in geological disposal, much is known worldwide about every aspect of the conceptual approach, design, evaluation and engineering of such facilities. This knowledge is based on extensive in situ and laboratory investigations and experiments, the construction and operation of underground research laboratories [27, 47–51] and repeated iterative assessments of the performance of individual barriers and of the safety of complete conceptual disposal systems.

Within any national programme, the stages in developing a geological repository would include the following. It should be noted that these stages do not need to be developed sequentially, but may be accomplished in parallel.

(1) General concept development, based on the precise nature and estimated quantity of the wastes requiring disposal and the geological constraints and local availability of materials in the country concerned. The safety concept for the possible disposal alternatives is developed and discussed.
(2) General concept evaluation, using available studies as baseline information and development of them in terms of the specifics of the national programme, including initial evaluations of likely geological environments for disposal. The principal alternative for the disposal concept, as well as its possible variants, is defined and the safety concept selected.
(3) Definition of general siting requirements to guide a site selection programme. These would probably include a combination of safety requirements (long term safety, operational safety and safety of transport) and waste transport, cost, social and planning considerations, with the greatest weight given to providing an adequate degree of radiological safety.
(4) Site selection, which may involve investigation and evaluation of a number of sites.
(5) Detailed characterization of a selected site, by both surface based and direct underground access exploration and experimental techniques. The need for characterization may also call for testing and demonstration of the important parts of the planned repository system.
(6) Design of the repository, making the best use of the characteristics of the site. Design includes the fitting of the adits to the repository and repository galleries in suitable volumes of rock.
(7) Construction of the repository, which might be in a phased manner such that emplacement of some wastes takes place and is evaluated before the repository is completely built and allows, if required and within determined time limits, the retrieval of emplaced waste packages.
(8) Operation, possibly over several decades, followed by decommissioning of surface facilities and closure of underground openings. This may again be phased over a long period of time in order to demonstrate and obtain acceptance for the final closure.

It should be noted that repository closure will require a specific authorization procedure which implies the final acceptance of the safety case for the disposal system. It is only after repository closure that the disposal system can be considered totally functional and the multibarrier isolation system fully effective. On the basis of scientific and technical considerations, and after closure of the repository, no monitoring and/or active surveillance of the site are required. However, reasons have been suggested, either for the sake of public reassurance or to ensure safeguards, for some kind of monitoring and surveillance to continue for an undefined period of time. It is also generally accepted that preservation of records and continuation of institutional controls after repository closure, regardless of the reason, would have the beneficial impact of minimizing the risk of inadvertent human intrusion.

Running in parallel to the developmental activities listed above, and acting from the outset in constant support of the decision making process which must track developments, would be a programme of R&D on both generic issues and concepts and site specific matters, and a rolling programme of performance and safety assessment. All this would enable evaluation of the behaviour of the system, identification of the key processes requiring R&D and optimization of the design for operability and cost, fulfilling simultaneously the safety requirements. The R&D aspects of the programme might involve numerous activities, from engineering and laboratory studies to work in underground research facilities. The parallel PA activity is critical, as it provides direct input to the licensing process, whereby predefined stages of the programme will be monitored, judged and approved.

The R&D programme, in practice, starts from overall requirements for the safe isolation of radioactive wastes as illustrated in Fig. 1. On the basis of these requirements a conceptual design for the geological disposal system is selected. Existing scientific knowledge and understanding of the natural system of the geological environment forms the basis for the development of functional requirements for designing the subsystems necessary for assuring the reliable performance of the multibarrier isolation system. The design basis developed in this manner will contain the specifications needed for testing and verification of the design solutions. SAs and PAs play important roles in giving reasonable assurance on the overall safety of the disposal system and performance of the system components, thus indicating the robustness of the system. Even assuming that performance has been found adequate, the system can be further optimized with evolving scientific knowledge and technology.

2.4. DEVELOPING THE SAFETY CASE

Building confidence in long term safety and producing any other information necessary to obtain approvals at each of the stages outlined above have dominated programmes aiming at geological disposal for many years. The focus of this book is thus on evaluating the state of the art in each of these stages and, in particular, on:

(a) Identifying generic conceptual issues which are well understood and where considerable reliance can be placed on the findings of international studies,

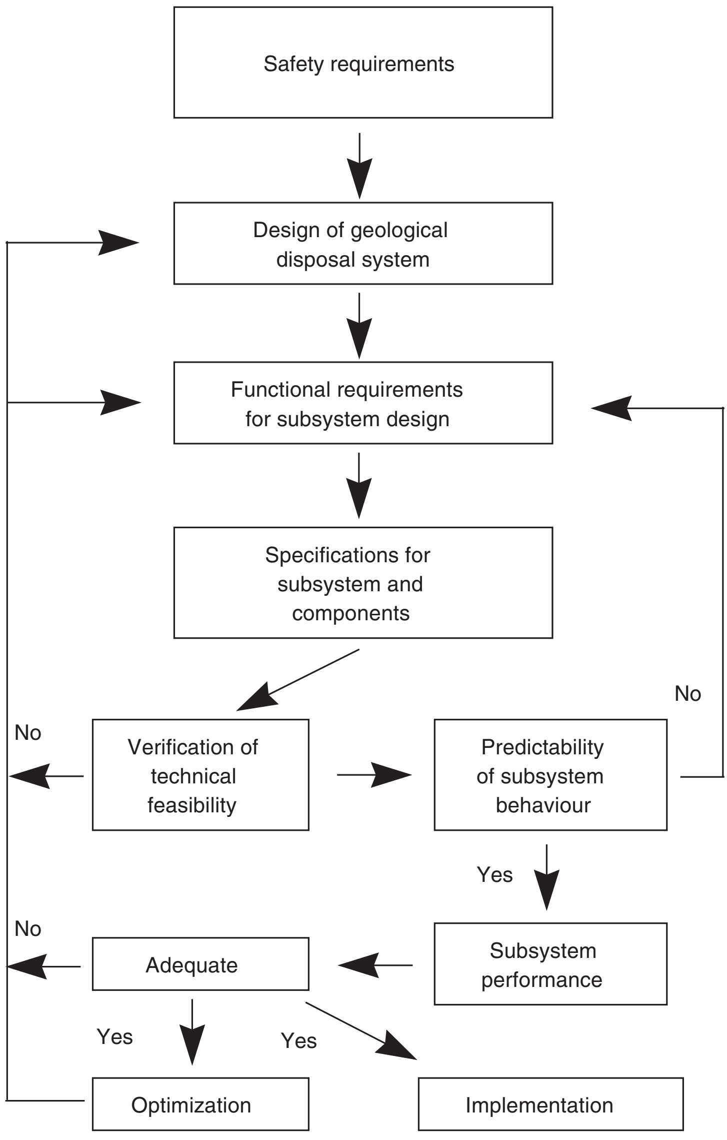

FIG. 1. Schematic illustration of the R&D programme involving SAs, PAs and engineering, as well as testing and demonstrations aimed at the implementation of geological disposal.

(b) Defining issues which are inevitably site and/or concept specific and where further work will inevitably be required within any national programme,
(c) Highlighting the central role of the safety case in the decision making process at each stage.

The safety case contains both SAs and PAs [52–60] but in addition to these it also gives more qualitative evidence and reasoning to support the quantitative modelling [61]. The safety case provides a train of arguments that a sufficient set of processes has been analysed and appropriate models and data have been used in showing that the overall measures and performance are within acceptable ranges, and allowing for uncertainties.

In developing the safety case a concept has to be selected around which the case will be built and confidence in adequate safety will be achieved. In different geological environments different safety concepts may be proposed for achieving adequate isolation of wastes and for demonstrating this. In all concepts, however, the leading principle is that long term safety is based on a multibarrier system. The aim of the multibarrier concept is to confine the radionuclides so that the failure of one component does not jeopardize the safety of the containment system as a whole.

The safety concept to be selected depends to a large extent on the geological environment of the most likely, or the available, candidate site for a geological repository. In fractured hard rocks, with a potential for significant groundwater flow, the safety concept may be based on the robustness of the EBS, comprising a long lived canister and effective buffer material. The role of the geosphere in this case is mostly to provide stable conditions in which the EBS can retain its good containment properties. The purpose of the site investigations is then to identify the zones of good rock, therefore allowing location of the disposal rooms of the repository away from fracture zones or other parts of the host rock with potentially adverse features. In some argillaceous rocks the safety concept may be based mainly on the containment capacity of the natural barrier instead of relying on the EBS. The movement of pore water in very tight argillaceous rocks is typically dominated by diffusion. The main tasks of site investigations are not only to define the large scale characteristics of the site but also to optimize the layout of the repository.

A safety concept based mainly on very stable conditions of the geological environment may also be developed. Such conditions could prevail in climatically stable areas which are also characterized by low relief and smooth topography together with very low hydraulic gradients. The long term safety of a repository located at a site with such environmental characteristics would depend almost entirely on the geological environment; thus, the engineered barriers would be needed essentially for the pre-closure phases of the repository. According to current knowledge, sites of this type would be limited to low permeability formations in tectonically stable, flat arid or hyper-arid areas.

Various potentially useful definitions in the following discussion of the safety case are listed below. In some cases both IAEA (1) and OECD/NEA (2) definitions are included for the reader's information.

(1) *Safety case:* A collection of arguments and evidence to provide reasonable assurance of the safety of a facility or activity. This will usually include a safety assessment, but would also typically include information (including supporting evidence and reasoning) on the robustness and reliability of the safety assessment and the assumptions made therein (modified from IAEA Safety Glossary).

(2) *Safety case:* A collection of arguments, at a given stage of repository development, in support of the long term safety of the repository. A safety case comprises the findings of a safety assessment and a statement of confidence in these findings. It should acknowledge the existence of any unresolved issues and provide guidance for work to resolve these issues in future development stages [62].

Safety concept: In this report this term is used as an informal term to conceptually describe different geological environments and EBSs individually or in combinations that provide the basis for safety assessments and performance assessments. The safety case presented as a collection of arguments at a given stage of repository development will be based on the selected safety concept.

(1) *Safety assessment:* An analysis to predict the performance of the overall system and its impact, where the performance measure is radiological impact or some other global measure of impact on safety (modified from IAEA draft Safety Glossary).

(2) *Safety assessment:* An evaluation of long term performance, of compliance with acceptance guidelines and of confidence in the safety indicated by the assessment results [62].

(1) *Performance assessment:* An assessment of the performance of a system or subsystem and its implications for protection and safety at an authorized facility. It differs from a safety assessment in that it can be applied to parts of a disposal system and does not necessarily require assessment of radiological impacts (modified from IAEA Safety Glossary).

(2) *Performance assessment:* An analysis to predict the performance of a system or subsystem, followed by comparison of the results of such analysis with appropriate standards or criteria. A performance assessment becomes a safety assessment when the system under consideration is the overall waste disposal system and the performance measure is radiological impact or some other global measure of impact on safety. Performance assessment can be used to describe the analysis and comparison of systems at a variety of levels and requirements [62].

All concepts share very similar requirements for the containment of wastes. These requirements, set in regulations, play a central role in decision making in various stages of repository development; for example, regarding advance to a subsequent phase of the repository development programme. For decision making purposes, an integrated safety case may be developed which describes the safety concept selected and presents the arguments supporting the safety of the planned repository system [61]. The core of the safety case, however, consists of the safety and performance assessments. In an SA, the estimated consequences of any releases from the repository are compared with the appropriate safety criteria, whereas in a PA the evolution and performance of the isolation barriers is estimated. The safety case may also contain other arguments supporting the safety of the disposal system, as well as the results of testing and demonstrations relative to the technology needed for the successful completion of the multibarrier system [63]. The need for these results may vary during the evolution of the disposal programme.

Performance assessment is a formal method of quantifying the behaviour of each component of the disposal system as it evolves with time and of translating this behaviour into estimates of its impact on the overall performance of the containment system. Safety assessment and PA share most data requirements and attempt to assess the quantitative impacts of the following factors characterizing the disposal system:

(a) The properties of the radioactive waste to be disposed of and their possible variabilities;
(b) The materials and structures planned to be used in the principal design alternative;
(c) The properties of the geological environment surrounding the repository and the knowledge of the processes taking place in the rock, as well as of their variability;
(d) The behaviour of the radionuclides in both geosphere and biosphere and their radiological impact on human health;
(e) The processes by which materials interact.

This knowledge is needed to evaluate the proposed disposal system and confirm that it can achieve the required performance. One of the purposes of the assessment tools is to estimate the consequences of one or more of the containment barriers not performing as designed and, consequently, of radionuclides being released from the repository in unexpected amounts.

The essence of SA/PA is the use of models of the time dependent behaviour of the components of the system, or of processes occurring within them, to make estimates of the future states of the system and of the impact of these states on radionuclide behaviour. These models should be tested as thoroughly as possible.

However, as a consequence of the need to project the behaviour of the disposal system into the distant future and to large spatial scales, SA/PA models also rely heavily on information which is extrapolated in both time and space. Part of this extrapolation includes deciding how best to represent the geometry of the repository and the host rock in the models. It is largely a result of spatial and temporal variability, in both the processes modelled and the properties which they affect, and of the potential biases introduced by modelling decisions, that there is considerable uncertainty surrounding SA/PA results. This uncertainty increases with the remoteness of the future time to which the estimates refer.

In SAs it is not assumed that our knowledge of the natural system or of the behaviour of the engineered barriers would be complete. Lack of knowledge and uncertainty are compensated for by making conservative assumptions. For example, conservative assumptions are adopted regarding the future evolution of the natural system or the performance of the repository components, or as an alternative favourable but uncertain conditions are excluded from the assessment. Overall, the safety case should not rely on properties of the geological environment or on the performance of the engineered barriers for which knowledge is poor or lacking. In SA, uncertainty and inadequate knowledge about the future evolution of the system can generally be taken into consideration by:

(1) Selecting appropriate scenarios;
(2) Making conservative assumptions (overestimating the consequences);
(3) Studying the influence of the assumptions used in PA results by sensitivity analyses and also by 'what if' analyses, if needed;
(4) Having peer reviews by external reviewers on the SA/PA methods applied and on the results obtained.

Sufficient confidence in the satisfactory performance of the disposal system within a safety case must thus depend on a thorough analysis of the various uncertainties and on a convincing definition of their potential impacts on the outcomes of the assessment. The need to understand uncertainties and to define their bounds drives many of the R&D requirements related to geological disposal, at both the generic and site specific levels. Apart from statistical and mathematical techniques for addressing uncertainties, there are also comparative approaches which allow improvement of confidence in long term estimates of performance. In addressing the question of uncertainty, the best use of current scientific knowledge within a safety case could easily become a critical issue. One approach, using so called 'natural analogues', is to assess the processes operating in, or the materials used within, the repository system, the context of similar processes or materials found in comparable environments which have already been evolving for extensive periods of time [64–69]. Studies into climate change have recently produced information relevant for understanding the past and future evolution of climate [70, 71]. This knowledge is also important for the interpretation of any 'palaeohydrogeological' evidence [72] obtained at the candidate site and for testing the models used to simulate the evolution of the natural system in the SA.

Owing to the long period of time that is likely to be required to develop, operate and close a geological repository (typically several decades), to the ongoing R&D activities and to the iterative nature of SA, further uncertainties can arise if the data acquisition process is not properly documented and the data produced are not carefully preserved. A well designed QA system is thus vital from the outset of a programme to ensure complete traceability of the decision making process [38, 73–75].

On the basis of geological knowledge, it should be possible to site repositories where the conditions at great depth will remain substantially unchanged, in spite of climate change (including future glacial episodes, in locations where they may occur) or other surface based variations. Future geological changes that, based on current knowledge, are thought to be possible are included in the assessment by developing and simulating appropriate evolution scenarios. In addition, the importance of individual features, events and processes (FEPs) in controlling the performance of the system is explored with a technique called sensitivity analysis. Using scenario and sensitivity analyses within the SA, the performance of the disposal system can be evaluated under conditions that differ from those expected for the normal evolution scenario. The way in which SAs and PAs are carried out and the ways in which confidence can be built around a safety case are discussed in detail in Section 5.

The adequacy of the safety of a geological disposal system is judged by comparing the results of the SA or the safety case with the appropriate national criteria, which are generally set on the basis of internationally agreed standards. National regulations may contain various requirements, although the main emphasis is generally on radiological criteria, such as:

(a) Meeting quantitative dose (mSv/a) or risk constraints to individuals within groups that might potentially be exposed to radioactivity from the repository;
(b) Providing similar levels of radiological protection to future generations as are provided at present;
(c) Showing that the additive impact of the disposal system on the natural radiation background is limited, and perhaps making comparisons between repository derived and natural concentrations/fluxes of radionuclides through the geosphere and within the biosphere over long time periods;
(d) Providing some measure of radiological protection for species other than human beings.

It is clear that meeting such regulations requires a detailed knowledge not only of the present day geological and environmental characteristics of the site but also of the repository components after emplacement and closure, as well as convincing estimates of their future evolution.

3. NEAR FIELD COMPONENTS AND PROCESSES

EBSs within the near field are intended to contain the radionuclides in the wastes completely for a certain period of time and then to control the rate at which they can be mobilized and released into the surrounding rock. The period of fast decrease of radioactivity depends on waste type and related radionuclide inventory. However, for most categories of long lived wastes, a complete containment period of some hundreds of years achieves considerable benefits in terms of activity reduction. Beyond this time, unless the wastes can be contained for some hundreds of thousands of years, the profiles of the radionuclide decay curves show that there is little advantage in trying to achieve longer total containment within the near field EBS, which, as generally acknowledged, will eventually break down anyway. The half-lives of many of the other radionuclides that are relatively mobile in groundwater are so long that it is impossible to contain them within the EBS; therefore, they are expected to become dispersed into the environment, at very low concentrations, at some distant time in the future. Thus, over the long term, the function of the EBS is to delay and disperse releases of mobile radionuclides once total containment is lost. Nevertheless, many long lived radionuclides are not mobile, even after the EBS has degraded, and are expected to be retained in the near field long enough to allow for significant or total decay.

This section describes the different materials that may be present in the near field of a geological repository for long lived wastes, how they interact with the surrounding rock and groundwater system, and how they evolve over long periods of time. The mechanisms that cause degradation of the EBS, including the conditioned waste, the mobilization of radionuclides within the near field and their transport through buffer and backfill materials and into the surrounding rock are discussed. The physical and chemical properties of the geological environment are clearly important as they control these processes. In particular, the way in which the near field environment evolves before and after closure will define the way in which the EBS performs [76–79].

A geological repository is expected to remain open for many years, owing to the duration of disposal operations, and, in some cases, for an undefined period even after waste emplacement has been completed. National programmes may require that the wastes remain retrievable, perhaps also readily accessible, until decision makers are comfortable to proceed to closure. An alternative retrievability option could be the partial or total closure of repository openings through the emplacement of EBSs in a reversible way. Depending on the disposal concept and on the closure strategy, at some time sections of the repository may be constructed and completely backfilled, while others would not be backfilled until final closure. Thus, over a period that might potentially last for many decades, it could be required that the repository remain stable and capable of maintenance and monitoring. This would require that the repository openings are excavated in stable blocks of rock and that any necessary support systems are designed to last for the necessary length of time (although with the possibility of remedial maintenance).

In many geological environments in which there is significant groundwater movement, the repository will need to be pumped and ventilated to keep it dry right up to the time of closure, although some sections that have been completely backfilled may start to resaturate, as hydraulic gradients begin to re-establish themselves and groundwater moves into regions that had previously been drained. Depending on the disposal concept, other parts of the EBS may not attain their final configuration or properties for a long period of time. For example, rooms filled with ILW might not be backfilled until just before closure, while some concepts envisage large volumes of such openings never being completely backfilled.

In all types of geological environment, during the open period, exposed rock surfaces will interact with ventilation air passing through the facilities. Rock may dry out or be oxidized, and some unlined excavations in sediments may crack and require support. If ventilation air were to flow from warmer to cooler sections of the repository, moisture would be condensed to water. Microbial activity will develop and flourish in regions where water carrying nutrients flows into excavations. Steel support systems will corrode and require maintenance while cement surfaces may be partially carbonated by interaction with atmospheric carbon dioxide. All these processes will need to be monitored and their effects accounted for during the entire pre-closure period.

Following closure of a repository located below the water table, the groundwater regime will be progressively re-established and the whole system will resaturate. Any remaining oxygen in trapped air will react with the rock and EBS materials, and the whole system will become chemically reducing. Microbes may play an important role in consuming the trapped oxygen. Rock stresses will re-equilibrate and lithostatic loads will be transferred onto parts of the EBS, particularly in weak host rocks that experience creep. The main determinants of the performance of the near field in the majority of disposal environments will, however, be the content, movement and composition of groundwater in the rock immediately surrounding the EBS.

3.1. THE GROUNDWATER ENVIRONMENT

Section 2 discussed the different types of geological environment and host rocks that are being considered for repository location. The behaviour of the EBS and the evolution of the near field of a repository are critically dependent on the local scale properties of the host rock and on the larger scale features of the surrounding geological environment. For many geological environments being considered for disposal, groundwater flow (advection) will be the most significant factor affecting near field performance [80–82]. In both saturated and unsaturated host rocks, groundwater flow processes control two key aspects of the near field:

(a) The rate at which water can enter the near field and reach the wastes and the rate at which it can transport released radionuclides away;
(b) The chemistry of the water entering the EBS and reaching the wastes.

In some extremely low permeability clay formations, or in extremely low groundwater flow situations, where diffusion is the dominant mechanism affecting solute transport, these two aspects can be better expressed as:

(a) The rate at which reactive species can diffuse into the EBS and the rate at which radionuclides can diffuse out into the surrounding rock,
(b) The chemistry of pore water in contact with the EBS.

In hydrogeologically ‘dry’ salt formations, there is expected to be no flow and no significant diffusion of radionuclides.

Groundwater flow and chemistry are discussed below in terms of how they affect the boundary conditions of the near field.

3.1.1. Groundwater flow rate

The occurrence of no or low groundwater fluxes around the EBS is considered an important positive factor in the selection of a suitable disposal site. In the environments being considered for disposal, advective groundwater flow can be highly variable.

3.1.1.1. Environments with groundwater flow

Among hard and fractured host rocks, granite and similar crystalline materials have been considered for disposal by several countries. Some volcanic tuffs can also possess both high porosities and well developed fracturing. In this respect they can be similar to many of the hard sedimentary rocks such as sandstone and limestone. Compacted indurated clays can also have non-negligible hydraulic conductivities which are often strongly anisotropic, being least in the vertical direction owing to the plate-like structure of the clay minerals which tend to be oriented parallel to the bedding structure of the clay formations. When such clays display fracturing which, if not self-healing due to swelling or plastic deformation of the clays, increases overall hydraulic conductivity, their groundwater flow properties eventually merge into those of the harder, fractured rocks. A good understanding of advective groundwater flow would be important for the PA of a geological repository planned to be located in a fractured clay formation. In all these rocks, water flow can be a combination of flow through the fracture network and flow through the unfractured matrix. Installation of a thermal source (HLW or spent fuel) in this system will affect the vertical gradients of groundwater flow. If matrix porosity and fracture density are high, then the flow characteristics of such formations can be relatively homogeneous over a large scale, which facilitates evaluation of fluxes in the near field.

The more compact hard fractured rocks, such as granites and gneisses, have lower matrix porosities with small pore sizes such that effectively all groundwater flow occurs through the fracture network. Characterizing the nature of the fractures, in terms of apertures, spacing and connectivity is a key element of site investigations in such rocks, as the fracture pattern can be spatially highly variable and the analysis of water flow is scale dependent. In such formations, channelled flow along particular groups of highly connected, high conductivity fractures can form the key pathway bringing water into and taking it out of a repository. Strongly channelled flow can produce potential ‘fast pathways’ for radionuclide migration. Clearly, site selection and repository design need to take such features into account and avoid them as far as possible.

3.1.1.2. Environments with insignificant groundwater flow

At one extreme, in salts and plastic clays, there is no discernible flux of groundwater. Free water present in these formations is confined to pores and is largely immobile. In the types of salt considered suitable for disposal, small quantities of brine occur in unconnected fluid inclusions trapped within salt crystals. Whilst these inclusions can migrate along temperature gradients, the flux of water and solutes is small. However, it may need to be taken into account when assessing waste package corrosion behaviour. Small quantities of water can also be present as intergranular films, but again this is of limited significance in terms of PA.

Evaporite formations can comprise a wide variety of minerals other than pure halite. Some of these minerals have limited thermal stability, especially those containing large amounts of bound water (water of crystallization). Heating can release this water. The presence of significant quantities of such minerals (e.g.

carnallite) would generally be avoided during site selection or during the design and utilization of rock volumes within a salt dome or bedded salt.

Plastic clays have a high porosity, combined with a very low hydraulic conductivity. A component of the pore water is strongly bound to the clay mineral surfaces in a structured layered fashion, while the remainder is free [83]. In some clays with small pore sizes, there may be very little free water. Owing to the small pore size, the tortuosity of the pore structure and the limited volume of free water, advection occurs at rates that are sufficiently slow as to approach those of molecular diffusion of water.

With time and loading by accumulating sediments, clays may become more consolidated and lose some of their original plasticity. Clays with a relatively high content of carbonate tend also to have reduced plasticity. As a result of these factors clays may become progressively stiffer and be subject to fracturing when exposed to sufficient stress, mostly as a result of tectonic movements. However some stiff clays, despite the existence of some recognizable fractures, are still characterized by very low permeability and, for all practical purposes, can be considered to be materials where groundwater flow has little significance in regard to radionuclide transport. The secondary permeability of clay formations has been investigated within the geological disposal programmes of several countries involved in the assessment of clays as potential host rocks for geological repositories [82–86].

Conditions of no effective flow at depth can also be found in hydrogeological environments characterized by extremely low hydraulic gradients and low groundwater recharge, such as may be found in some sedimentary formations and in extensive areas of flat desert terrain. In some regions, such conditions can be stable over geological periods of time. Some offshore (coastal, sub-seabed) environments would also display extremely low advective flow, as a result primarily of very low hydraulic gradients.

3.1.2. Groundwater chemistry

Slow groundwater movement over long periods of time, a positive feature of a suitable disposal environment, results in the development of waters at geochemical equilibrium with the minerals forming the surrounding rock. In some deeply buried, very low hydraulic conductivity sedimentary formations, the pore water may be the water originally trapped when the sediments were deposited. Over long periods, the chemical reactions between the pore water and the rock forming minerals have resulted in complex but stable pore water chemistries. Similar conditions of groundwater chemical stability can occur in cases of slowly flowing groundwater in deep basement metamorphic and igneous rock environments, where brines are often encountered. Sites which are, or could in future, be located in coastal regions, may be subject to shallow ingress of saline sea water into the upper regions of the rock. Whilst this is unlikely to affect the near field chemistry, it could affect the overall groundwater flow regime and would need to be accounted for in modelling groundwater fluxes.

Deep groundwater is often characterized by high solute concentrations as a result of the interactions mentioned above. It is to be expected that both pore water and water in fracture networks in many potential disposal environments might be quite saline or even dense brines. Clearly, the response of EBS materials could be affected if inflowing water were saturated or oversaturated in many species, and this would need to be taken into account in many facets of PA modelling. Vice versa, water chemistry will be affected by contact with EBSs and other construction materials, composition of which may differ significantly from the host rock. Typically, concrete leachate with high pH value can initiate reactions which may display both positive (iron passivation) and negative (zinc dissolution) impacts. Introduction of heat generating wastes in the system results in increasing saturation levels and, consequently, in a change of equilibrium values, as discussed also in Section 5.2. However, most local natural backfill materials being considered for use in geological repositories are close to chemical equilibrium with deep groundwater, thus they already have an intrinsic long term stability in the disposal environment.

Fresh, meteoric, waters are generally typical of the upper zones of the geological profile. In the majority of disposal concepts, which involve construction well below the water table, occurrence of fresh waters will be limited to the upper, more dynamic regions of the groundwater system, for example, in regions of the geosphere which are more heavily weathered or fractured.

With increasing depth, as discussed above, groundwater becomes more saline and more reducing, in most environments. The absence of oxygen causes slow corrosion rates of metallic components of the EBS and very limited mobilization and transport of some important radionuclides. Free oxygen trapped during the operational phase of the repository is consumed by reactions with microbes and reducing minerals in the rock, such as pyrites and siderite (and by reaction with entrained humic materials from the soil zone for waters percolating down fracture zones from the surface). Over long periods of time, at high latitude or high elevation sites, transient oxidizing groundwater conditions may be caused by ice cover during glacial episodes. Site characterization should include evaluation of the evidence for such events having occurred in the past, and the PA should include evaluation of the potential impacts on the near field, if such a scenario is conceivable at the site. For the time being no evidence has been uncovered that oxidizing water has ever penetrated to great depths in the regions which underwent repeated glaciations.

Consequently, for most repository concepts, once restored to equilibrium, the near field will be characterized by reducing conditions and be saturated by possibly saline or even briny groundwater. Transport of radionuclides in such conditions would be by diffusion or by slow advection. However, great care should be taken in site evaluation studies to groundwater flow within the host rock.

3.2. WASTE FORMS

Long lived wastes destined for geological disposal can comprise a variety of materials conditioned and packaged in many different ways [24, 33, 35–39, 42, 76]. The principal groups that are considered here are:

(a) Spent nuclear fuel (whole or dismantled fuel bundles or elements, containing the original metallic uranium, uranium dioxide or mixed oxide (MOX) fuel matrices and the fission products and transuranics that were formed while the fuel was in the reactor);
(b) Vitrified HLW containing fission products and transuranic residues from reprocessing spent fuel (with a variety of ceramic waste forms also being developed but not yet produced on an industrial scale);
(c) Long lived low and intermediate level wastes (LL-LILWs) that include a wide range of materials such as reactor internal parts from maintenance or decommissioning, fuel element and cladding parts, other materials contaminated by various levels of alpha emitters such as plutonium (from nuclear fuel or weapon activities), other fissile materials and depleted uranium.

Some geological disposal concepts also include short lived LILW, which can include various admixtures of metals, concrete, organic resins, plastics and other chemicals.

Over long periods, radionuclides contained in solid waste forms can be mobilized, released and then migrate away through the EBS and the surrounding geological media.

3.2.1. Spent fuel

The most common form of spent fuel considered for disposal contains pellets of uranium oxide ceramic. Spent fuel is comprised of more than 95% uranium dioxide; most fission products and actinides generated during reactor operation are incorporated in the spent fuel. The uranium dioxide is in the form of small crystals, tens to hundreds of micrometres in size, that are aggregated into pellets of about 1 cm diameter. The fuel pellets are typically contained in zirconium or aluminium alloy or stainless steel tubes, which can be several metres long, depending on the reactor type. These alloys are stable in water and corrode only very slowly, but microscopic cracks could develop eventually, forming passages through the tube walls. Consequently, there is some current discussion as to how much short term credit can be taken for the tubes as part of the multibarrier system.

Uranium dioxide is also stable in water and will dissolve extremely slowly. The release of any radionuclides held within the crystalline matrix of the pellets will thus be slow. However, some radionuclides, as they are formed during reactor operation, accumulate at the grain boundaries or move to the outside surface of the pellets. Iodine, caesium and the noble gases belong to this category. Typically about 15% of these substances are outside the crystalline matrix and are much more readily mobilized if the fuel comes into contact with water.

Spent fuel can easily withstand the elevated temperatures that will be reached during its early phase in the repository, since the temperatures experienced in reactors are very much higher. The repository EBS may, however, be much more sensitive to elevated temperatures, and its long term performance in the context of the thermal evolution of the repository will need to be estimated with care. In this respect, MOX fuels generate more heat, and for a longer period, than normal uranium oxide fuel.

3.2.2. High level waste

The standard procedure for the solidification of HLW is dispersal in a glass matrix. However, alternative techniques have been and are being investigated. Among them, incorporation in a ceramic matrix is considered very promising. Both glass and ceramic HLW waste matrices are stable to thermal and radiation effects and dissolve extremely slowly in water. Radionuclides are strongly bound in glass or within the crystal structures of ceramic waste forms such as Synroc. Unlike spent fuel, no radionuclides are readily mobilized when the waste contacts water in a repository, but, because these HLW forms are produced by spent fuel dissolution and subsequent manufacturing at high temperatures, volatile radionuclides originally contained in spent fuel, such as iodine or ruthenium, become separate from HLW during reprocessing and solidification. A further difference from spent fuel is that reprocessing removes almost all the uranium and plutonium from these waste forms. Partitioning also separates minor actinides.

The principal vitrification medium in use is borosilicate glass. Radionuclides are added to the glass forming chemicals as a dried residue from originally liquid HLW and melted at high temperatures, with the resultant homogenized melt being poured into steel containers. These are sealed and may contain a void above the solidified glass. As the glass cools and is handled it may crack, which increases its surface area. Recently, with the development of a new glass melter (cold crucible), the use of phosphate glass, which provides high flexibility to the chemical composition of the conditioned waste, has been investigated.

There are many compositions of ceramic HLW being studied and developed. They are formed, for example, by sintering or hot pressing dried HLW residue with various ceramic precursor materials, and produced as small blocks which can be packaged in batches in metal containers. Some processes include a metallic container during the hot pressing so that an integrated solid product of waste form and container is produced. The technology of ceramic production is well advanced, and many variations in waste form composition and specification are possible.

Both techniques may also be used for immobilization of dilute concentration ex-weapon plutonium materials for disposal [87]. In the waste forms under development, glasses or ceramics containing low concentrations of plutonium are packaged within larger containers such that they can be surrounded by HLW glass or fission product doped glass, to give the packages similar overall levels of radioactivity to standard spent fuel or HLW packages. The aim is to make the plutonium as difficult to access as it was in the spent fuel from which it was originally extracted, thus helping to preserve nuclear safeguards.

3.2.3. Cement and concrete

Cement is used as a matrix for incorporating many types of LILWs and as grouting for metallic wastes, where the heat production is small. Typically, waste materials might be broken apart, cut up or otherwise fragmented into manageable pieces and mixed with cement paste or concrete in their intended disposal containers, which may be steel drums or concrete boxes. The waste form and the container are essentially the same in the latter case.

Cement is a mixture of different oxides of aluminium, silicon and calcium forming a number of mixed oxide mineral phases. Some calcium and minor amounts of sodium and potassium oxides will form hydroxides when wetted as the concrete paste is mixed. The sodium and potassium hydroxides make the pore water in the cement very alkaline (initial pH ≈ 14). The pore water may be progressively flushed out of the waste packages, particularly if they develop cracks and a higher hydraulic conductivity. The high pH fluids can be very reactive with other materials in the repository, such as clay minerals present in backfill and the host rock itself. An important aspect of these high pH conditions is that they reduce considerably the solubility of many radionuclides, thus limiting their release from the waste form. Cements also provide a good sorbing medium for radionuclides. It has been estimated that it would take hundreds to thousands of flushing cycles to effectively flush out the alkalinity of the pore water. Under deep, low flow disposal conditions, this would be expected to take hundreds of thousands of years [88].

Cement and concrete are generally stable in water that contains little carbon dioxide (as would be expected in a geological repository) and are themselves highly impermeable, other than through cracks that may form after the waste packages are emplaced in their disposal locations and exposed to natural rock stresses or the production of gases from metal corrosion. In many cases, however, additives are introduced to concrete to improve its strength or flow properties. These materials often contain organic components which have to be taken into account when considering the use of cement based construction materials in the near field.

3.2.4. Bitumen

Bitumen has been used in several national programmes for the conditioning of LILWs. While the use of bitumen for this purpose is currently quite limited, some existing waste packages containing bitumen may need to be emplaced in a geological repository. While bitumen is a natural geological material known to last for millions of years under favourable geochemical conditions, the behaviour of bitumen conditioned waste under the physicochemical conditions of a geological repository will need to be evaluated with the greatest care.

3.2.5. Metallic waste

During operation and decommissioning of nuclear reactors, constructional metallic wastes containing long lived radionuclides (^{59}Ni, ^{63}Ni and ^{94}Nb) are generated. These will be disposed of directly or placed in a repository after being melted to ingots and grouted by a concrete mixture. The performance of this waste form is described in Section 3.3. Nevertheless, mobilization of the mentioned radionuclides should be considered in SAs.

3.3. CONTAINER MATERIALS

Depending on the disposal concept, spent fuel and HLW are generally placed first in a primary metallic (usually iron or steel) container that is then placed inside an overpack or canister [24, 35, 36, 38, 39, 76, 79]. Normally, only the overpack/canister is intended to have a barrier function once emplaced in the repository. One of the functions of the primary or inner container (e.g. the steel container into which molten glass is poured) is to facilitate handling by providing the required mechanical strength. In regard to spent fuel, bundles might be placed singly into slots in a composite disposal canister (i.e. one without an inner container).

Overpacks/canisters are designed to contribute to the containment capacity of the EBS. Two conceptual approaches are possible: corrosion allowance and corrosion resistance. The first involves the use of readily corrodible metals (e.g. mild steel and cast iron) with sufficient thickness to delay container failure for some thousands of years, i.e. until the short lived fission products in the wastes have decayed. Thereafter, the corrosion products may have some chemical barrier role (see later). The second involves the use of corrosion resistant materials (e.g. copper and titanium alloys) that are intended to prevent water access for much longer periods (up to 100 000 years), possibly even until all the most mobile radionuclides have decayed and the waste hazard has declined to levels similar to those of natural uranium ore. As noted in the introduction to Section 3, it is generally accepted, on the basis of SA results, that there are no additional advantages to be gained from containers designed to have intermediate lifetimes.

Containers for LILW destined for geological disposal are normally made from mild or stainless steel, or concrete. Stainless steel is used to give long term stability during storage, thus avoiding the need for repackaging for shipment and disposal. In the multibarrier concept, containers for these wastes are generally attributed no barrier function, even though they may keep water from the wastes for many hundreds of years. Some containers for ILW may incorporate gas vents, to allow any gases generated by corrosion and slow degradation of the wastes to escape without causing problems from overpressurization.

The behaviour of some of these container materials under disposal conditions is described briefly below.

3.3.1. Mild steel and cast iron

Mild steel and cast iron corrode in water at reasonably predictable rates. Steel or cast iron containers for HLW or spent fuel are made with thick walls (several centimetres) so that it will take a long time for the corrosion to penetrate through the container. During iron corrosion under anaerobic or reducing conditions, such as would be expected in most geological repositories after closure, once the oxygen in entrapped air has been consumed by reactions with the rock or initial reaction with the steel surfaces, hydrogen gas is formed. The corrosion products of iron form a layer that helps to slow down the progress of corrosion, and the mass of iron oxyhydroxides remaining after a container has been completely penetrated can have a significant sorptive capacity for radionuclides mobilized from the wastes.

3.3.2. Stainless steel

Stainless steel corrodes very slowly in water, because protective oxides form on the surface that slow down further attack. It is possible that cracks or pits may form due to stress corrosion, long before there has been any serious general corrosion. This effect is more pronounced in saline waters. Stainless steel containers can be made with thin walls and are readily welded and sealed. The slow corrosion of stainless steel, and the comparatively lower amounts of it used for packaging, result in significantly reduced rates of hydrogen production compared with that from the mild steel present in the repository (structural steel, for example, in concrete).

3.3.3. Copper and titanium

Copper is essentially stable and, in practice, non-reactive in water. A corrosive agent must be present in the water to initiate and sustain corrosion. Corrosive agents, such as sulphides, are present in trace concentrations in most groundwaters and in some other EBS materials. Nevertheless, copper canisters can be expected to maintain their integrity for exceptionally long times. Some canister designs for spent fuel combine an inner cast iron filler that holds a group of fuel bundles and takes up the mechanical stresses in the repository, with a thin outer copper shell that is corrosion resistant. Titanium has also been proposed as a corrosion resistant outer container that is also stable in deep groundwater and particularly durable under reducing brine conditions.

3.3.4. Concrete

Concrete containers may typically include reinforcements, for example, steel bars. Under disposal conditions, these containers may be expected to be relatively stable and impermeable for many hundreds of years, until stresses in the rock, internal gas production or slow corrosion of the reinforcement causes cracking. Resaturation times of several thousands of years have been estimated for some large underground concrete vault structures.

3.4. BACKFILL MATERIALS

As noted at the beginning of this section, the backfilling of a repository may take place in stages, possibly over a protracted period. Different materials would be used in different regions of the facility, to perform a variety of functions, for example, acting as carefully engineered components of the EBS immediately around waste packages or simply providing a mass backfill for the void spaces in less critical regions of the repository [34, 76–78]. Backfills are natural, reworked materials, such as clays (including specially prepared bentonite, which usually would have to be imported to the repository site) and crushed host rock, extracted during excavation (salt, granite, etc.), used either separately or mixed. Various mixtures with crushed rock are being considered as backfill materials. They are intended to condition or control the physicochemical conditions (the chemistry, thermal conductivity and hydraulic conductivity) in the repository. Cement and concrete may also be used to backfill regions of the repository containing ILW.

Engineered barriers for spent fuel and HLW in saturated hard rocks have highly compacted bentonite to provide a buffer material around the waste canisters, either in tunnels or in deposition holes in the floor of the disposal galleries. This material has to be carefully manufactured to rigorous QA standards as it needs to have homogeneous and predictable properties to provide the required functions, including the preservation of waste canister integrity. Such materials may also be used to form seals in critical regions of a repository. This buffer material should be distinguished from mass backfill used to fill tunnels, shafts and other access ways. Here, crushed rock or sand would be used, possibly mixed with clay in regions where a particularly low permeability is required.

3.4.1. Role of clay buffers in HLW/spent fuel, saturated rock EBSs

The purpose of the buffer, described above, is to isolate or 'decouple' the waste containers from the processes taking place in the geological environment. The buffer protects HLW or spent fuel canisters from mechanical damage should small rock movements take place (due to the thermal load of the wastes or to tectonic displacements). It has a high capacity to deform and a very low hydraulic conductivity, efficiently limiting the flow rate of water that can contact the canister and carry away any dissolved nuclides. It also has a high sorption capacity that retards radionuclide migration. Diffusion of anionic species is impaired by the mechanism of ion exclusion, and diffusion of cationic species is retarded by sorption processes. Compacted bentonite expands when absorbing water from the surrounding rock during resaturation and develops high swelling pressures which cause it to enter, fill and seal any voids in the surrounding near field region. In typical groundwater found in crystalline rocks, expanded bentonite extruded into voids forms a gel-like mass and does not release any particles to slowly passing water, so is not prone to physical or chemical erosion. Bentonite is chemically very stable in the brackish groundwater expected to occur in typical hard rock repository locations. It is also stable at temperatures lower than 100°C. As a consequence, repositories incorporating bentonite based engineered barriers should be designed to meet that temperature limit.

Compacted clay has very small pores and forms an effective filter for any colloidal particles that could be released from the degrading waste form and might otherwise be able to sorb and transport radionuclides. Any hydrogen gas formed by the corrosion of iron can escape through compacted bentonite by forcing open and flowing through microscopic pathways [89, 90]. These pathways close again when the pressure drops after the release of the gas. Bentonite is very stable in deep groundwater that is at equilibrium with surrounding rock minerals. Strong acids or bases can degrade bentonite, and its properties could potentially be affected by the very alkaline pore water of concrete, if they were to come in contact. Highly saline waters affect the swelling capacity of compacted bentonite markedly, and a bentonite buffer may not perform adequately if the salinity of the groundwater approaches brine concentration levels.

The physical and chemical evolution of bentonite in a repository environment is now well understood. Issues that remain to be explored in more depth include:

(a) Development of a workable method of emplacing the buffer on a routine basis in an active, working repository environment;

(b) Evaluation of the impacts of variable resaturation rates (as may occur in fractured rocks with spatially variable inflows of water to tunnels and deposition holes) on the development of the bentonite's properties;
(c) A more detailed understanding of the combined effects of dissolution and mineralization processes along the temperature gradient away from a waste container and of whether these might affect diffusion or gas release properties.

3.4.2. Role of the repository backfill

The crushed rock backfill used to fill the bulk of void spaces in a repository is intended to reduce the hydraulic transmissivity of openings and to provide support to prevent large scale failure and consequent significant movements in the surrounding host rock. In concepts involving the use of swelling bentonite buffers in canister deposition holes below the floors of galleries, the backfill has to be dense enough that the buffer does not extrude into the galleries and lose its properties. In the case that mixtures of bentonite powder and crushed rock are considered as a massive backfill material to seal tunnels, special attention has to be paid to the density of the material in order for it to retain its properties (swelling capacity) in brackish or saline groundwater environments. In LILW repositories containing large amounts of metal, the backfill may need to be designed to allow the escape of hydrogen gas produced by corrosion: both crushed rock and porous cement have been evaluated. In salt repositories, the backfill, consisting of crushed salt, is expected to creep and recrystallize becoming part of the surrounding salt mass and completely sealing openings. These varied demands mean that backfills need to be designed with a range of porosities, hydraulic conductivities and mechanical strengths. This is normally achieved by crushing rock spoil from the excavations, grading the spoil into different size ranges and then mixing with sand or clay if necessary. Some repository designs require the use of a mixture of dried bentonite powder or pellets with sand, which is then sprayed into place.

There has been limited practical testing of backfill compositions and emplacement, but there is almost no large scale experience in the emplacement of backfills and in the evaluation of their long term development. The extent to which homogeneous properties can be produced in an inhomogeneous rock and groundwater system and the effects of mineralogical reactions between fresh rock surfaces and groundwater or pore water from nearby EBS materials (such as cement) have not been fully tested. Repository developers need to evaluate how important it is to have predictable properties in different types of backfill. In some concepts, the overall safety achieved may be insensitive to backfill behaviour. Where performance of the containment system does depend on backfill properties, long term experiments might usefully be considered in forthcoming URL programmes.

3.5. CONSTRUCTION MATERIALS

It is difficult to conceive a geological repository being built without some use of concrete and other common construction materials. In addition to making the underground construction possible these are needed to secure a safe working environment for long periods of time. Concrete will be used for lining shafts and drifts or as shotcrete sprayed on the walls and roof. In host rocks with significant groundwater flow it is necessary to limit the water inflow into underground openings by sealing the fractures, especially fast flow features often related to ‘channelling’, using cement based grouts. Cement is also needed to attach the rock bolts necessary to provide additional stability to repository rooms.

The construction materials used and their potential impact on the waste form or other EBs, as well as on these properties of the host rock significant in relation to long term waste isolation, have to be considered in terms of long term safety. Special attention should be paid to such materials, injected cement grouts for example, which are virtually impossible to remove from the repository before closure.

3.6. MOBILIZATION OF RADIONUCLIDES

Radionuclides can be mobilized as soon as waste containers are breached and water comes into contact with the waste. The time at which this may occur depends on the repository concept and can vary from a few decades after closure (for some categories of LILW in simple concrete or steel containers) to hundreds of thousands of years (for spent fuel in copper containers). As discussed previously, some radionuclides may be released readily as soon as water comes into contact with the waste (e.g. the so-called instant release fraction on the surface of spent fuel), but mobilization of the majority of radionuclides, from any waste material, depends on the rate at which the matrix of the waste form dissolves in groundwater. This, in turn, depends principally on the groundwater composition and on the occurrence of radiolytic processes (for HLW and spent fuel) that can produce locally oxidizing conditions at the waste surface. For many waste forms, the groundwater may already be close to saturation for some elements present in the matrix (e.g. silica, aluminium and uranium as a result of rock–water equilibrium conditions). Consequently, the amount of waste material that can dissolve will always be small, as groundwater conditions are naturally close to chemical equilibrium. In addition, when processes are driven by diffusion, dissolution is very slow. Mobilization of radionuclides can be enhanced by microbes introduced into the disposal system during the operational period. Potential long term effects of microbial activity on the performance of the isolation barriers and on the migration of radionuclides should be evaluated.

Anaerobic species will be most significant for repositories located below the water table, while aerobic species will dominate any biological activity in the unsaturated zone.

3.6.1. Waste form dissolution

The waste form will dissolve very slowly and give rise to radionuclide release. For example, borosilicate glass is not thermodynamically stable and will slowly form secondary minerals at its surface on contact with water. During this slow change some of the radionuclides in the changing surface layer will not be reincorporated into the secondary phases formed. The radionuclides can then dissolve in water and migrate away. Some of the secondary phases, among them clays, will have good sorption properties for most cations. Some of the material from the glass surface layer may enter surrounding water as colloidal particles, which may contain radionuclides. These particles cannot migrate through the clay buffer as the pores are too small, and they are effectively filtered out.

The solubility of many radionuclides in water is extremely low, such that, even if they were released from the waste form, the whole inventory could not be dissolved. Particularly under reducing conditions (the prevailing natural conditions of deep groundwater), technetium and many of the redox sensitive actinides have very low solubilities. Therefore, they cannot migrate away at the same rate as they are released from the degrading waste matrix, and precipitates may form in the altered layer.

Diffusion through the matrix of vitrified waste, cementitious waste and bitumen, as well as the uranium oxide crystals of spent fuel, is a very slow process and does not contribute noticeably to radionuclide release. Diffusion may play some role in the altered layers of the waste matrices. It is, however, the rate of formation of the altered layers that determines the overall release rate. Intercrystalline diffusion between crystals in spent fuel facilitates the release of the fraction of nuclides that has accumulated at the crystal boundaries. Some mobile radionuclides (particularly ^{129}I) also congregate in the gap between the fuel and its cladding. Intercrystalline and 'gap' inventories are released as soon as water breaks through the cladding. A so-called instant release fraction then constitutes a primary control on the performance of the repository.

Glass dissolution is not sensitive to redox conditions in the water at its surface. This is in contrast to the conditions for spent fuel [89]. Uranium is present in spent fuel as uranium dioxide, in the tetravalent oxidation state. Tetravalent uranium is very sparingly soluble in reducing groundwater and the dissolution of the fuel will be extremely slow. However, the redox conditions may be influenced by radiation, since radiolysis may split the water molecules, producing radicals which are highly reactive. They can react with themselves forming oxygen, hydrogen peroxide and hydrogen, but may also react with dissolved radionuclides and with the waste matrix. Hydrogen is inactive under repository conditions; it also forms a small and highly mobile molecule. It is generally assumed that most of it will escape from the near field, leaving the oxidizing components behind. Uranium dioxide, when oxidized, cannot retain its original crystal structure. In addition, uranium oxidized to the hexavalent state is much more soluble, especially in the presence of carbonates in the groundwater. The oxidation of the crystal surfaces will release the radionuclides that were originally present inside the crystals. However, the buffering capacity of the EBS and the geosphere will again give rise to reducing conditions and thus allow for immobilization of these radionuclides.

Bitumen can also be degraded by oxidizing radicals and by the oxygen and hydrogen peroxide resulting from radiolysis. Bitumen will break down and form increasingly soluble fragments.

The most important source of oxidizing substances is alpha radiolysis because the reactions take place very close to the surface of spent fuel pellets so the oxidants have a very short distance to migrate to reach the fuel. Competing scavenging reductants such as organic material (in a bentonite buffer) and ferrous iron minerals in the clay and rock, and even the iron of an iron canister or its corrosion products, are generally present at much larger distances and have to be reached by molecular diffusion. A considerable amount of the oxidants produced near the fuel surface can potentially react with it. Radionuclides that sorb or precipitate in the backfill can also give rise to a low level of radiolysis and oxidant production. All these sources of oxidants, as well as hexavalent uranium, which itself is an oxidant of organic matter and ferrous ion compounds such as pyrites, can deplete the reducing capacity of the near field and cause an oxidizing zone to develop. This oxidizing zone could eventually reach the rock and penetrate into fractures with flowing groundwater.

Thus, the main factors controlling radionuclide release from any waste form are:

- Waste surface area exposed to water,
- Location of radionuclides in the waste matrix,
- Water composition and rate of access to the waste,
- Solubility limits for certain radionuclides,
- Potential for radiolysis.

These factors are well understood for most wastes and disposal environments and, while there is still ongoing research taking place to evaluate the details of, for example, spent fuel dissolution (particularly MOX fuel), the data required for SA and design purposes are considered to be adequate.

3.6.2. Transport mechanisms through the buffer and backfill

Once radionuclides have been mobilized from the dissolving waste form and the region of the degraded containers, they must pass through the buffer and backfill before they can start migrating into the surrounding rock.

Buffers based on clays are designed to have very low permeability to water flow. The advective transport by water of dissolved radionuclides is generally considerably smaller than that due to molecular diffusion. Dissolved radionuclides will diffuse in the pore water in the clay. Uncharged molecules will interact little with the surfaces of the clay [91]. Negatively charged (anionic) species will have a smaller accessible pore volume to move in because of the repulsive electrical forces from the negatively charged mineral surfaces. The rate of transport of iodine, as iodide, for example, will be much less than that of uncharged species. Positively charged species (cations), the form in which the majority of radionuclides exist, will be attracted by the surfaces.

The actinides are generally strongly sorbed and retarded. Some alkali and alkaline earth metals are mobile within the concentrated layer at the surface of the clay particles. The transport rate of these substances can be considerably larger than that of uncharged species. Although these species are concentrated within the clay by what would be called sorption, they are to some extent mobile in the sorbed state, and thus not as effectively retarded as other species that are sorbed by specific interaction forces (surface complexation). The latter are retarded in their migration through the clay, and tend to have a much longer residence time in the near field than that of non-charged species. This allows for more decay.

The salt content of clay pore water has a strong influence on ion exclusion and surface migration. These processes are quite pronounced in low salinity waters and their effect decreases markedly when the waters become more salty. The sorption of the actinides is influenced by the salt content of the water much less than that of alkaline and alkaline earth metals.

The groundwater flow rate in low permeability rocks is so small that this can strongly limit release from the near field. For example, uptake of radionuclides into the water flowing past a compacted bentonite buffer can be considerably smaller than the possible migration rate through the backfill. The backfill properties then no longer determine the escape rate from the near field. This is not an uncommon feature of low permeability crystalline rock environments. The backfill becomes a limiting barrier in the case that the water flow rate in the rock becomes large, for some reason.

Backfills containing cement buffer the geochemical system at high pH, reducing radionuclide solubilities; they also display good sorptive properties. Migration of radionuclides across cement walls, liners and backfills is initially limited to diffusion, owing to the low hydraulic conductivity of the intact material. There is more likelihood, however, that a cement EBS will degrade and crack than a bentonite buffer. It is generally assumed that after several hundred years that cement and concrete will have degraded to such an extent that advective flow can occur through them, at rates similar to the flow through surrounding rocks.

3.7. GAS PRODUCTION AND ITS CONSEQUENCES

Hydrogen gas formed by corrosion of iron will partly dissolve in the pore water of the surrounding EBS and diffuse out to the mobile groundwater. If this escape rate is less than the gas production rate, the gas pressure will build up to become larger than the water pressure in the surrounding rock. For the gas to escape through a bentonite buffer (if present), the pressure must also be able to overcome the capillary pressure in the fine pores of the material. The capillary pressure, which is about as large as the swelling pressure of the clay, depends on the degree of compaction of the clay and can be of the order of many tens of bars. The gas will force its way through the clay in microscopically small capillaries, which are later resealed when the gas has passed.

Gas would escape readily through a fractured concrete or porous cement backfill, but if there are no fractures, then pressure buildup may actually contribute to fracture development.

Provided the gas production rate is matched by the gas dissipation rate, the consequences for the physical stability of the near field of any deep repository are considered to be insignificant. Nevertheless, the escape of a large amount of hydrogen gas from the surface does need to be evaluated on a site specific basis, particularly if the escape were to occur over a relatively short period and be focused along a small number of major conductive features in the rock [92].

4. FAR FIELD BARRIERS AND PROCESSES

The geological environment is expected to contribute to the safety of disposal by playing three main roles:

(a) Providing physical isolation of the wastes from the near surface environment and the potentially disruptive processes that occur there;
(b) Maintaining a geochemical, hydrogeological and geomechanical environment favourable to the preservation and performance of the EBS;
(c) Acting as a natural barrier restricting the access of water to the wastes and the migration of mobilized radionuclides.

The relative importance of the three roles is not the same in all disposal concepts. In fact, significant variations are possible as a consequence of the nature of the host rock and the design of the repository. Thus for a repository in hard crystalline rock, roles (a) and (b) are likely to be the most important ones, while for a repository in rock salt or argillaceous sediments, role (c) is expected to dominate.

In addition, by acting as a stable cocoon that smoothes out the effects of near surface processes at depth, both spatially and temporally, the far field makes it easier to predict the long term behaviour of the wastes and the EBS. Consequently, the far field provides stability to the disposal system by assuring that processes in the disposal zone occur extremely slowly, such that changes in the physical and chemical surroundings of the EBS are small over time periods of hundreds of thousands of years.

In greater detail, stability can be defined in terms of the following desirable characteristics:

(1) Absence or very low probability of tectonic and exogenous processes or events that could produce significant changes in the host rock on a timescale of hundreds of thousands of years (e.g. faulting, volcanism, uplift and erosion).
(2) Lack of susceptibility of host rock and groundwater flow to major climatic changes and related events such as the site being covered by ice, water or permafrost.
(3) A geotechnically stable rock mass located in an area characterized by a stable stress field, allowing the excavation of openings large enough to accommodate the necessary tunnels and rooms at a depth of some hundreds of metres.
(4) A low energy groundwater system, which could result from various combinations of low hydraulic gradients over a large region, low recharge over considerable periods of time (which could be associated with very long term climate stability in the area) and low hydraulic conductivity of the host rock and/or surrounding formations; such systems will generally exhibit very old groundwater at repository depth.
(5) Chemical conditions which, if the repository is planned to be in the saturated zone, are controlled and buffered by equilibrium between groundwater and rock forming minerals, in a reducing environment.

At the most extreme level of stability, the far field would display properties that would not change at depth over millions of years, would not be significantly perturbed by the presence of the repository and would result in the groundwater present at repository depth being practically stagnant. In such environments, a very simple EBS would be sufficient, as practically all the requisite containment capacity would be provided by the geological barrier.

Since such ideal disposal environments are not found in many countries, it becomes necessary to increase the containment capacity of the near field, which involves devising a reliable EBS, such as the waste packages and the buffers described in Sections 3.2–3.4. The principal reason why more sophisticated EBSs have been found to be necessary is because many groundwater systems, particularly in fractured rocks, are relatively dynamic down to depths of several hundred metres. Thus, there is much emphasis in geological disposal programmes on the characterization of the groundwater flow system so as to assess both near and far field performance.

4.1. TRANSPORT IN GROUNDWATER

Radionuclides released from the near field as solutes in groundwater will enter the pore and fracture system and be transported by diffusion or advection. For diffusion to play an important role in transport, the rocks must be extremely impermeable, with hydraulic conductivities as low as 10^{-12} m/s, or the hydraulic gradient driving advection must be negligible. Such low hydraulic conductivities are only found in some categories of argillaceous rocks, in which the connectivity of pores is highly restricted and any fractures present are sealed under the stress conditions at depth.

For many repository concepts, particularly when crystalline rock is the chosen disposal medium, advection of water through rock fracture systems is the key transport mechanism for radionuclides. This means that the nature of fracture networks and their hydraulic properties need to be well understood. Much work has been carried out in this area, over more than twenty years [93–99]. Table III gives details of the different host rocks and their characteristics relevant to groundwater circulation and radionuclide transport.

4.2. SOLUTE PATHWAYS

Any radionuclide released from the repository will normally have to flow through the host rock matrix before entering a fracture network or nearby water bearing layers such as a sedimentary cover. In crystalline environments, blocks of rock where radionuclide migration is controlled by matrix properties are limited by fractures on their boundaries. In sedimentary environments, the rock matrix remains continuous over large distances; small fractures may occur and regional scale fractures may determine hydraulic boundary conditions.

4.2.1. Rock matrix properties

Rock matrices are made up of individual, generally small, crystals, which are often separated by microscopically small pores or microcracks that form a continuous

TABLE III. HOST ROCKS, ROCK CHARACTERISTICS, GROUNDWATER FLOW AND RADIONUCLIDE TRANSPORT

Host rock		Rock characteristics and groundwater regime	Radionuclide transport mechanisms
Crystalline rocks	Granite Gneiss	Fractured rock Groundwater flow in open fractures Some flow in fractures is possible	Transport by advection Some transport by diffusion
Argillaceous formations	Strongly consolidated clays: claystone, mudstone Consolidated clays: shale, marl Plastic clays	No open fractures Stagnant pore water	Transport by diffusion
Rock salt	Bedded salt Salt domes	No open fractures No pores No groundwater	No transport (possibly transport with fluid inclusions during thermal phase only)
Volcanic tuffs	Above water table	Fractures and pores, unsaturated Occasional flow of percolation water	Possibly some transport with percolation water

network of pores. The porosity of the matrix can vary strongly between different rock types. Sedimentary rocks, i.e. rock salt, mudrocks and soft clays, have porosities ranging between a few per cent and tens of per cent or more. Crystalline rocks, such as granites and gneisses, have much lower porosities, typically ranging from 0.1 to 0.5%. However, the determining factor for transport processes is the connectivity of pores rather than the porosity.

4.2.2. Fractures and fracture zones

Consolidated hard rocks have been subject to strong stresses and changing stress fields over geological times. The stresses have induced fractures of varying magnitudes. On a very large scale there are major fracture zones that can be hundreds of metres wide and extend for tens of kilometres or more. They can be seen on aerial photographs. The larger ones are often visible on maps and from the air as they affect topography by causing valleys or scarps.

Major fracture zones delineate large rock masses that usually contain smaller fracture zones. These in turn can bound rock volumes that contain progressively smaller blocks of rock bounded by progressively smaller fracture zones. Eventually small fracture zones can consist of clusters of a few fractures with a thickness of a few tens of centimetres. The distance between individual fractures can range between tens of centimetres and tens of metres or more, depending on rock type and location. The fractures and fracture zones, if not sealed by the deposition of secondary minerals, form conduits for water flow and solute transport. The fracture sealing materials generally consist of alteration products, such as clay minerals, or minerals accumulated by chemical deposition, for example quartz or carbonates. Fracture filling can strongly influence the hydraulic properties of flow paths and the migration of solutes.

4.3. HYDROGEOLOGY AND WATER MOVEMENT

4.3.1. Flow of water

Under saturated conditions, the driving force for groundwater flow is the pressure head gradient. The way water moves through the rock is controlled by its hydraulic properties. In permeable and homogeneous rocks the water flow takes place according to Darcy's law and is easy to predict. In fractured rocks, all or most flow occurs in fractures and fracture zones. The hydraulic conductivity of the matrix in dense crystalline rocks and compact argillaceous rocks is so small that water flow there is negligible. In more porous sedimentary rocks and tuffs, water can also move in the rock matrix between fractures. Flow in fractured rocks is significantly more difficult to characterize in detail.

In the vadose zone, water movement, while basically controlled by gravity, tends to be more complex and variable. In respect of geological repositories, unsaturated flow is relevant only when the disposal zone is above the water table or to understand the upper regions of potential migration pathways.

4.3.2. Water pathways

In many environments studied for geological disposal, fractures and fracture zones are the pathways for water movement. The hydraulic properties in the individual fractures and fracture zones are very variable. The hydraulic transmissivity of the features typically varies by many orders of magnitude at closely located points in the same feature. Most of the water flow will take place in that part of the discontinuity where the transmissivity is largest. Such pathways on the plane of an individual fracture will connect to other pathways in other fractures to form a complex three dimensional network of water conducting ‘channels’. In site investigations, it is practically impossible to locate all important water pathways deterministically, but the stochastic properties of the transmissivities found can be used to build models where the expected characteristics (permeability, flow rates and travel times of radionuclides), as well as their expected variability, can be estimated [96, 98].

4.3.3. Channelling

Owing to the extremely large variability in flow and transport properties of individual fractures, there is a probability in fractured rocks that connected fast pathways exist from the repository to the accessible environment. This is often called channelling. The understanding and quantification of the potential impacts of channelling on the performance of individual barriers or on the overall safety of a repository are being intensively studied at present.

4.4. WATER CHEMISTRY AND CHEMICAL RETARDATION

4.4.1. Chemical setting and sorption

Free moving water is the main transport medium for solutes, including radionuclides. However, radionuclides react with rock materials in widely different ways and most move at a much slower pace than the water. In areas with low fluxes, the water velocity has little influence on the migration of most radionuclides. A few radionuclides, in particular those that are present in anionic form (such as iodine and chlorine isotopes), interact little with rocks and migrate at the same velocity as the water flow. For the majority, however, it is the interaction with the rock that determines their rate of movement. The interaction is both physical and chemical, the latter causing the largest retardation effects. The salinity of the groundwater has also an impact on retardation; for a reliable estimate of radionuclide migration, it is thus essential to understand the chemistry of the water–rock system.

4.4.2. Rock and water chemistry

The basic composition of some common host rocks has been described in the section on the near field (Section 3). Some additional aspects with a special bearing on the performance of the far field are described here. The overall composition, pH and redox (Eh) properties of water in rock are buffered by the interaction between the water and the rock forming minerals. Owing to the long residence time typical of most candidate host rocks, geochemical equilibrium generally exists between water and minerals. Understanding the processes that regulate water chemistry is highly important because this allows prediction of its evolution in the presence of the foreign materials introduced with the repository. Chemical equilibrium is the result of various ongoing processes, such as the dissolution of rock forming minerals and the precipitation of secondary minerals. Under natural conditions, the extent of the reactions is very small; it is determined by the concentration of mobile anions in the water, mainly Cl^-, and by temperature. Low salinity waters will generally lead to alkaline conditions, whereas more saline waters will give rise to near neutral, slightly alkaline, conditions. In all cases, the water found at depths of a few hundred metres originates from past precipitation. The oxygen, initially contained in this meteoric water, is consumed during water–rock interactions. The Eh value is commonly determined by the presence of iron minerals in oxidation states II and III. Considerable amounts of minerals containing bivalent iron are present in hard rocks, often more than per cent quantities. Thus, deep geological environments are basically in reducing conditions.

Regulation mechanisms play an important role in stabilizing the chemistry and allowing the conditions under which the radionuclides are expected to migrate to be known. The solute content of the water can vary, depending on the concentration of mobile anions. The cations are generally dominated by sodium or calcium; less abundant species, such as potassium, magnesium and iron, can vary within wide limits, but always at the equilibrium concentration with the rock forming minerals. In general, the most important features of groundwater, from the point of view of radionuclide migration, are pH, Eh, ionic strength (total concentration of dissolved ions) and carbonate content.

In low flow, hard rocks the total salt content of groundwater increases with depth. At great depths very salty waters, essentially brines, have been found. This indicates that the waters have resided there for very long periods; it might also be an indication that they are likely to experience very little movement in the future.

4.4.3. Importance of secondary minerals for retardation processes

Under the equilibrium conditions existing at depth, rock forming minerals dissolve very sparingly in groundwater, either because they are protected from contact, such as rock salt, or due to their geochemical stability. However, despite their stability, some alteration takes place particularly along fracture zones and other regions where flow may be focused. Under some conditions, shallow groundwaters can temporarily penetrate deep into the rock. The substances dissolved in groundwater can react to form secondary minerals such as clay and iron oxyhydroxide minerals. Secondary minerals can have a beneficial impact on retardation of radionuclides because they generally have high sorption capacities.

At depth, alteration is a very slow process, even on geological timescales, because there is little water flow in fractures, compared with the volume of rock, and because the reactive substances in the water are present in small concentrations. The rock is therefore chemically very stable and the conditions seen today at repository depths can be anticipated to remain substantially unchanged during the time of interest for a repository for long lived radioactive wastes. However, performance assessments will need to analyse this assumption with care, particularly in cases where the presence of the repository might justify evolution scenarios involving variations of the conditions in the disposal zone.

4.5. TRANSPORT BY GROUNDWATER

4.5.1. Advection and dispersion

Solutes are transported by moving water and travel along the different water conducting pathways that exist in the rock. In unfractured porous rocks the flow takes place in the pores, but even in these rocks water does not necessarily move at the same rate in all pathways. In fractured rocks, the difference in water velocity among pathways and the different distances travelled cause much greater variability in the advection velocity. This results in a wide spread of the travel times of the solutes among different pathways, which is generally referred to as dispersion.

4.5.2. Transfer between water and rock

The solutes transported by water along the flow paths can, by random movement or molecular diffusion, find their way into the pores of the surrounding rock matrix. This is called matrix diffusion. The total water volume of the matrix is generally larger than the volume of flowing water. In many low porosity rocks the water in the pores is practically stagnant. The solute that has accessed the stagnant water in the pores of the matrix will diffuse within a relatively large volume of water, being thus temporarily removed from the flowing solution. This purely physical effect can contribute considerably to prolonging the travel time of the radionuclides.

4.5.3. Sorption and retardation

Radionuclides exist in water in ionic form or as uncharged complexes. Rock forming minerals in the majority of candidate host rocks have negative surface charges under the chemical conditions prevailing at depth. The positively charged species will be attracted to the surfaces by the opposite charges and can concentrate in the very thin layer of structured water molecules surrounding the mineral grains.

The mass of radionuclides held in the layer of bound water can be orders of magnitude larger than the mass residing in the free pore water. This sorption process can be thought of as ion exchange and can thus be expected to be strongly influenced by the salinity of the groundwater, higher salinities decreasing its effect.

The species bound by the diffuse electrostatic forces described above have, in many cases, been found to have very low mobility along the surfaces. Thus, although they are accumulated on the surfaces and withdrawn from the truly mobile pore water, they can still migrate, but with much lower velocities. Caesium and strontium exhibit this sorption and migration mechanism.

The mineral surfaces also have a large density of reactive groups. Silica, aluminium and iron oxides, present as hydroxyl groups, can form surface complexes with many radionuclides, especially the actinides. In many cases radionuclides in the neutrally charged, dissolved complexes can also be bound to the surfaces. This process is called surface complexation. Both these sorption mechanisms are reversible, and if the concentration of the radionuclides in the water decreases the attached species can be released, depending on competition effects. Other minerals, for example carbonates and phosphates, can also contribute to the sorption capacity. Sorption by surface complexation has been found to be less sensitive to the salinity of groundwater than sorption by true ion exchange. Most actinides are sorbed by surface complexation.

The amount of mineral surfaces available for sorption is thus a key factor and will determine the extent to which the radionuclides can be extracted from the water moving in the fractures, and from the stagnant pore water which they entered by molecular diffusion. These sorption processes are extremely important as they can retard significantly the movement of radionuclides in respect of the water moving freely within the fractures. The larger the ‘flow wetted surface’, between the flowing water and the rock, the more efficient will be the retardation of the radionuclides.

4.5.4. Colloidal transport

There are concerns that colloid particles can move with the velocity of water and that any radionuclides attached to them will thus not be retarded by the retardation mechanisms described above.

Three types of colloidal particles can be considered:

(a) Rock debris transported within the water flow; such processes are well known in surface waters, or in fast flowing waters, which is not the case for deep geological environments such as those which are required for disposal.

(b) Natural colloidal particles, consisting of natural polymers of silica, aluminium, iron or other materials; such colloids can be formed in the early stages of alteration processes, but in deep geological environments equilibrium has been reached between water and well formed mineral phases. The presence of natural colloids would also reflect short residence times of water, which is not the case for deep geological environments such as those required for disposal.

(c) Colloidal particles which can form from radionuclides and other materials released from waste packages; these colloids must escape being filtered by EBSs or by the rock matrix if they are to be of concern.

Much work has been performed to sample colloids and analyse their possible role, but there are still some basic questions in regard to the potential significance of this transport mechanism.

4.6. FLOW IN PARTIALLY SATURATED ROCKS — TUFFS

Some transport mechanisms are specific to partially saturated conditions. The only geological repository being considered in partially saturated rocks is that at Yucca Mountain, Nevada, USA. This rock is a welded volcanic tuff with rather high porosity and permeability, it is fractured on different scales and contains a large proportion of amorphous vitreous phases, with crystalline phases such as zeolites. Water in the rock is to a large extent contained in the fine pores of the rock matrix. This water is strongly bound by capillary forces and is essentially immobile. The pores are air filled and the conditions are oxidizing.

The repository will be located several hundred metres above the water table. Normally there will be little water in the rock, but heavy rains (although infrequent) may cause water to infiltrate rapidly along large fractures and fracture zones. Some water will be drawn into the partially saturated matrix by capillary suction forces. Fractures with less water flow can be sucked empty by matrix inhibition at some point above the water table. In fractures with high water flow rates the water may flow down to perched or regional water tables.

The water that has entered the rock matrix can either move upward to the surface again to evaporate during dry periods or slowly move down to the water table.

For a long time after the emplacement of heat generating waste containers, there is little chance that water will reach them because decay heat generation keeps the canisters warm and water in the vicinity evaporates and moves outwards by vapour flow and diffusion to condense again in colder regions. A counteracting driving force is the capillary suction that draws the water towards the regions with less capillary water. This process is sometimes called the heat pipe effect and contributes strongly to heat dissipation from canisters.

Radionuclides that eventually escape from the wastes may dissolve in the moisture in pores. Radionuclide bearing pore water may be transported by infiltrating water during periods of heavy precipitation if it occurs in proximity to a high flow feature. The dissolved radionuclides may also migrate by molecular diffusion in the water films in the rock matrix if the films are continuous. The films will be more continuous at higher water saturations.

4.7. LONG TERM STABILITY OF THE DISPOSAL SYSTEM

The stability of the geological environment is important for the very long periods of time during which waste isolation is required; this is usually far beyond the time frame of any kind of human activity. Stability does not mean, however, that there will be no changes in the geological environment. On the contrary, when developing and assessing the disposal system, the natural evolution of the geosphere needs to be considered. The long term evolution of the geological environment may comprise slow or episodic processes. On the basis of the knowledge accumulated in the field of earth sciences, these processes are well understood and therefore their impact on the disposal system, and predictions on the likely behaviour of the natural barriers, can be estimated to assess their importance in respect to the long term safety of the repository.

From the geological disposal perspective, in particular in relation to the long term safety of the system, there are two categories of natural events and/or processes to be considered. The first category includes tectonic and magmatic activity. The second category includes weathering and erosion. The processes in the second category may be influenced by climatic changes resulting in changes of near surface water circulation and glaciations. Table IV gives details of the key processes and their effects on groundwater and radionuclide transport and on the repository.

4.7.1. Tectonic stability

In general, there is a wealth of information available which allows the geological history of any particular area to be assessed over the past 1–10 million years, and hence to make predictions for scenarios of future evolution and their effects on the disposal system, groundwater circulation and radionuclide transport.

Furthermore, investigations such as periodic geodetic surveys, global positioning system (GPS) surveys for detection of vertical and horizontal crystal movements, earthquake monitoring, and satellite and aerial photographic analyses for detection of active faults and associated displacements produce scientific data on tectonic stability. The continuous accumulation of this type of information together with knowledge of the geological history increases confidence in the scenarios of future site evolution.

TABLE IV. LONG TERM EVOLUTION OF THE GEOSPHERE AND EFFECTS ON GROUNDWATER REGIME, RADIONUCLIDE TRANSPORT AND REPOSITORY SYSTEM

Key processes	Key effects	Effects on groundwater and radionuclide transport	Effects on repository
Tectonic and magmatic activity	Fault movements Crystal uplift/subsidence Earthquakes Volcanism	Shift of groundwater infiltration zone Shift of exfiltration zone (outlet) of radionuclide containing groundwater and affected biosphere (surface water) Change of hydraulic gradients and rock permeabilities Change of redox conditions of groundwater Variations of water table level and of groundwater composition	EBS disturbance due to fault movements Repository exposure due to erosion of overlying rocks
Weathering, erosion	River erosion Sedimentation		
Climatic changes: glaciations	Glacial erosion Permafrost Sea level changes Regional isostatic subsidence/uplift		

4.7.2. Potential impacts of climate change

During the Quaternary period the earth has been subjected to repeated cycles of glaciation that have resulted in periodic ice cover of large parts of the northern hemisphere [70, 71]. It is expected that the next 100 000 years or so will see one or two further cycles of glaciation, with the potential for more in later periods. In addition, anthropogenic factors may cause short term variations that are not expected to modify this long term trend significantly. The climate cycling in the Quaternary has caused global changes in sea level. At present, sea levels worldwide are close to their Quaternary high; a future glaciation may result in a fall in global sea levels of up to about 150 m and in changes in rainfall and consequent groundwater recharge patterns.

Ice sheets have covered immense areas of what are currently land and sea. Ice over 1000 m thick has depressed the land in ice covered regions far below present day sea levels. In northern Scandinavia there is still considerable rebound taking place from the most recent ice cover about 10 000 years ago. Current isostatic rebound can be of the order of half a metre to a metre per 1000 years and may induce changes of the stress field and cause movements along shear zones.

The consequences of a glaciation need to be considered when evaluating how a repository will evolve over the next 100 000 years or more:

(a) Sea level fall will affect coastline position and consequent drainage patterns, erosion rates and hydraulic gradients in deep groundwaters. The chemistry of deep waters may also be modified if, for example, more saline waters are flushed by fresh waters. The discharge points of deep waters to the biosphere will move, which could significantly affect the dilution and dispersion of far field releases.
(b) At the margins of ice sheets a high hydraulic gradient may occur. This might cause considerably larger water flow rates infiltrating from under the ice to pass through the repository and to emerge in regions where there is no ice. The intruding melt water could be nearly saturated with oxygen.
(c) Ice cover significantly increases the lithostatic load at repository depth, and movement and readjustment, both during and after glaciations, may cause enhanced stress and strain along certain fracture zones and in their vicinity; the potential for disturbance of the EBS needs to be considered.
(d) Periglacial regions, unaffected by ice cover, may develop thick layers of permafrost that could penetrate several hundred metres into the rock, again modifying groundwater flow patterns. Permafrost development progressively modifies groundwater chemistry. Variations in water flow, chemistry and discharge points should be taken into account.

5. CONFIDENCE IN ADEQUATE ISOLATION

5.1. CONTAINMENT REQUIREMENTS

In the development of a safety case for a deep repository, national regulations governing radiological safety will be used to gauge whether requisite levels of containment appear to be achievable by a proposed disposal system. Clearly, these regulations concern principally the acceptability of the radiological impact of releases of radionuclides when they reach the biosphere, in terms of radiation doses and associated risks. They may also contain specific non-radiological performance requirements for separate components of the disposal system, stipulating, for instance, the minimum acceptable duration of container integrity. In due course, it is also likely that regulations will impose nuclear safeguards constraints on geological repositories containing fissile materials. Several Member States are also paying increasing attention to the issues of waste retrievability or reversibility of disposal operations, by trying to evaluate the implications and the possible requirements of such options for the design of repositories and for the characteristics of the wastes which they may contain.

The time periods of containment and the times that need to be considered in SAs are often discussed. In some countries, it is required that radiological impacts on human health be estimated quantitatively for all time after repository closure, while others recognize the increasing uncertainty involved in such estimates and require alternative measures of acceptability to be used after a given time; values between 10 000 and a million years after closure have been proposed. A point about which almost general consensus exists is that the time of the assessment should include the time when the peak radiological impacts of the repository are expected to occur. In regulatory guidance it is often emphasized that the SA should be conservative. In other words, the safety case should endeavour to overestimate the radiological impacts. The purpose of this conservatism is to mitigate the influence of uncertainty and thus increase the safety margins of the system.

Developing a transparent and appropriate set of regulatory performance measures against which to judge containment requirements is thus an important early step in a disposal programme. The nature of the regulations will be one of the factors that influence the type of information which is required from R&D and site characterization programmes [100–102].

5.2. COUPLED PROCESSES

Many of the processes described in Sections 3 and 4 can influence each other and, consequently, need to be considered in the assessment of repository performance in a coupled way. While coupling of processes is particularly important in the description and modelling of the near field barriers, consideration of their potential impact will be necessary also in the far field.

The temperature rise within the repository is a critical factor in a series of possible processes. Effects include the stress distribution within engineered barriers and the host rock. Additional phenomena that can be affected are flow of fluids, biological activity, physicochemical and thermodynamic conditions. A good understanding of such coupling of processes is essential for the reliable assessment of repository performance and for the production of a convincing safety case.

5.3. UNDERGROUND INVESTIGATIONS

A reliable understanding of the behaviour of a disposal system in a particular host rock will eventually require that in situ experiments and other R&D work be performed at representative disposal depths. This information is needed for the detailed design of the repository and the optimization of the EBS in accordance with the site specific geological conditions.

5.3.1. Underground research laboratories

The above requirement has led to the establishment and operation of a number of URLs. Such facilities allow the study and clarification of the characteristics of a candidate host rock, the effects of excavation and the engineering aspects of repository construction. The coupling of processes, as mentioned above, and the performance of particular components of the repository are also important aspects that can be investigated in such facilities. All of these aspects are essential for the reliable modelling of repository performance.

5.3.2. Demonstration activities

Repository development programmes are likely to include underground activities connected with licensing and especially aimed at demonstrating that some operations foreseen in the disposal of wastes are actually feasible. Such demonstrations may refer to particular operations, such as construction of specific repository components, or to the emplacement of some waste packages and surrounding engineered barriers. The potential benefits of demonstration activities may include the optimization of the EBS and the strengthening of the PA.

5.4. SAFETY AND PERFORMANCE ASSESSMENTS

Whatever style of regulatory guidelines are set in place, SAs and PAs are the principal tools which are used to demonstrate compliance with safety standards and performance targets. Safety assessment aims at using information relative to the behaviour of the disposal system to derive the consequences of calculated radionuclide releases as a function of time, generally by reference to safety standards defined by regulations. Performance assessment seeks to quantify the evolution in the properties and behaviour of the various components of the disposal system.

SA/PA can be carried out at many levels of detail, making use of the information available at any stage of progress, and can thus be used as an iterative development and optimization tool throughout a repository programme. Typically, relatively simple SAs/PAs are used to guide the concept development stage for the selection of the safety concept and the early stages of site selection, often making use of largely generic information.

Knowledge about the future evolution of a repository over many thousands of years is surrounded by unavoidable uncertainties which must be identified and quantified. In this context, SA can be seen principally as a technique for managing uncertainty and presenting results to decision makers in a structured fashion. The entire safety case is, however, more than a calculation of the radiation doses caused by releases from the repository. However, SA/PA has to be seen in the wider perspective of a repository development programme. For example, testing and demonstration of important aspects of repository technology and of the performance of the EBS under 'real conditions' in underground facilities can be seen as a critical support of PA and thus as an important part of the safety case, since they contribute to the study of uncertainties and building confidence that the disposal system is capable of achieving the required safety targets [103].

'Multiple lines of reasoning', which make the best use of independent scientific arguments to reach consistent conclusions about the evolution of the site or the performance of particular barriers, are also an important part of a safety case. They may be effective in improving the confidence of a broader audience in the overall safety of the disposal system.

The uncertainties that need to be dealt with in a safety case are often regarded as falling into five categories:

(a) Those stemming from insufficient knowledge about the system configuration, about the interrelationships between processes or even about the processes themselves; generally prevalent in natural more than engineered systems; referred to as *system uncertainties*.
(b) Those concerning how the environment of the system will change in the future, either as a result of natural causes or human activities; sometimes referred to as *scenario uncertainties.*
(c) Those concerning the most appropriate way in which to model the evolution of the system, particularly when there appear to be alternative ways of doing so; referred to as *conceptual model uncertainties.*
(d) Those concerning the correct performance of the mathematical models used to calculate the evolution of the various system components; referred to as *mathematical model uncertainties.*
(e) Those concerning the correct values or ranges of values of parameters to be used in modelling calculations; referred to as *parameter uncertainties*.

While the final consequence analysis calculations within an SA might be relatively simple, even in a sophisticated safety case, they are always underlaid by much supporting detailed modelling and interpretation of the system being studied. It is sometimes convenient to think of an assessment as comprising three levels of activity:

(1) *Core modelling* or *R&D modelling* of detailed aspects of the behaviour and interactions of each component of a system, ranging, for example, from detailed container corrosion models to complex models of groundwater flow in fracture networks; this is part of the lengthy process of building up an understanding of a system.
(2) *Simulation modelling*, which is when the system understanding is used in a predictive mode to project forward in time and evaluate possible future evolution scenarios of the whole or parts of the system.
(3) *Consequence analysis modelling*, which is when the range of possible future behaviours of the system is used to calculate both possible radionuclide releases as a function of time and their radiological impacts.

5.4.1. Structuring safety and performance assessments

With any type of assessment, the first step is to define the exact purpose and context as this affects the way the assessment is carried out and how the results are presented and used. SA/PA may be carried out for a variety of reasons, including to compare alternative disposal concepts or sites, to optimize design, to demonstrate regulatory compliance at some important stage of the project, to identify uncertainties and thus to guide R&D activities or the site characterization programme and to illustrate impacts using different types of performance measures. Careful definition of the purpose of an SA/PA will help in deciding how it is to be carried out. For example, for a particular purpose, it may be necessary to examine only part of the system or to calculate only one type of consequence.

Setting the scale of the system to be analysed is an equally important requisite. A full SA (Fig. 2) necessarily has to examine many processes and interactions and, without a clear definition of the system boundaries, it is difficult to establish how to carry out representative calculations of system evolution. The requirement to define the system carefully has grown from experience of many SA/PA studies of geological disposal systems. Essentially the problem is that of distinguishing between what is sometimes called the ‘normal’ or ‘unperturbed’ evolution of the system and the evolution when some ‘external’ event or process acts on the system. Recent SA/PAs have handled this in different ways, but what usually emerges is some type of central case which reflects the progressive ‘as designed’ evolution of the multibarrier system under largely unchanging natural conditions, plus a set of scenarios which represents

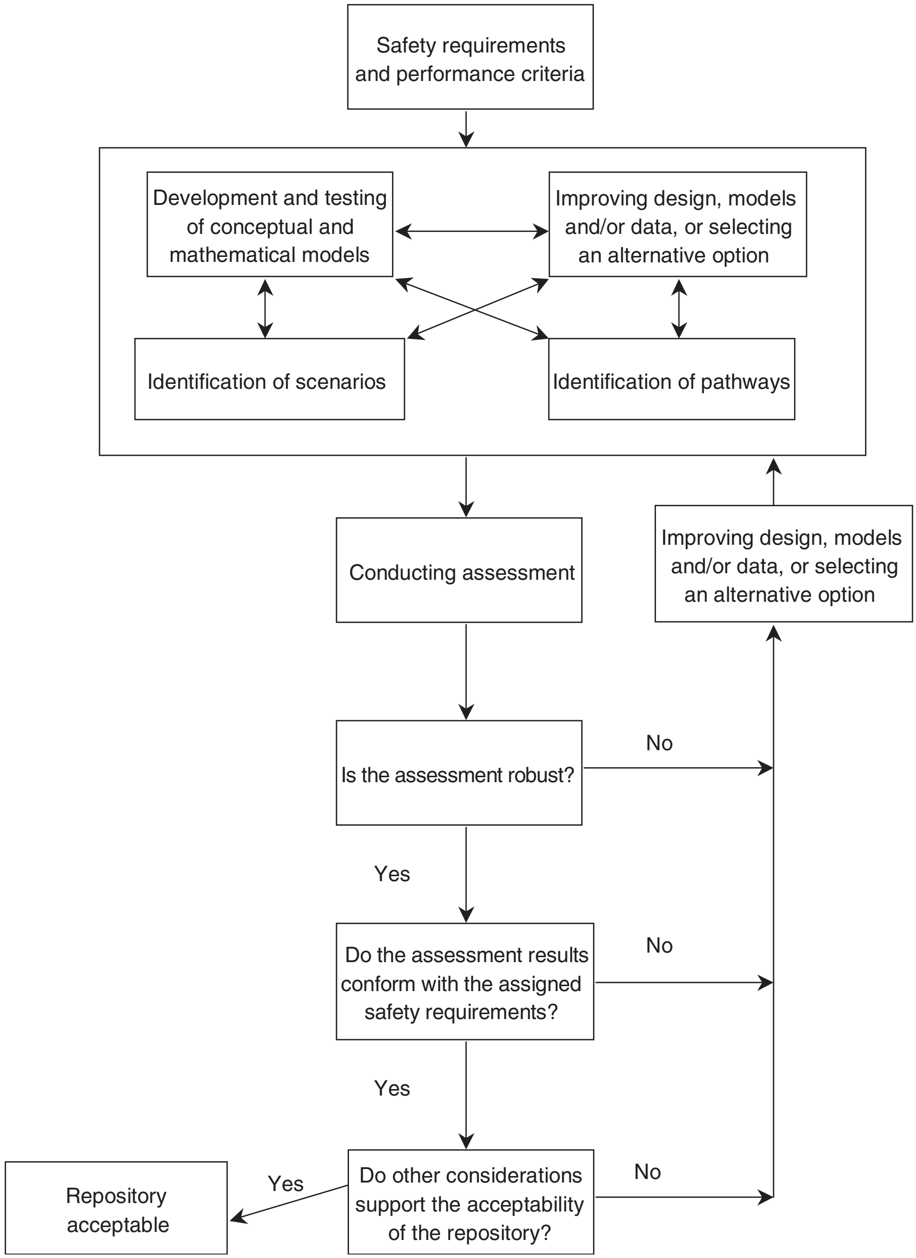

FIG. 2. Outline structure of a typical recent SA, from the system definition stage, through system analysis and interpretation, description of processes, scenario definition and analysis, to consequence analysis.

progressive or event driven perturbations to both the internal evolution and the natural driving forces outside the repository system. The need to establish system boundaries and content in this context is clear.

Having established the scale and boundaries of the system, the SA/PA modeller must then decide how to represent it geometrically. For example, in the final stages of an SA, when carrying out a consequence analysis, a model of possible migration pathways will be required in order to evaluate release mechanisms and radionuclide fluxes. Owing to the generally complex and heterogeneous nature of the natural environment it is not possible to represent actual migration pathways through the rock in a precise (deterministic) manner. The modeller must represent these schematically at a given scale or statistically. The potential for bias in this process needs to be recognized and allowed for. One approach to this is to carry out sensitivity analyses and uncertainty and bias audits, using expert reviewers. This activity is closely related to the definition of alternative conceptual models for processes, which is discussed in Section 5.4.2.

The last decade has seen a number of milestone studies which have developed the methodology of SA/PA to a high level of sophistication. Many studies have used a deterministic scenario approach to select and examine a range of possible future states of the disposal system. Because this approach can never hope to identify all possible future states of a system, it is generally considered most appropriate to provide a set of illustrative scenarios which describe situations which are clearly of interest or relevance to the site or to the concept. The guiding principle in making this selection is to have carried out a thorough analysis of the FEPs which describe the system and that may affect its behaviour, and to have evaluated the impacts of the most relevant or important of these.

There is always a problem of generating sufficient confidence that the scenarios analysed provide a reasonably complete picture of the range of possible responses of the system to the most probable and credible range of 'futures'. Some SA/PAs have addressed this 'completeness' issue using probabilistic techniques to sample a wide range of parameter values which could represent system response to many different future conditions. Each approach has its advantages and limitations and it is important to recognize that neither is able to predict the actual future evolution of the system, since this cannot be known, but only to evaluate possible ranges of behaviour. As such, it is widely accepted that both methods can provide useful information and guidance to assist decision takers.

5.4.2. Uncertainty management

The discussion above illustrates how a safety case may deal with the first two types of uncertainty (defined earlier in Section 5.4) in evaluating disposal system performance. These are the uncertainties in the description of the system itself and

Human impacts on containment

In developing scenarios of the future evolution of a repository system for an SA/PA exercise, it is important to include an analysis of the likely consequences of future human activities. These might be limited to changing the land use in the repository area, thus affecting groundwater recharge or chemistry, or they may, in the extreme, involve intrusion into the repository by drilling or excavation. While a number of SA/PAs have attempted to address these issues, this remains an area where there is continuing discussion on the most appropriate way to estimate and judge likely consequences.

Even a cursory review of the technological and social history of the last three centuries, and the way in which the surface of the earth has been developed and transformed by human activity, is sufficient to indicate that the probability that future human actions will affect a geological repository in some measure is far from negligible. This may occur within a short time relative to the expected performance life of the disposal system and could occur notwithstanding any attempts to control the site and its environs. Any significant interference with one or more components of the containment system could render large elements of the 'normal evolution' scenario central in most SA/PAs of only subsidiary relevance.

Accommodating such a possibility in the design, siting and licensing of a repository is essentially a regulatory issue and one which requires a rather different approach to that used for normal evolution. In some SA/PAs, the matter has been addressed by establishing the probabilities of future human impacts and then estimating the consequent radiological health risks to people. While there is currently no international consensus as to how this might best be considered for a generic geological repository, the ICRP has suggested that it would best be analysed using a set of simple stylized scenarios. For example, drilling through the repository or through the groundwater contamination plume has been assumed in some cases.

uncertainties in the nature and driving forces affecting future evolution, or system and scenario uncertainties. SA/PA is also a valuable tool for exploring the other types of uncertainty inherent in geological disposal: conceptual and mathematical model uncertainty and parameter uncertainty. Again, recent SA/PA studies have developed effective techniques for managing such uncertainties.

Conceptual model uncertainty arises when there are alternative possible ways of representing a process. Typical examples of areas where alternative conceptual models can exist are in the description of groundwater flow and of radionuclide sorption. It is likely that any site specific programme will identify alternative models for groundwater movement on the local or regional scales and need to explore how the assumptions made in each model could affect potential releases of radionuclides. The best way of representing processes at different spatial scales may give rise to quite different modelling approaches. Identifying alternatives is a matter of expert judgement and it is thus important for a safety case to include as wide a range of expert input and peer review as possible. In the early stages of a detailed site specific SA/PA there may be many alternative conceptual models identified and it is normal practice to reduce these through an iterative process of model testing. This is discussed later in this section. A further aspect of conceptual model uncertainty lies in the possibility that the rates and mechanisms of some processes change with time. Owing to the long time periods involved, it is possible that boundary conditions and driving forces may change and that the relative importance of processes may be modified. Two techniques for addressing this possibility are discussed in Section 5.5.

Having defined a range of models to represent system behaviour, the next step is to find appropriate ranges of parameter values to apply to them. Data fall into several categories; clearly some are generally accepted values of physical properties such as decay constants and thermodynamic properties. Some are generic and can be taken from literature values and previous national and international studies, provided the appropriateness of the values can be justified. Many are site specific and will be generated from field and laboratory tests and experiments. A comprehensive R&D programme [102, 104] will aim to establish the ranges of all relevant parameter values, the most probable values of critical parameters (often represented as a probability distribution function) and the correlation of certain values of one parameter with certain values of another. In this context, it is important to understand that many of the parameters measured during geological site characterization programmes can display considerable variability within different regions of a site and when measured at different spatial scales. This is true variability, not uncertainty, but its existence clearly gives rise to uncertainty in overall system behaviour.

A number of parameters cannot be measured directly and have to be derived by interpretation of other data using models and assumptions which may themselves be uncertain. This latter group is of prime concern in SA/PA because it currently contains some of the most significant parameters used in many assessments (such as the Darcy velocity, the commonly used term for groundwater flux; flow wetted surface area; groundwater 'return' time) and the SA/PA results are highly sensitive to their variation. Such parameters originate from a requirement to scale up local or present day properties into what are sometimes called 'effective parameters', representative of much larger spatial or temporal scales.

The requirement for effective parameters in SA/PA stems from the unavoidable simplification of finely detailed models of components of the system so as to include that behaviour in a representative fashion in the larger scale models used to describe long term radionuclide transport and release. Much effort in any safety case is likely to be expended on providing a thorough justification for the derivation and choice of appropriate effective parameters and their values for a specific site. An alternative, which may see increasing application in safety cases, is to use the inexorable growth in computational power to include an increasing amount of the real spatial and temporal variability in the SA/PA models, rather than using effective parameters. There is already a trend in this direction in terms of spatial variability in the hydrogeological properties of rock formations.

5.4.3. Testing models

Apart from pure data gathering to establish characteristics, much effort in the later stages of R&D and site investigation programmes goes into testing and comparing the alternative conceptual models of system behaviour that have arisen as work proceeds. The purpose of model testing is to demonstrate that a particular model or group of models is appropriate for application to the specific circumstances of a safety case. Historically, most effort tends to have been expended on testing site specific models of the geological environment.

Testing begins with the early interpretation of system properties, for example the hydrogeological regime governing groundwater movement at a site. Alternative interpretations may be possible to explain the data and these may be represented by different conceptual models. An example might be the explanation of groundwater pressure or chemical variation by local variability in rock properties and topographically derived heads, compared with a model which considers long term coupled evolution of regional groundwater density and heat flow. In reality, elements of both models may be important and each must be tested to assess its contribution.

The accepted mode of testing alternative models is to use some of the available data to set up the models and the remainder of the data (or additional data generated later) to test them. The test is carried out by using the models to predict some well defined measurable property of the system and comparing the results of the prediction with real measurements. Formally, the modelling and measurement aspects of this process need to be carried out by different groups of people and the results judged by an entirely independent group against a pre-defined set of ‘acceptability’ criteria.

Generic testing of specific models describing particular processes has been attempted, and is conceptually possible, using data provided by natural analogue studies or by specific geological investigations, for example in the fields of hydrogeology or geochemistry. However, the usually insufficient definition of boundary conditions during the evolution of natural systems leads to uncertain conclusions; thus this approach, in practice, has not proven very useful in model testing. However, the study of natural systems, as described later in Section 5.5, can play an important role in confidence building.

A considerable amount of experience in model testing techniques has accrued as a result of international projects, often based around laboratory experiments or experiments in underground research laboratories. The results of such experimental activities can be used also to test the models from the point of view of the correctness of the mathematical representation of the simulated processes. There is only limited experience to date of testing and discriminating between alternative models at potential repository sites, especially with the use of large scale site characterization data rather than the results of small scale experiments. A developing repository programme will need to allow time for inclusion of the requisite steps in the safety case and R&D programme to identify testing needs and to carry out a properly peer reviewed testing and comparison exercise for key aspects of the SA/PA modelling.

5.5. CONFIDENCE BUILDING IN RESULTS OF SA/PA

The key issues in confidence building are:

(a) How to ensure that everything which potentially could significantly affect the performance of the repository system has been considered,
(b) How to ensure the reliability of the knowledge used to describe the behaviour of the geological environment and the engineered repository system,
(c) How to evaluate the changes that might take place in the geological environment surrounding the repository in the future.

The two first issues can be resolved, and confidence be built, to a great extent by carrying out systematic high quality work in SA/PA, which is also open for review [105, 106]. Typical examples of such systematic work will include URLs and 'demonstration' or 'pilot plant' activities. Owing to the long time periods which must be dealt with in SA/PA modelling, it can be difficult to provide a direct and convincing resolution of the third issue. This limitation applies in particular to processes and properties which have to be extrapolated to long time periods on the basis of short term measurements alone. Two well developed techniques exist which can assist in this matter; the use of 'natural analogues' and the application of palaeohydrogeological analysis. The former has been used extensively for the last twenty years [107, 108]; indeed, the concept of deep geological disposal is based, to some extent, on the containment analogy provided by deeply buried bodies of ore, and the widespread use of 'natural' materials in the EBS is based on their demonstrable longevity. Palaeohydrogeological analysis has been developed more recently, has not yet been applied to any great extent in the support of PA and is only now starting to drive the data gathering specifications of site characterization programmes [109].

5.5.1. Natural analogues

Studies of natural systems and processes that are similar to those that will occur in a repository environment are generally termed ‘natural analogues’. The scope of such studies is so broad, including many aspects of geological and biospheric systems, archaeological materials and the environmental impacts of anthropogenic activity, that natural analogues are most readily defined by the common methodology used in applying them to SA/PA. Essentially this comprises:

(a) Identifying an area of uncertainty in the PA process; for example, the most appropriate model or range of parameter values to use.
(b) Seeking a natural or human made occurrence of the same or an analogous process or material in a relevant environment which has been in existence for a long period of time.
(c) Studying the effect of the process or the state of the material and identifying how this has changed as a function of time.
(d) Interpreting these findings to provide support for the assumptions used in the repository system PA or in its quantitative results.

By definition, appropriate analogues can be found in many environments and they are rarely site specific for the planned repository (i.e. it is unusual to find that a material or process of interest has been present at the potential repository site in a sufficiently convenient form for study). Consequently, much existing analogue information is generic and can be applied quite broadly at the concept development stage of repository programmes. Typical applications include providing confidence that:

(1) The correct processes have been identified which influence the evolution of some component of the system over a relevant timescale.
(2) Any time dependent changes in process or mechanism are taken into account.
(3) There is evidence that the predicted nature and scale of the effects of a process (such as radionuclide dispersion in a groundwater system) which has operated for many thousands or hundreds of thousands of years are appropriate.

Carefully applied, analogues can also provide useful illustrations or serve to support the overall concept being developed, providing, for example, natural, long term evidence that repository materials can have great longevity in relevant environments or that deeply buried radioactive substances can be quite immobile in natural systems. Occasionally, they can also provide direct quantitative information to help bound parameter values; for example on the long term corrosion rates of metals or the evolution of cement chemistry with time.

There is a wealth of literature now available from natural analogue studies in many countries [64–67, 107, 108]. Most information is concerned with chemical processes associated with the properties of materials and the migration and retardation of radionuclides and non-active species in natural groundwater and biological systems. There is also extensive experience of using this information in repository development and PA programmes.

Natural analogues have the unique advantage of being readily understood and can provide better justification of some aspects of a programme than the more arcane outputs of SA/PA modelling. Consequently, it can be expected that any future safety case, especially at a late licensing stage of a repository development programme, will utilize analogue information quite widely in support of assumptions and conclusions. In fact, some national regulations already require this.

5.5.2. Palaeohydrogeology and climate change

SA/PA modelling, of necessity, predicts what may happen to a disposal system in the distant future. For most potential disposal environments these predictions are principally concerned with the potential for mobilization and transport of radionuclides in groundwater. While some concepts (e.g. disposal in rock salt and plastic clays) may be more centrally concerned with near field processes, all PAs have to deal with groundwater transport to some extent.

Because the groundwater transport models generally predict transit times that are of the order of thousands to hundreds of thousands of years, it is important to use whatever evidence is available to demonstrate that the flow patterns and rates and transport mechanisms predicted have also operated over commensurate periods in the past history of a site. If the origins, recharge epochs, residence times and movement patterns of water entering and moving through the system can be quantified, this provides strong support for the hydrogeological models underlying the SA/PA. If the fate of solutes originating from the proposed depth or location of a repository can be traced, in terms of their transport mechanisms, transit times and their mixing and dilution with various bodies of water at different depths, then this provides considerable confidence in the transport models used in SA/PA.

The understanding of how groundwater systems have evolved in the past is called palaeohydrogeology, and palaeohydrogeological investigations are clearly site specific activities [72]. Information to develop a palaeohydrogeological model of a site is obtained from a combination of hydraulic measurements of the distribution of groundwater flow properties of the rock and of geochemical and isotopic signatures found in the hydrochemistry of groundwater and in the mineralogy of pore and fracture surfaces in the various rock formations [83, 109]. It is also vital to have an understanding of how climate change in past millennia might have affected recharge rates and temperatures, surface conditions, sea level and other relevant properties of a site or region [70, 71].

The importance of understanding climate change and its impact on the groundwater regime has become apparent in many site investigation programmes. In many parts of the northern hemisphere, the impacts of repeated glaciations and periglacial conditions are recorded in the deep groundwater system. Flow rates and groundwater chemistry have been affected at many sites. Similarly, any site in a present day coastal environment is likely to have been affected by climate driven sea level changes in the past and could be affected by them on a relatively short timescale in the future. At other sites, tectonic influences on past groundwater flow, such as uplift, subsidence or changes in the deep thermal regime may have affected hydrogeological conditions, although probably on much longer timescales than climate change. Some of these past events will be recorded in the palaeohydrogeological record, and the importance of designing site characterization programmes to look for such evidence cannot be overemphasized. In some potential repository locations, particularly in sites which have been subject to ice cover, site investigations should focus primarily on obtaining palaeohydrogeological information as this will give the best input to predictive PA models of groundwater flow on timescales of relevance to SA.

5.6. THE CURRENT POSITION

Several detailed SA/PAs of geological repositories for various categories of long lived waste have been performed in recent years [88, 104, 110–118]. They cover a variety of repository concepts and disposal environments and provide useful pointers to some of the key issues in confirming safety. The development of the SA/PA work towards more comprehensive safety cases tries to meet the needs in decision making when siting a repository or granting a construction license, for example. The scientific knowledge used, the SA/PA modelling executed, and the testing and demonstration carried out for a safety case are, of course, the main interests of the regulators and the reviewers. For decision making it is important, however, that a convincing safety case, supported by sound arguments or observations and subjected to open review, is produced. The safety case needs to address all issues of potential interest to decision makers and the public. For this purpose it may be necessary to have an interaction between these groups to allow their interests to be accounted for in the safety case [62].

During the last decade, data sets from actual candidate sites have been increasingly utilized in SA/PA. The experience gained from this may require more resources to be put into SA/PA work in the future. However, the experience shows that no new insurmountable problems have been encountered and therefore it can be judged that safety can be evaluated within a safety case using SA/PA as the main tools. Significant advances which have been made in SA/PA are [115]:

(a) Comprehensive identification of relevant FEPs;
(b) Dealing with large data sets and formal methods of reduction of data for use in SA/PA models;
(c) More sophisticated use of thermodynamic and geochemical codes and data to simulate the chemical evolution of multibarrier systems;
(d) Use of three dimensional models of groundwater flow including density and transient effects and use of spatially variable hydrogeological models based on site specific data;
(e) Greater understanding of the transport of radionuclides through fractured hard rocks and unsaturated rocks;
(f) More sophisticated use of probabilistic analyses, including representation of time dependent processes (changes in their rates and mechanisms).

It has been noted that individual programmes can benefit significantly from co-operation in developing their safety cases. Co-operation in underground research laboratories enables demonstration and testing of the repository technology designed to meet the safety requirements. The sharing of scientific knowledge will also help to focus programmes on the issues needed to assess proposed design solutions at particular sites.

6. SUMMARY AND CONCLUSIONS

A geological repository for solid radioactive wastes can be defined as properly packaged wastes emplaced in an EBS, within excavated or drilled openings, located at a depth of some hundreds of metres, in a stable geological environment. The components of the system act in concert, initially to prevent and then to limit releases of radionuclides, in what is widely known as the ‘multibarrier concept’.

Disposal in a geological repository is the generally accepted solution for management of long lived wastes in practically all countries faced by the problem. It also represents the most practical, perhaps the only, option and is in line with the general principles defined in the IAEA Safety Fundamentals and with the principle of sustainability.

Potentially suitable disposal locations exist in many types of host rocks and geological environments. Even in regions characterized by some tectonic activity it may be possible to identify areas with adequate stability and to design the engineered components of the disposal system in such a way that safe isolation can be reasonably assured.

The development of a geological repository is a lengthy process that can be subdivided into phases, moving from site selection, through site characterization, repository design, construction and operation, to the final phases, i.e. closure and any required post-closure activities. The start of most phases is likely to require a specific authorization supported by ad hoc planning and an assessment of how the repository is expected to behave in the future. The assessment is called a PA when it describes the evolution of the containment barriers and an SA when the outputs are compared with safety standards. In general, SA/PAs for geological repositories are expected to be iterative in nature, becoming progressively better defined and more reliable with the passage of time and the expansion of the scientific and technical basis. However, since the future cannot be predicted with any certainty, a level of uncertainty in the results of SAs is unavoidable; the uncertainty tends to increase with the remoteness of the estimated consequences. This is generally addressed by assessing a variety of evolution scenarios. The results should provide decision makers with a reasonable assurance of safety within a tolerable range of uncertainty. It is important to recognize that decisions made on this basis will always involve an element of judgement.

Owing to the lack of urgency in many countries, a reticence among decision makers to confront controversial issues and the opposition of some sections of society to proposed disposal options, decisions to achieve progress in many waste disposal programmes have been difficult to obtain. This has led to the search for additional arguments for the safety of geological disposal systems. Consequently the current position has been reached, where confidence in the safety of a specific repository is expected to be obtained through the development of a safety case, where different arguments are developed, following various lines of reasoning, such as using additional safety indicators and strengthening assessment outcomes, for example through the study of natural analogues and palaeohydrogeology. In particular the safety case will need to be revised during the process of repository development taking into account ongoing improvements in the scientific and technical basis. In addition, any additional impacts of the disposal system on the environment and society are being analysed with increasing attention.

Moreover, although there have been over twenty years of study of deep geological disposal systems, there is a danger that the 'corporate' knowledge involved in individual programmes may be lost unless a special effort is made to preserve it. The long time periods involved in any repository development programme (several decades at least) mean that a provision and commitment must be made to long term data gathering and to the furtherance and wide transmission of knowledge.

There must be a long term commitment to publication of R&D findings and to peer review of deep repository programmes [26].

Geological disposal systems can vary in respect to the nature of the host rock, the repository design and a variety of additional geological and environmental conditions. The objective of geological disposal, to achieve adequate isolation of the wastes and overall safety of the disposal system, can be reached by different balances of rock and EBS properties. No particular disposal concept is necessarily superior to any other.

Different geological situations impose different constraints on repository design: softer clays limit the depth of construction; layered sedimentary sequences in geologically less complex regions favour the construction of more laterally extended repositories; fractured hard rocks favour the construction of multilevel repositories to take advantage of the presence of good rock to greater depths and to avoid major subvertical fracture zones which may limit the lateral extent of good rock masses.

Some concepts and environments may be particularly appropriate for large or small volumes of waste. Deep boreholes may be most appropriate for very small volumes of high activity wastes. The ability to excavate large volume caverns in hard rocks would facilitate disposal of large quantities of LILWs.

In respect to all pre-closure phases of the repository life cycle, different host rocks and different repository designs can have significantly different requirements with regard to the scientific and technical basis; for example a repository in an argillaceous host rock will need more geotechnical data, particularly in relation to excavation and lining methods, repository design, operational safety and the impact of the EDZ on long term safety. A second example is the characterization of engineered barriers, buffers and backfills, which is more important in hard rocks than in plastic ones, such as clay and rock salt, in which creep can be expected to improve their future performance.

Regarding the post-closure phase, the required scientific and technical data are mainly related to the development of the safety case. The main focus is on estimating the evolution of the containment barriers, on the migration of radionuclides in the geosphere and on the development of supporting arguments indicating the safety of the system.

In a generic way, it can be stated with confidence that deep geological disposal is technically feasible and does not present any particularly novel rock engineering issues. The existence of numerous potentially suitable repository sites in a variety of host rocks is also well established.

Materials properties, radionuclide transport processes, sorption mechanisms and solute chemistry are sufficiently well understood to allow confident modelling of behaviour in most disposal environments. The interactions of these factors are less well characterized but the uncertainties which arise as a result can be covered by accepted PA techniques.

The results of generic SAs and PAs of geological disposal concepts show that the disposal systems can contain the majority of the radioactivity in the wastes completely until it has decayed away. Under ‘normal evolution’ scenarios only the long lived radionuclides are likely to be released and their activity is relatively low, representing only a small fraction of the original activity contained in the wastes. The peak doses calculated by SA/PAs arise from the long lived radionuclides, take place far in the future and are usually well below the regulatory standards. In fact, the results of many sophisticated SAs all indicate that geological disposal of a variety of long lived waste types can be carried out safely and meet regulatory requirements.

Obviously to reach the same conclusions for a specific repository design and a specific site, significant focused investigations would be required; the following list includes examples of fields where additional work is likely to be required to expand the scientific and technical basis.

(1) Some uncertainty surrounds the eventual fabrication quality, durability and consequent failure rate of long lived (>10 000 years) waste containers and the long term performance of other near field barriers. Disposal concepts which rely to any great extent on the long term integrity of containers and other engineered barriers will need to be able to achieve the required level of confidence in their longevity by further R&D on full scale manufactured products, including, when necessary, in situ testing.

(2) Site characterization produces more data than can be integrated in SA/PA and there is a need, on a site specific basis, to develop and apply techniques for interpreting, upscaling and simplifying site properties into effective properties for SA/PA work. Conversely, increasing computer capabilities may allow better data management and more ‘realistic’ simulations. Underground work, however, means disturbance of the geological environment and therefore safety related constraints, as well as the need to develop criteria for evaluation of site suitability. These constraints may provide the guidance necessary for the planning of underground work.

(3) There is a widely recognized need to include a phase of underground testing at the chosen repository site, following the initial period of surface based investigations. The main purposes of underground testing, in the phases of site characterization and repository design, are:

   (i) To improve rock characterization;
   (ii) To confirm the capability to emplace in the facility all foreseen components;
   (iii) To determine that emplaced engineered barriers meet the required specifications, considering also the coupled nature of many ongoing processes.

   Testing and demonstration activities would provide data to be used for confirming the feasibility of repository construction and the assumptions on which the preliminary SA/PA is based.

(4) Further refinement of SA/PA is desirable as this is an essential tool for managing the unavoidable uncertainties involved in the development

programmes for geological repositories, for integrating the wide variety of multidisciplinary information which is required by such programmes and for optimizing the design of the disposal system.

(5) Evolution scenarios, including those different from 'normal evolution' cases, need to be studied with great care in SA/PA. Since some impacts from external processes, such as variations of groundwater flow, climate change and human activities, seem to be inevitable, close attention should be paid to them.

(6) A special effort needs to be maintained to identify, update and evaluate FEPs within the system description as a programme becomes more site specific. This means keeping FEP lists under rolling expert review as programmes progress.

(7) While stable and simple geological environments are the obvious choice for siting repositories for long lived radioactive wastes, it is generally recognized that there is always a scale on which natural systems can be considered complex and heterogeneous; in addition, their properties may vary over the time periods relevant to the SA. This is particularly relevant for far field groundwater flow systems. The temporal and spatial scale dependences need to be accounted for in SA/PAs.

(8) Palaeohydrogeological techniques may contribute significantly to building up confidence in the safety case by providing evidence of stable conditions over time and, therefore, by supporting the SA/PA. Therefore, obtaining the relevant geochemical, isotopic and hydraulic data should be one of the principal objectives of any site investigation programme.

(9) In fractured rocks, where localized groundwater flows may be relatively higher in some locations, the presence of a very low hydraulic conductivity buffer to provide a diffusive barrier around the wastes is considered to be a central feature of the containment system. Some aspects of the behaviour of such barriers need to be kept under investigation (e.g. by full scale testing).

(10) Radiolysis on the surfaces of spent fuel exposed to water and its impact on the results of SA/PA would benefit from further study.

(11) Whilst the mechanisms of gas production by corrosion and waste degradation are well understood, there has as yet been limited effort to evaluate the gas transport pathway in full detail in SA/PA studies (which tend to concentrate on the groundwater pathway). For disposal concepts involving repositories containing substantial amounts of iron and other metals which produce gas when in contact with water, this would be an important issue to pursue.

(12) In the building of geological repositories, construction materials are needed; for example, concrete and rock bolts. The potential impact of these materials is mostly chemical and especially the possibility that these materials could affect the favourable conditions provided by the geological environment has to be assessed. For this reason, careful evaluation of the interactions between the construction materials and the other components of the disposal system is

needed. Simultaneously, possibilities can be explored to develop materials having properties of more limited impact on the long term safety of the disposal system (low alkaline concrete, for example).

(13) Some Member States have adopted, or are considering, regulations that require waste packages emplaced in the repository to be retrievable during a given time period. This requirement could be met by delaying the emplacement of near field barriers and closure of underground openings or by emplacing engineered barriers in a reversible way. Retrievability/reversibility requirements are based on political decisions; they can have a major influence on a repository development programme and bring additional and new constraints to the repository design and operation. The consequent modifications, which depend significantly on the nature and properties of the host rock and on the design of the repository, may have important consequences on the disposal concept (cost, safety, etc.). These impacts, particularly in respect to the overall safety of disposal, will need to be evaluated with the greatest care.

REFERENCES

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, The Principles of Radioactive Waste Management, Safety Series No. 111-F, IAEA, Vienna (1995).

[2] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Radiation Protection Recommendations as Applied to the Disposal of Long-lived Solid Radioactive Waste, Publication 81, Pergamon Press, Oxford and New York (2000).

[3] US NATIONAL RESEARCH COUNCIL/NATIONAL ACADEMY OF SCIENCES, The Disposal of Radioactive Waste on Land, Publication 519, National Research Council, Washington, DC (1957).

[4] INTERNATIONAL ATOMIC ENERGY AGENCY, Underground Disposal of Radioactive Wastes: Basic Guidance, Safety Series No. 54, IAEA, Vienna (1981).

[5] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Radiation Protection Principles for the Disposal of Solid Radioactive Waste, Publication 46, Pergamon Press, Oxford and New York (1985).

[6] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety Principles and Technical Criteria for the Underground Disposal of High Level Radioactive Wastes, Safety Series No. 99, IAEA, Vienna (1989).

[7] OECD NUCLEAR ENERGY AGENCY, Environmental and Ethical Aspects of Long-Lived Radioactive Waste Disposal (Proc. Int. Workshop Paris, 1994), OECD, Paris (1995).

[8] OECD NUCLEAR ENERGY AGENCY, The Environmental and Ethical Basis of Geological Disposal of Long-Lived Radioactive Wastes: A Collective Opinion of the Radioactive Waste Management Committee of the OECD Nuclear Energy Agency, OECD, Paris (1995).

[9] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Radiological Protection Policy for the Disposal of Radioactive Waste, Publication 77, Pergamon Press, Oxford and New York (1997).
[10] INTERNATIONAL ATOMIC ENERGY AGENCY, Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, INFCIRC/546, IAEA, Vienna (1997).
[11] SWEDISH NATIONAL COUNCIL FOR NUCLEAR WASTE (KASAM), Nuclear Waste State-of-the-Art Reports 1998, KASAM, Stockholm (1999).
[12] OECD NUCLEAR ENERGY AGENCY, Feasibility of Disposal of High Level Radioactive Waste into the Seabed, Vols 1–8, OECD, Paris (1988).
[13] INTERNATIONAL ATOMIC ENERGY AGENCY, Inventory of Radioactive Waste Disposals at Sea, IAEA-TECDOC-1105, IAEA, Vienna (1999).
[14] US ENVIRONMENTAL PROTECTION AGENCY, Implementation of the Waste Isolation Pilot Plant Land Withdrawal Act, Rep. EPA 402-R-99-011, EPA, Washington, DC (1999).
[15] INTERNATIONAL ATOMIC ENERGY AGENCY, Retrievability of High Level Waste and Spent Nuclear Fuel (Proc. KASAM–IAEA Sem. Saltsjoebaden, 1999), IAEA-TECDOC-1187, IAEA, Vienna (2000).
[16] LAWRENCE BERKELEY NATIONAL LABORATORY, UNIVERSITY OF CALIFORNIA, Geological Problems in Radioactive Waste Isolation: A World Wide Review (Proc. 28th Int. Geological Congr. Washington, DC, 1989), Lawrence Berkeley Natl Lab., Berkeley, CA (1991).
[17] INTERNATIONAL ATOMIC ENERGY AGENCY, Radioactive Waste Management: An IAEA Source Book, IAEA, Vienna (1992).
[18] INTERNATIONAL ATOMIC ENERGY AGENCY, Geological Disposal of Spent Fuel and High Level and Alpha Bearing Wastes (Proc. Joint IAEA/CEC/NEA Symp. Antwerp, 1992), IAEA, Vienna (1993).
[19] INTERNATIONAL ATOMIC ENERGY AGENCY, Report on Radioactive Waste Disposal, Technical Reports Series No. 349, IAEA, Vienna (1993).
[20] US NATIONAL RESEARCH COUNCIL/NATIONAL ACADEMY OF SCIENCES, Technical Bases for Yucca Mountain Standards, National Academy Press, Washington, DC (1995).
[21] SAVAGE, D. (Ed.), The Scientific and Regulatory Basis for the Geological Disposal of Radioactive Waste, Wiley, New York (1995).
[22] OECD NUCLEAR ENERGY AGENCY, Geological Disposal of Radioactive Waste: Review of Developments in the Last Decade, OECD, Paris (1999).
[23] EUROPEAN COMMISSION, Euradwaste 1999: Radioactive Waste Management Strategies and Issues (Proc. 5th EC Conf. Luxembourg, 1999), Rep. EUR 19143 EN, EC, Brussels (2000).
[24] MATERIALS RESEARCH SOCIETY, Scientific Basis for Nuclear Waste Management (Proc. 23rd Symp. Boston, 1999), Vol. 608, MRS, Warrendale, PA (2000).
[25] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety of Radioactive Waste Management (Proc. Int. Conf. Córdoba, 2000), IAEA, Vienna (2000).
[26] UNITED KINGDOM NIREX Ltd, The Scientific Foundation of Deep Geological Disposal, Rep. N/016, Nirex, Harwell (2001).

[27] INTERNATIONAL ATOMIC ENERGY AGENCY, The Use of Scientific and Technical Results from Underground Research Laboratory Investigations for the Geological Disposal of Radioactive Waste, IAEA-TECDOC-1243, IAEA, Vienna (2001).
[28] INTERNATIONAL ATOMIC ENERGY AGENCY, Radioactive Waste Management Glossary (An Update of IAEA-TECDOC-447), IAEA, Vienna (1994).
[29] INTERNATIONAL ATOMIC ENERGY AGENCY, Siting, Design and Construction of Underground Repositories for Radioactive Wastes (Proc. Int. Symp. Hannover, 1986), IAEA, Vienna (1986).
[30] INTERNATIONAL ATOMIC ENERGY AGENCY, Siting of Geological Disposal Facilities, Safety Series No. 111-G-4.1, IAEA, Vienna (1994).
[31] SWEDISH NUCLEAR FUEL AND WASTE MANAGEMENT COMPANY, What Requirements does the KBS-3 Repository Make on the Host Rock? Geoscientific Suitability Indicators and Criteria for Siting and Site Evaluation, Rep. TR-00-12, SKB, Stockholm (2000).
[32] INTERNATIONAL ATOMIC ENERGY AGENCY, Experience in Selection and Characterization of Sites for Geological Disposal of Radioactive Waste, IAEA-TECDOC-991, IAEA, Vienna (1997).
[33] INTERNATIONAL ATOMIC ENERGY AGENCY, Qualitative Acceptance Criteria for Radioactive Wastes to be Disposed of in Deep Geological Formations, IAEA-TECDOC-560, IAEA, Vienna (1990).
[34] INTERNATIONAL ATOMIC ENERGY AGENCY, Sealing of Underground Repositories for Radioactive Wastes, Technical Reports Series No. 319, IAEA, Vienna (1990).
[35] INTERNATIONAL ATOMIC ENERGY AGENCY, Performance of Engineered Barriers in Deep Geological Repositories, Technical Reports Series No. 342, IAEA, Vienna (1992).
[36] INTERNATIONAL ATOMIC ENERGY AGENCY, Concepts for the Conditioning of Spent Nuclear Fuel for Final Waste Disposal, Technical Reports Series No. 345, IAEA, Vienna (1992).
[37] INTERNATIONAL ATOMIC ENERGY AGENCY, Classification of Radioactive Waste, Safety Series No. 111-G-1.1, IAEA, Vienna (1994).
[38] INTERNATIONAL ATOMIC ENERGY AGENCY, Quality Assurance for Radioactive Waste Packages, Technical Reports Series No. 376, IAEA, Vienna (1995).
[39] INTERNATIONAL ATOMIC ENERGY AGENCY, Characterization of Radioactive Waste Forms and Packages, Technical Reports Series No. 383, IAEA, Vienna (1997).
[40] INTERNATIONAL ATOMIC ENERGY AGENCY, Issues in Radioactive Waste Disposal, IAEA-TECDOC-909, IAEA, Vienna (1996).
[41] UK ENVIRONMENT AGENCY, Interpretation of Optimisation in the Context of a Disposal Facility for Long-Lived Radioactive Waste, R&D Tech. Rep. P259, EA, Bristol (1999).
[42] INTERNATIONAL ATOMIC ENERGY AGENCY, Review of the Factors Affecting the Selection and Implementation of Waste Management Technologies, IAEA-TECDOC-1096, IAEA, Vienna (1999).

[43] OECD NUCLEAR ENERGY AGENCY, The Case for Benchmark Biospheres and Decoupling of Biosphere and EBS/Geosphere Analysis, NEA PAAG DOC (98)6, OECD, Paris (1998).
[44] INTERNATIONAL ATOMIC ENERGY AGENCY, Critical Groups and Biospheres in the Context of Radioactive Waste Disposal, IAEA-TECDOC-1077, IAEA, Vienna (1999).
[45] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety Indicators in Different Time Frames for the Safety Assessment of Underground Radioactive Waste Repositories, IAEA-TECDOC-767, IAEA, Vienna (1994).
[46] EUROPEAN COMMISSION, Testing and Modelling of Thermal, Mechanical and Hydrogeological Properties of Host Rocks for Deep Geological Disposal of Radioactive Waste (Proc. Workshop Brussels, 1995), Rep. EUR 16219 EN, EC, Brussels (1995).
[47] OECD NUCLEAR ENERGY AGENCY, Geological Disposal of Radioactive Waste. In Situ Research and Investigations in OECD Countries, OECD, Paris (1988).
[48] OECD NUCLEAR ENERGY AGENCY, International Stripa Project, Vols 1–3, OECD, Paris (1993).
[49] EUROPEAN COMMISSION, In Situ Testing in Underground Research Laboratories for Radioactive Waste Disposal (Proc. Cluster Sem. Alden Biesen, 1997), Rep. EUR 18323 EN, EC, Luxembourg (1998).
[50] EUROPEAN COMMISSION, The Praclay Project: Demonstration Test on the Belgian Disposal Facility Concept for High Activity Vitrified Waste. Final Report, Rep. EUR 18047 EN, EC, Luxembourg (1998).
[51] SWEDISH NUCLEAR FUEL AND WASTE MANAGEMENT COMPANY, Aespoe Hard Rock Laboratory: Annual Report 1999, Rep. TR-00-10, SKB, Stockholm (2000).
[52] INTERNATIONAL ATOMIC ENERGY AGENCY, Concepts and Examples of Safety Analyses for Radioactive Waste Repositories in Continental Geological Formations, Safety Series No. 58, IAEA, Vienna (1983).
[53] INTERNATIONAL ATOMIC ENERGY AGENCY, Performance Assessment for Underground Radioactive Waste Disposal Systems, Safety Series No. 68, IAEA, Vienna (1985).
[54] COMMISSION OF THE EUROPEAN COMMUNITIES, Performance Assessment of the Geological Isolation Systems for Radioactive Wastes, Rep. PAGIS EUR 11775 EN, CEC, Luxembourg (1988).
[55] OECD NUCLEAR ENERGY AGENCY, Safety Assessment of Radioactive Waste Repositories (Proc. Joint CEC/IAEA/NEA Int. Symp. Paris, 1989), OECD, Paris (1990).
[56] OECD NUCLEAR ENERGY AGENCY, Disposal of Radioactive Waste: Can Long-Term Safety be Evaluated? An International Collective Opinion, OECD, Paris (1991).
[57] OECD NUCLEAR ENERGY AGENCY, Review of Safety Assessment Methods, OECD, Paris (1991).
[58] OECD NUCLEAR ENERGY AGENCY, Systematic Approaches to Scenario Development, OECD, Paris (1992).
[59] OECD NUCLEAR ENERGY AGENCY, Safety Assessment of Radioactive Waste Repositories: Future Human Actions at Disposal Sites, OECD, Paris (1995).
[60] OECD NUCLEAR ENERGY AGENCY, Features, Events and Processes (FEPs) for Geological Disposal of Radioactive Waste, OECD, Paris (2000).

[61] INTERNATIONAL ATOMIC ENERGY AGENCY, Regulatory Decision Making in the Presence of Uncertainty in the Context of the Disposal of Long Lived Radioactive Wastes, IAEA-TECDOC-975, IAEA, Vienna (1997).

[62] OECD NUCLEAR ENERGY AGENCY, Confidence in the Long Term Safety of Deep Geological Repositories, Its Development and Communication, OECD, Paris (1999).

[63] INTERNATIONAL ATOMIC ENERGY AGENCY, Extrapolation of Short Term Observations to Time Periods Relevant to the Isolation of Long Lived Radioactive Waste, IAEA-TECDOC-1177, IAEA, Vienna (2000).

[64] COMMISSION OF THE EUROPEAN COMMUNITIES, Natural Analogues in Radioactive Waste Disposal (Proc. Int Symp. Brussels, 1987), Rep. EUR 11037 EN, CEC, Brussels (1987).

[65] INTERNATIONAL ATOMIC ENERGY AGENCY, Natural Analogues in Performance Assessments for the Disposal of Long Lived Radioactive Wastes, Technical Reports Series No. 304, IAEA, Vienna (1989).

[66] INTERNATIONAL ATOMIC ENERGY AGENCY, Use of Natural Analogues to Support Radionuclide Transport Models for Deep Geological Repositories for Long Lived Radioactive Wastes, IAEA-TECDOC-1109, IAEA, Vienna (1999).

[67] EUROPEAN COMMISSION, EC Natural Analogue Working Group Meeting (Proc. 8th Int. Workshop Strasbourg, 1999), Rep. EUR 19118 EN, EC, Brussels (2000).

[68] SWEDISH NUCLEAR FUEL AND WASTE MANAGEMENT COMPANY, A Natural Analogue for Copper Waste Canisters: The Copper–Uranium Mineralised Concretions in the Permian Mudrocks of South Devon, United Kingdom, Rep. TR-00-11, SKB, Stockholm (2000).

[69] SWEDISH NUCLEAR FUEL AND WASTE MANAGEMENT COMPANY, Oklo: A Review and Critical Evaluation of Literature, Rep. TR-00-17, SKB, Stockholm (2000).

[70] UNITED KINGDOM NIREX Ltd, A Critical Review of the Climate Literature Relevant to the Deep Disposal of Radioactive Waste, Rep. S/97/009, Nirex, Harwell (1997).

[71] SWEDISH NUCLEAR FUEL AND WASTE MANAGEMENT COMPANY, Late Quarternary Changes in Climate, Rep. TR-98-13, SKB, Stockholm (1998).

[72] OECD NUCLEAR ENERGY AGENCY, Palaeohydrogeological Methods and their Applications (Proc. Workshop Paris, 1992), OECD, Paris (1993).

[73] INTERNATIONAL ATOMIC ENERGY AGENCY, Application of Quality Assurance to Radioactive Waste Disposal Facilities, IAEA-TECDOC-895, IAEA, Vienna (1996).

[74] NEYAMA, A., ISHIHARA, Y., FUSAEDA, S., “Quality assurance program with computer-oriented management system for performance assessment”, in High-Level Radioactive Waste Management (Proc. 8th Int. Conf. Las Vegas, 1998), American Nuclear Society, La Grange Park, IL (1998).

[75] INTERNATIONAL ATOMIC ENERGY AGENCY, Maintenance of Records for Radioactive Waste Disposal, IAEA-TECDOC-1097, IAEA, Vienna (1999).

[76] OECD NUCLEAR ENERGY AGENCY, Status of Near-Field Modelling (Proc. Tech. Workshop Cadarache, 1993), OECD, Paris (1993).

[77] UK ENVIRONMENT AGENCY, US DEPARTMENT OF ENERGY, The Uses of Backfill in Nuclear Waste Repositories (Proc. Int. Workshop Carlsbad, 1998), Rep. P178, USDOE, Carlsbad, NM (1998).

[78] SWEDISH NUCLEAR FUEL AND WASTE MANAGEMENT COMPANY, Long Term Test of Buffer Material: Final Report on the Pilot Parcels, Rep. TR-00-22, SKB, Stockholm (2000).
[79] SWEDISH NUCLEAR FUEL AND WASTE MANAGEMENT COMPANY, Thermodynamic Data for Copper: Implications for the Corrosion of Copper under Repository Conditions, Rep. TR-00-13, SKB, Stockholm (2000).
[80] INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS, Hydrogeology and Safety of Radioactive and Industrial Hazardous Waste Disposal (Proc. Int. Symp. Orleans, 1988), Vols 1 and 2, IAH-BRGM, Orleans (1988).
[81] OECD NUCLEAR ENERGY AGENCY, Characterisation of Water-Conducting Features in Migration (Proc. Workshop Barcelona, 1998), OECD, Paris (1999).
[82] INTERNATIONAL ATOMIC ENERGY AGENCY, Hydrogeological Investigation of Sites for the Geological Disposal of Radioactive Waste, Technical Reports Series No. 91, IAEA, Vienna (1999).
[83] OECD NUCLEAR ENERGY AGENCY, Porewater Extraction from Argillaceous Rocks for Geochemical Characterisation: Methods and Interpretation, OECD, Paris (2000).
[84] COMMISSION OF THE EUROPEAN COMMUNITIES, Natural Analogue and Evidence of Long Term Isolation Capacity of Clays Occurring in Italy, Rep. EUR 11896 EN, CEC, Brussels (1989).
[85] AMBROSETTI, P., et al., "Analysis of the geo-environmental conditions as morphological evolution factors of the sand–clay series of the Tiber valley and of the Dunarobba forest preservation", Rep. EUR 17479 EN, EC, Brussels (1997) 189–207.
[86] OECD NUCLEAR ENERGY AGENCY, Fluid Flow through Faults and Fractures in Argillaceous Formations (Proc. Joint NEA/EC Workshop Berne, 1996), OECD, Paris (1998).
[87] MERZ, E.R., WALTER, C.E. (Eds), Disposal of Weapon Plutonium (Proc. NATO Workshop St. Petersburg, 1995), Kluwer Academic Publishers, Dordrecht (1996).
[88] UNITED KINGDOM NIREX Ltd, Nirex-97: An Assessment of the Post-Closure Performance of a Deep Waste Repository at Sellafield, Rep. S/97/012, Nirex, Harwell (1997).
[89] GRAMBROW, B., et al., Source Term for Performance Assessment of Spent Fuel as a Waste Form: Final Report, EUR 19140 EN, EC, Brussels (2000).
[90] SWEDISH NUCLEAR FUEL AND WASTE MANAGEMENT COMPANY, SR 97: Radionuclide Transport Calculations, Rep. TR-99-23, SKB, Stockholm (1999).
[91] SWEDISH NUCLEAR FUEL AND WASTE MANAGEMENT COMPANY, Diffusion of Organic Colloids in Compacted Bentonite: The Influence of Ionic Strength on Molecular Size and Transport Capacity of the Colloids, Rep. TR-00-19, SKB, Stockholm (2000).
[92] EUROPEAN COMMISSION, Research into Gas Generation and Migration in Radioactive Waste Repository Systems (PROGRESS Project): Final Report, EUR 19133 EN, EC, Brussels (2000).
[93] OECD NUCLEAR ENERGY AGENCY, The International HYDROCOIN Project: Groundwater Hydrology Modelling Strategies for Performance Assessment of Nuclear Waste Disposal: Summary Report, OECD, Paris (1992).

[94] EUROPEAN COMMISSION, Radionuclide Transport through the Geosphere into the Biosphere, Review Study of the Project MIRAGE, Rep. EUR 16489 EN, EC, Brussels (1995).
[95] OECD NUCLEAR ENERGY AGENCY, The International INTRAVAL Project: Developing Groundwater Flow and Transport Models for Radioactive Waste Disposal: Final Results, OECD, Paris (1996).
[96] SWEDISH NUCLEAR FUEL AND WASTE MANAGEMENT COMPANY, Test Plan for the TRUE (Tracer Retention Understanding Experiment) Block Scale Experiment, Rep. HRL-ICR 97-01, SKB, Stockholm (1997).
[97] OECD NUCLEAR ENERGY AGENCY, Disposal of Radioactive Waste. The Probabilistic System Assessment Group: History and Achievements (1985–1994), OECD, Paris (1997).
[98] OECD NUCLEAR ENERGY AGENCY, Field Tracer Experiments: Role in the Prediction of Radionuclide Migration (Proc. 1st NEA/EC GEOTRAP Workshop Cologne, 1996), OECD, Paris (1997).
[99] OECD NUCLEAR ENERGY AGENCY, Modelling the Effects of Spatial Variability on Radionuclide Migration (Proc. 2nd NEA/EC GEOTRAP Workshop Paris, 1997), OECD, Paris (1998).
[100] US NUCLEAR REGULATORY COMMISSION, Disposal of high-level radioactive wastes in proposed geological repository at Yucca Mountain, Nevada, Fed. Reg. (Washington, DC) **64** 34 (1999) 8640–8679.
[101] SWEDISH NUCLEAR POWER INSPECTORATE, Regulatory Perspectives on Model Validation in High-Level Radioactive Waste Management Programs: A Joint NRC/SKI White Paper, Rep. 99:2, SKI, Stockholm (1999).
[102] SWEDISH NUCLEAR FUEL AND WASTE MANAGEMENT COMPANY, Geoscientific Programme for Investigation and Evaluation of Sites for the Deep Repository, Rep. TR-00-20, SKB, Stockholm (2000).
[103] McCOMBIE, C., KICKMAIER, W., "Underground research laboratories: Their role in demonstrating repository concepts and communicating with the public", Euradwaste 1999: Radioactive Waste Management Strategies and Issues (Proc. 1st EC Conf. Luxembourg, 1999), Rep. EUR 19143 EN, EC, Brussels (2000) 274–281.
[104] US DEPARTMENT OF ENERGY, Viability Assessment of a Repository at Yucca Mountain, Vols 1–5, DOE/RW-0508, DOE Yucca Mountain Site Characterization Office, Las Vegas, NV (1998).
[105] OECD NUCLEAR ENERGY AGENCY, International Peer Review of the 1996 Performance Assessment of the US Waste Isolation Pilot Plant (WIPP), Report of the NEA/IAEA International Review Group, OECD, Paris (1997).
[106] OECD NUCLEAR ENERGY AGENCY, Safety Report 97: Post-closure Safety of a Deep Repository for Spent Nuclear Fuel in Sweden — An International Peer Review, OECD, Paris (2000).
[107] MURPHY, W., "Natural analogues in performance assessment for geologic disposal of nuclear waste", Scientific Basis for Nuclear Waste Management (Proc. 23rd Symp. Boston, 1999), Vol. 608, MRS, Warrendale, PA (2000).
[108] SMELLIE, J., GRUNDFELT, B., KARLSSON, F., "Natural analogues (NA) approach: Have they provided quantitative data applicable to repository performance assessment

(PA) and contributed to a better public perception of radioactive waste disposal?", Euradwaste 1999: Radioactive Waste Management Strategies and Issues (Proc. 1st EC Conf. Luxembourg, 1999), Rep. EUR 19143 EN, EC, Luxembourg (2000).

[109] BATH, A., BOULTON, G., MARIVOET, J., BLOMQVIST, R., "What approach and tools do we have for understanding the past evolution of groundwater systems as a guide to future evolution for repository performance assessment?", ibid., pp. 257–273.

[110] COMMISSION OF THE EUROPEAN COMMUNITIES, PACOMA Project: Performance Assessment of the Geological Disposal of Medium-Level and Alpha Waste in a Clay Formation in Belgium, Rep. EUR 13042 EN, CEC, Brussels (1990).

[111] COMMISSION OF THE EUROPEAN COMMUNITIES, PACOMA Project: Rock Salt Option: Performance Assessment of Confinements for Medium-Level and Alpha-Contaminated Waste: Final Report, EUR 13634 EN, CEC, Luxembourg (1991).

[112] ATOMIC ENERGY OF CANADA LIMITED, Environmental Impact Statement on the Concept for Disposal of Canada's Nuclear Fuel Waste, Rep. AECL-10711, COG-93-1, AECL, Mississauga (1994).

[113] NATIONAL CO-OPERATIVE FOR THE DISPOSAL OF RADIOACTIVE WASTE, Kristallin-I Safety Assessment Report, Rep. NTB 93-22, NAGRA, Wettingen (1994).

[114] EUROPEAN COMMISSION, EVEREST Project: Evaluation of Elements Responsible for the Effective Engaged Dose Rates Associated with Final Storage of Radioactive Waste: Summary Report, Rep. EUR 17122 EN, EC, Brussels (1996).

[115] OECD NUCLEAR ENERGY AGENCY, Lessons Learnt from Ten Performance Assessment Studies, OECD, Paris (1997).

[116] SWEDISH NUCLEAR FUEL AND WASTE MANAGEMENT COMPANY, SR 97: Post-Closure Safety, Deep Repository for Spent Nuclear Fuel, Main Report, Vols 1 and 2, SKB, Stockholm (1999).

[117] POSIVA Oy, TILA-99: Safety Assessment of Spent Fuel Disposal in Haestholmen, Kivetty, Olkiluoto and Romuvaara, Rep. 99-07, VTT Energy, Helsinki (1999).

[118] EUROPEAN COMMISSION, SPA Project: Spent Fuel Disposal Performance Assessment: Final Report, Rep. EUR 19132 EN, EC, Brussels (2000).

CONTRIBUTORS TO DRAFTING AND REVIEW

Äikäs, T.	Posiva Oy, Finland
Chapman, N.	QuantiSci Ltd, United Kingdom
Federov, A.	VNIPIET, Russian Federation
Gera, F.	International Atomic Energy Agency
Han, K.-W.	Korea Atomic Energy Research Institute, Republic of Korea
Heinonen, J.	American University Concordia, Estonia
Manfroy, P.	ONDRAF/NIRAS, Belgium
Nachmilner, L.	Radioactive Waste Repository Authority, Czech Republic
Neretnieks, I.	Royal Institute of Technology, Sweden
Ouzounian, G.	ANDRA, France
Raynal, M.	International Atomic Energy Agency
Sakuma, H.	Japan Nuclear Cycle Development Institute, Japan
Thury, M.	NAGRA, Switzerland
Vovk, I.	International Atomic Energy Agency
Williams, D.R.	Yucca Mountain Site Characterization Office, United States of America

Consultants Meetings

Vienna, Austria: 17–21 November 1997,
26–30 June 2000

Advisory Group Meeting

Vienna, Austria: 11–15 June 2001