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Scientific and Technical Basis for the Near Surface Disposal of Low and Intermediate Level Waste

INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA, 2002

SCIENTIFIC AND TECHNICAL BASIS FOR THE NEAR SURFACE DISPOSAL OF LOW AND INTERMEDIATE LEVEL WASTE

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FOREWORD

Providing guidance on the disposal of radioactive waste constitutes an important and integral component of the IAEA programme on radioactive waste management. Low and intermediate level waste, even though it contains only a small fraction of the total activity produced in the world, makes up more than 90% of the total volume of radioactive waste. Most of the radioactive waste produced in many developing Member States is low and intermediate level waste.

This report discusses, in a generic sense, the scientific and technical basis for the disposal of low and intermediate level waste in near surface facilities, drawing on the experience of Member States that have existing operational disposal facilities and on relevant national and international research and development studies. The focus is on basic principles, approaches, methodologies and technical criteria considered to be relevant for the design and safe operation of a near surface disposal facility, and for providing a convincing safety case that also covers the periods following repository closure and the end of institutional controls. As a result of the generic nature of the discussion, the described scientific and technical basis is quite comprehensive. For a specific repository, depending on the quantities and characteristics of the waste, the nature of the engineered barriers and the features of the site, the relative importance of the different scientific and technical elements is subject to change. As a consequence, the detailed scientific and technical basis for a specific repository depends on the various features of the disposal system.

It is worth noting that the information presented in this report is based on the experience of Member States with sizeable nuclear programmes and significant inventories of radioactive waste. It is logical for such Member States to adopt progressively more sophisticated repository designs; this high level of sophistication is reflected in the content of this report. Member States with limited nuclear activities and small amounts of radioactive waste may find that simple repositories with minimal engineering are acceptable, provided such designs are supported by a convincing safety case.

It is anticipated that this publication will be of use to scientists, engineers and managers involved in radioactive waste disposal programmes. In addition, decision makers and members of the general public concerned with the scientific and technical issues affecting decisions relating to radioactive waste management may also find the information presented in this publication of use in making informed judgements on the subject.

This report was developed with the help of consultants and through an Advisory Group Meeting held in 2000. The IAEA officers responsible for the completion of this report were R. Dayal of the Division of Nuclear Fuel Cycle and Waste Technology and I. Vovk of the Division of Radiation and Waste Safety.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Low and intermediate level radioactive waste (LILW) is being generated in increasing quantities in many countries as the demand for nuclear applications in medicine, research and industry, including nuclear power, is continually increasing. The potential hazards of radioactive waste to human health and the environment have long been recognized. Hence national and international standards and guidelines dealing with radiation protection and radioactive waste management, including disposal, have been developed [1–11]. These are based on a substantial body of scientific and technical knowledge accumulated worldwide as a result of many years of experience in radioactive waste management and associated research and development [12–30].

The IAEA Radioactive Waste Safety Standards (RADWASS) classification system [31] was developed to provide a generic approach to radioactive waste management, identifying potential disposal options for various waste categories on the basis of their specific characteristics, with the specific activities and the half-lives of the radionuclides in the waste being the key distinguishing features. Thus geological disposal is required for the most active high level waste (HLW), spent fuel and long lived LILW, the radionuclides in which may take tens of thousands to hundreds of thousands of years to decay to acceptably low levels. Near surface disposal is an option suitable for short lived LILW that contains mainly radionuclides which decay to radiologically insignificant levels within a few decades or centuries [4, 31, 32]. LILW that contains limited concentrations of long lived radionuclides may also be suitable for near surface disposal [33–35].

For near surface repositories where the disposal units are close to the surface (within a few metres), institutional controls are needed to provide assurance of the adequate performance of the waste isolation barriers during the initial period when the activity of short lived radionuclides is still high. The anticipated duration of institutional controls is an important strategic decision with significant implications for various aspects of the development of the disposal system, including the definition of waste acceptance criteria. If disposal takes place at greater depths, of tens of metres, as in the case of rock cavity repositories or moderately deep boreholes, which are also considered types of near surface disposal system, less reliance is placed on institutional controls.

The available disposal options for LILW can involve a variety of repository components subjected to a range of environmental conditions. In order to assess and predict repository behaviour and performance over repository timescales, the underlying scientific issues, as well as the behaviour of different materials, have to be clearly understood and appreciated. Thus it is imperative that relevant information on the scientific and technical basis for establishing disposal facilities be available before such a project is undertaken.

The process of repository development is a dynamic one in the sense that it is constantly evolving in response to the enforcement of more stringent regulatory controls and criteria, increasing public concern and awareness about environmental matters and radioactive waste issues, and the need for greater transparency, greater accountability and more prudent management of waste materials. This is evident from the experience of earlier disposal facilities, largely resulting from activities during the 1940s to 1960s. These facilities ceased operation many years ago, did not employ the multiple barrier concept and design approaches, and were not subjected to stringent performance and safety assessments of the kind that are in common use today.

Near surface disposal of LILW has been practised for over half a century, and there are more than 80 near surface repositories around the world [30]. The methods employed have advanced considerably since the early days. Over the last 20 years or so, considerable resources have been devoted to refining the disposal concepts and the approaches to site characterization and siting, and to the development and application of more realistic and representative models and of more sophisticated approaches to performance and safety assessment. It is the improved understanding of the underlying scientific and technical issues that has contributed to the better design and improved performance of currently operating disposal facilities, compared with the facilities that ceased operation decades ago.

Given this background, it is clear that there is a continuing need to develop a good understanding of the underlying scientific and technical issues involved in the disposal of LILW, as well as to keep abreast of major developments in science, technology and materials that are likely to contribute to improved repository design and performance. This is particularly important when one considers that there will be a great deal of activity during the next several decades with regard to the development and implementation of new disposal facilities, especially in developing countries, in eastern European countries and in the Newly Independent States of the former USSR. In addition, it is anticipated that many existing facilities will be upgraded to comply with new safety requirements.

Several Member States have already acquired a great deal of scientific and technical knowledge as a result of having established disposal facilities for their waste. Scientists, engineers and managers involved in the LILW disposal programmes of Member States, especially those in developing countries, need to have easy access to information on the underlying science and technology and to state of the art knowledge for the implementation of disposal facilities in their respective countries. In addition, decision makers and the general public are also concerned with scientific and technical issues affecting decisions related to waste disposal and repository development.

1.2. OBJECTIVE

The objective of this report is to discuss the scientific and technical issues relevant to the disposal of LILW in near surface facilities, drawing on the experience of Member States that have existing operational disposal facilities and on relevant national and international research and development studies.

The report is intended to provide relevant scientific and technical information to Member States that are considering, or are in the process of developing, near surface disposal facilities. It is anticipated that this publication will be of use to scientists, engineers and managers involved in radioactive waste disposal programmes. The wider audience, consisting of decision makers and the general public, that is also concerned with the scientific and technical issues affecting decisions relating to radioactive waste management may also find the information presented in this publication of use in making informed judgements on the subject.

1.3. SCOPE

This report presents an overview of the scientific and technical basis for the disposal of LILW in near surface repositories. The focus is on basic principles, approaches, methodologies and technical criteria that can be used to develop and assess the performance of a disposal facility, and for building confidence in repository safety. This includes consideration of the multiple barrier concept, the performance of engineered barriers, the role of natural barriers and the development of a safety case.

The emphasis is on defining the conditions relevant to the containment of the radionuclides in the repository and the processes that may affect the integrity of the engineered barriers. Both generic and specific data requirements for repository development and the assurance of safety are addressed. A large number of bibliographical references are given to support the information provided in this report.

This report does not consider the disposal of tailings produced by the mining and milling of uranium ores or other naturally occurring radioactive materials. The scientific basis for the disposal of HLW, spent fuel and long lived LILW in geological repositories is treated in a companion publication [36].

1.4. STRUCTURE

Section 2 gives a description of near surface disposal concepts. This includes a description of the different types of facility, the types of waste that may be disposed of in such facilities, the various components of a repository, the stages in the development of a repository and its associated safety case, and the importance of monitoring and surveillance activities.

The discussion of disposal concepts is followed by a description of the important processes in the various system components affecting the performance of the disposal system: the near field (Section 3), the far field (Section 4) and the biosphere (Section 5). Section 6 then discusses in greater detail how confidence in repository safety can be developed. Finally, Section 7 presents the overall conclusions and a summary of the report.

2. NEAR SURFACE DISPOSAL CONCEPTS

This section provides an overview of the different types of near surface disposal facility and the types of radioactive waste that are suitable for disposal in such facilities. It also discusses the main phases of the repository development process, the development of a safety case, and the monitoring and surveillance of the site.

2.1. MULTIPLE BARRIER CONCEPT

The near surface disposal of radioactive waste is intended to isolate the waste from the accessible environment during a period sufficiently long to allow substantial decay of the shorter lived radionuclides and, in the longer term, to limit releases of the remaining radionuclides. In order to achieve these objectives, a multiple barrier concept is employed in which the waste form, the engineered barriers and the site itself all contribute to the isolation of the radionuclides. The multiple barrier concept has been developed for both near surface and geological disposal options [17, 36–41]. It has reached a state of maturity due to the experience gained from developing and operating near surface repositories, and from associated research and development; both have provided valuable information for improvements in repository design and the technologies needed to implement them. Robust designs of engineered barrier systems may be employed in which a combination of physical barriers and chemical controls can provide a high level of containment.

Previously a multiple barrier system was viewed as a set of independent individual barriers working sequentially, but this concept is now viewed in a more integrated and synergistic manner, with complementary barriers operating concurrently and in conjunction with each other. The internationally accepted approach to developing a safety case focuses on the integration of repository design and site characteristics. Defence in depth is provided by using, as appropriate, engineered design features in combination with favourable site conditions, controls on the form and content of the waste, operating procedures and institutional controls [4]. The relative contributions of the various barriers to the overall safety of the disposal facility will depend upon the characteristics of the waste, the site conditions and the disposal system concept. The relative importance of the barriers will also change with time.

The duration of post-closure institutional controls can be expected to be up to a few hundred years. A period of 300 years, for example, would correspond to around ten half-lives of radionuclides such as ^{137}Cs and ^{90}Sr, which are considered important radionuclides in short lived LILW. Even after that period, it can be anticipated that the degraded engineered barriers will continue to limit releases of longer lived radionuclides, largely by physicochemical processes such as sorption and solubility control.

The near surface disposal concept usually envisages continued monitoring and surveillance of the site as a part of active controls to be in effect for a period of several decades to a few hundred years after repository closure. During this period, monitoring and surveillance represent an additional safety measure and contribute to confidence in the satisfactory performance of the facility. The acquisition of data from monitoring also contributes to general scientific and technical knowledge that can be used in the development and improvement of mathematical models for radionuclide transport and for assessing repository impacts.

2.2. DISPOSAL SYSTEMS

This section introduces some basic system concepts that are used in near surface disposal, including the different types of near surface repository. This is followed by a discussion of the system components that are considered in repository design, including the near field (waste form, waste package and other engineered structures), the far field (geosphere) and the biosphere.

2.2.1. Basic disposal system concepts

A range of technical solutions are feasible for the emplacement of radioactive waste in the near surface environment, and the selection of a particular option depends on many factors, such as the sources, characteristics and inventories of the waste, climatic conditions, characteristics of the site, national legislative requirements and radioactive waste management policies. Near surface disposal options include two main types of disposal system: (a) shallow facilities consisting of disposal units located either above (mounds, etc.) or below (trenches, vaults, pits, etc.) the original ground surface; and (b) facilities where the waste is emplaced at greater depths in rock cavities or boreholes. In the first case, the thickness of the cover over the waste is typically a few metres, whereas in the second case, the layer of rock above the waste can be some tens of metres thick. These depths can be contrasted with the case of geological disposal of long lived radioactive wastes, where the wastes are emplaced at depths of hundreds of metres.

During the past 50 years, concepts for radioactive waste disposal have developed considerably. Most experience has been gained for near surface disposal facilities. During this period, there have been many examples of successful repository development, but also of failures in repository performance. Examples of such failures include the rapid leaching of radionuclides from wastes and radionuclide releases due to the flooding of disposal trenches by rainwater or a rising water table (bathtubbing). The reasons for some of these negative experiences include inadequate characterization of the site, unsatisfactory performance of engineered barriers, and inadequate control of the nature and inventory of radionuclides and other toxic substances introduced into the repository. The lessons learned from these experiences have led to the adoption of improved concepts and technologies, such as those applied at IRUS in Canada [41], Centre de l'Aube in France, Rokkasho-mura in Japan, El Cabril in Spain, Drigg in the United Kingdom, and Barnwell and Richland in the United States of America. Many smaller repositories, constructed in various countries, are described and discussed in Refs [14–20, 24–30, 37, 38].

In near surface facilities, the basic disposal units (typically trenches or vaults) are often located in the vadose zone, i.e. above the water table. However, in some countries, local conditions require the disposal units to be constructed in the saturated zone. In both cases, the disposal units have to be designed and constructed to limit the flow of water through the waste. To this end, near surface repository designs may include engineered components such as impervious covers, drainage systems, leachate collection systems and cut-off walls. A network of ditches may be used to facilitate the drainage of rainwater and avoid surface accumulation of stagnant water in the vicinity of the disposal units. Underground drains may be used to keep the disposal units dry, if the wastes are placed above the water table. A leachate collection system may be used to collect any water that has infiltrated the disposal units. Cut-off walls may be constructed to limit horizontal groundwater flows or to provide structural integrity to a disposal facility.

Rock cavities can be either natural or excavated in various geological formations [42]. A rock cavity repository, SFR, has been constructed at Forsmark in Sweden, in crystalline rock about 60 m below the sea. It consists of different types of mined chamber designed to accommodate LILW [17]. Two rock cavity repositories, similar to the Swedish repository in terms of both the design and the type of host rock, are in operation in Finland at Olkiluoto and Loviisa [20]. All of these repositories are located below the water table. An example of a rock cavity repository in the vadose zone is the Richard II disposal facility, located in an abandoned limestone mine near Litomerice in the Czech Republic. In this repository, in operation since 1964, the disposal rooms are situated about 50 m above the water table [20].

The borehole concept has been developed for the disposal of disused radioactive sealed sources and LILW exceeding the waste acceptance criteria for shallow facilities [35]. In some current disposal borehole designs, the boreholes are lined, for example with reinforced concrete and stainless steel, and are filled in situ with cement grout or a low melting point metal alloy. Aspects of the post-closure safety of disposal in boreholes are still being evaluated.

Most human activities that could lead to wastes being disturbed inadvertently, for example by home construction, farming and road building, generally penetrate a few metres below the surface, which means that near surface facilities are susceptible to human intrusion. The greater depth (tens of metres) of rock cavity and borehole facilities makes these disposal concepts more intrusion resistant than shallow near surface facilities and therefore less dependent on institutional controls to ensure safety. Exceptions are activities such as mining and the drilling of wells, where the depth of penetration can be expected to be much greater. Therefore an important aspect of near surface disposal is the requirement to ensure institutional control over the repository site for a period of time.

2.2.2. Repository design components

The major components of a disposal system generally include the waste form, the waste package, the engineered barrier system, the natural barrier system (geosphere) and the biosphere.

The waste form is the solid matrix in which the radionuclides are immobilized after treatment and/or conditioning, prior to packaging. Some wastes may not be conditioned. In this case the waste form will consist of the originally contaminated material (paper, rubber, wood, animal carcasses, etc.), possibly in a compacted form. Different types of conditioning material are used to stabilize waste, with cement being the most commonly used material [43]. Bitumen and polymers are some of the other materials that have been used. Combustible wastes, such as contaminated clothing, plastics, paper, wood and other organic matter, are often incinerated and the ashes incorporated into a solid matrix [17, 44].

The waste package, consisting of the waste form and container, is designed to meet the requirements for handling, transport, storage and disposal. In order to limit the release of radionuclides and other contaminants, some packages include additional features such as absorbing materials and liners. Concrete and carbon steel are the most commonly used materials for waste packages. Plastics, such as high density polyethylene (HDPE), are being used for the fabrication of high integrity containers (HICs). The integrity of waste packages is particularly important, considering the potential for the retrieval of waste. Waste packages are discussed further in Section 3.2 and in Refs [44–49].

The engineered barrier system may consist of a number of separate components, including structural walls, buffer or backfill materials placed around the waste packages, chemical additives, liners and covers. Depending on the disposal system concept, the engineered barrier system may be supplemented by other engineered components, including leachate collection and drainage systems, cut-off walls, gas vents and monitoring wells.

Because of the variety of engineered components that can be used in a disposal facility [14, 15, 37–39, 49–53], a repository developer has a great deal of flexibility in selecting the appropriate components to address the specific performance requirements of a planned disposal facility.

- Below the water table, the disposal units can be lined with clay, concrete, bitumen or other materials to improve the isolation of the waste; above the water table, the same materials could be used to produce impermeable covers to prevent or minimize the ingress of percolating water into the disposal units.
- The space between the waste packages may be backfilled (for example with cementitious grout) to provide structural support for the waste packages.
- In some designs, wastes are combined with protective materials in monolithic blocks in special overpacks to facilitate their retrieval (for example at El Cabril in Spain).
- Capillary barriers (consisting of a coarse grained material, for example gravel, that has a higher permeability than the surrounding finer grained materials) may be used to limit the ingress of water into the disposal units.
- Weatherproof buildings (for example those at Centre de l'Aube in France), and water diversion and drainage systems can be constructed to direct water away from the disposal units.
- The disposal units can be protected from intrusion by a layer of rock (in rock cavity type repositories) or by capping (as in the case of the reinforced concrete roofs in the IRUS facility design in Canada), and from erosion by the planting of vegetation or the use of a rock rubble cover.

In order to ensure that the engineered barrier system is robust enough to perform as specified in the design, materials should be used that have the necessary characteristics to maintain their function and integrity under anticipated repository conditions for the required period of time.

The repository near field consists of the waste, the engineered barriers and the adjacent geological media disturbed by excavation and other construction and operational activities.

The natural barrier system consists of the geological media hosting the repository and any other geological formations contributing to waste isolation. In safety assessments, the natural barrier system is often referred to as the far field or the geosphere. The geosphere comprises the vadose and the saturated zones (generally, above and below the water table). The geosphere protects the disposal facility, and retards and dilutes any radionuclides released from the near field. The natural barrier system is normally long lasting, although it may be affected by erosion, climate change, seismic events, and other processes and events. Guidelines relating to the desirable properties of the site and identification of the types of data needed to demonstrate compliance with the regulatory criteria or to enhance the reliability of the safety case are further discussed in Sections 3 and 4 and are elaborated in Refs [42, 51, 54].

The biosphere is that part of the environment normally inhabited by living organisms. In the biosphere, radionuclides released from the repository, directly or through the geosphere, may be diluted, retarded or concentrated before resulting in any radiological impacts to humans and other species. For a near surface facility, the distinction between the geosphere and the biosphere may to some extent be arbitrary. However, this distinction is often retained in safety and performance assessments.

From the above description, it is clear that repository design is both waste specific and site specific. It should be developed in conjunction with a safety assessment that addresses both the anticipated evolution of the system and credible deviations from it. In the repository design, consideration has to be given to the compatibility of the engineered barriers with the waste and site characteristics (for example the chemical properties of waste and groundwater and the mechanical properties of rocks and soils).

2.3. TYPES OF RADIOACTIVE WASTE

The wastes that need to be managed in any particular country will depend on the extent of the use of nuclear energy and radioactive isotopes.

The IAEA RADWASS waste classification [31] and more recent work on the development of waste acceptance criteria [35] emphasize that wastes suitable for disposal in near surface facilities are primarily short lived LILW containing low concentrations of long lived radionuclides. Institutional and decommissioning waste and much of the large volume of operational trash from nuclear power plants (paper, gloves, clothes, etc.) are contaminated with low levels of long lived radionuclides and fall into this category. Safety assessments can be used to derive both generic and site specific waste acceptance criteria [35], which involves defining a series of unacceptable waste characteristics and placing limits on concentrations and inventories of radionuclides in the waste or the waste package.

Large volumes of LILW, containing a wide range of radionuclides, are produced in the nuclear industry from research, uranium enrichment, fuel fabrication, reactor operations and fuel reprocessing. In countries with reactor operations, waste arisings from that source are generally greater than those from institutional producers. Decommissioning of nuclear facilities is another potential source of large volumes of LILW; generally about 95% of the total volume of radioactive waste produced in reactor decommissioning can be categorized as LILW. Countries with high rates of radioactive waste production need a well developed radioactive waste management infrastructure with treatment and conditioning facilities. In these countries, packaged waste will generally be better characterized, with more uniform waste forms [44]. Detailed information on waste arisings from different waste generating activities can be found in Ref. [49].

Medical and research applications of radioisotopes are common worldwide. These generate solid radioactive wastes, including animal carcasses produced by research activities. The following radioisotopes may be present in these wastes: ^{3}H, ^{14}C, ^{18}F, ^{22}Na, ^{24}Na, ^{32}P, ^{33}P, ^{35}S, ^{36}Cl, ^{41}Ca, ^{45}Ca, ^{47}Ca, ^{46}Sc, ^{51}Cr, ^{57}Co, ^{58}Co, ^{59}Fe, ^{85}Sr, ^{89}Sr and ^{99m}Tc. Liquid wastes (including organic solvents and liquid scintillators) are also produced, but these wastes have to be conditioned before they are suitable for near surface disposal [5].

Disused sealed radioactive sources can be considered as a special type of waste derived from medical, research or industrial uses. A number of different radionuclides are used in sealed sources, including ^{60}Co, ^{90}Sr, ^{137}Cs, ^{226}Ra, ^{241}Am and ^{252}Cf.

Experience based on the performance of existing near surface repositories and a variety of safety assessments, both generic and repository specific, show that the radiological impacts of near surface repositories are generally linked to the mobility and/or longevity of a limited number of radionuclides that are critical for specific exposure scenarios. For example, highly mobile radionuclides, such as ^{3}H, are usually critical for scenarios involving mobilization and transport in aqueous or gas phase, while long lived radionuclides are relevant in the case of human intrusion scenarios, which are generally assumed to be realistic only after the end of institutional controls.

2.4. DEVELOPING A REPOSITORY

Repository development can be considered as a series of sequential steps or stages, for each of which scientific and technical issues need to be addressed [55]. In a repository development programme, various activities, such as the selection of the disposal concept, siting and repository design, will normally be subject to licensing procedures before approval is received to proceed to the next activity in the programme. All repository development activities need to be planned and co-ordinated taking into account post-closure safety and repository public acceptance issues. Public involvement and participation is an important aspect of the overall repository development process. It is imperative that a quality assurance programme be established at the start of the programme.

Three main phases can be considered for a repository: pre-operational, operational and post-closure. The pre-operational phase includes the development of the disposal system concept, siting and design studies, and construction. The operational phase includes the period of repository operation, followed by closure. The post-closure phase comprises activities following repository operation and closure [4]. During this phase, institutional controls, which are designed to enhance repository safety, are implemented. The various activities related to each of these phases are described below. There are many constraints on the implementation of a disposal concept due to, for example, waste properties, site characteristics, design features, and construction methods and activities. Details can be found in Refs [13, 33, 36, 38, 42, 44, 52, 54].

2.4.1. Pre-operational phase

The pre-operational phase begins with a conceptual and siting stage. It starts with the development of the initial disposal concept, which is based on the nature and estimated quantity of the waste requiring disposal, environmental constraints, the availability of necessary materials, waste transport routes, cost, and social and planning considerations. General siting requirements may be developed to guide a site selection programme. Site selection may involve investigating, characterizing and evaluating a number of candidate sites.

The design of the repository takes into consideration the characteristics of the site and the properties of the waste in accordance with the regulatory requirements. As the design process proceeds and evolves, information from site specific studies and safety assessments can contribute to optimization of the design [56, 57].

The design process takes into account repository operation under both normal and accident conditions. Thus, for example, fire alarms and dust suppression systems need to be considered as well as monitoring, inspection and maintenance provisions.

The design of the auxiliary facilities, such as buildings for the treatment, conditioning and storage of wastes, electricity and water supply, and other engineered systems, is outside the scope of this publication. However, the repository design needs to take account of the interdependence of any auxiliary facilities with repository operations. For example, provision may be required for managing secondary wastes arising from decontamination activities or waste conditioning facilities.

The construction stage can only start after regulatory authorization has been issued. This usually requires that safety assessment documentation has been reviewed, the detailed repository design has been approved, the respective licensing procedures have been completed and an appropriate quality assurance programme has been established.

Construction of the repository may be carried out in a phased manner; in particular, it can continue and extend into the operational phase to provide additional disposal space for waste as it becomes available and is received at the facility. For example, in Sweden it is envisaged that the existing operational disposal facility will be extended to accommodate waste expected to arise from the decommissioning of the nuclear power plants currently in operation. Depending on the size of the facility and national circumstances, the period of time from concept development to the completion of construction activities may range from a few years to around 15 years.

2.4.2. Operational phase

As discussed above, the operational phase covers both the operational and the closure stages. The operational phase usually comprises the following activities: commissioning, waste receipt and emplacement, closure (including backfilling, covering and sealing), operational monitoring and surveillance, and any emergency activities. It may also include variable periods of storage and pre-disposal conditioning and packaging of wastes.

The licence to operate the repository may be subject to conditions imposed by the regulator to ensure that the operations are consistent with the applicable regulations. In addition to the radiological and industrial safety requirements for these activities, there may be requirements for physical security, fire protection and other safety related matters.

Emplacement of waste comprises both the physical placement in the repository and subsequent management until that part of the repository is covered or sealed. The repository may have a number of units progressively constructed and used for disposal. As soon as a particular part of the repository is filled with waste to its capacity (and under some conditions even when it is in operation), the voids around the waste packages are usually filled with backfill material. It may also be necessary to protect that part of the repository with a temporary cover or seal to limit infiltration of water and to provide radiation shielding.

During the operation of the repository, the operator must be able to demonstrate that the repository is performing as designed with respect to its impact on workers, members of the public and the environment, and is in compliance with the conditions of the licence. This may require, for example, inspections of waste emplacement activities, the monitoring of effluents released (under the terms of the licence), the assessment of worker exposures and the operation of a monitoring system to detect any abnormal releases from the repository. The repository operational period may last between 30 and 40 years.

Closure of the repository takes place after the receipt of waste ceases and waste emplacement operations have been completed. Engineered barriers, in particular the final cover, are emplaced to ensure the integrity of the repository, to minimize the ingress of infiltrating water to the waste, thereby limiting radionuclide releases, and to reduce the likelihood of disturbance by human activities. This is particularly important for shallow facilities, where the waste is emplaced relatively close to the surface. For rock cavity and borehole repositories, the closure process includes the sealing of engineered access routes such as shafts, drifts or other penetrations into the repository, and boreholes. Closure should be conducted in accordance with a closure plan that includes an updated safety assessment and a description of the institutional controls intended for the post-closure phase [4].

2.4.3. Post-closure phase

After repository closure, institutional controls are considered an integral part of the overall system of protection for a near surface disposal facility. The controls can be either active (for example monitoring, surveillance and, if necessary, corrective actions) or passive (for example land use control and record keeping). Controls maintained over a repository after closure are designed to enhance its safety, in particular by preventing intrusion into the disposal units. However, in accordance with the principle of not imposing undue burdens on future generations [1], such controls are not to be used to justify a reduction in the level of performance designed into a multiple barrier isolation and containment system. The safety of a closed disposal facility does not rely solely on institutional controls that require extensive and continuing active measures [4]. For rock cavity repositories and borehole facilities with waste emplaced tens of metres below the surface, safety during the post-closure phase relies less on active institutional controls than is the case for near surface disposal facilities.

Institutions designated for post-closure control of near surface repositories can be instrumental in providing scientific and technical support for safety in the following ways:

(a) *Consequence reduction.* Once a situation giving rise to excessive radiation exposure is identified, the institution can evaluate a range of options intended to reduce the exposure. This is usually referred to as remediation or intervention. It is necessary to consider whether any action is justified [2, 10]; for example, remedial actions should result in more good than harm.

(b) *Reduction of the likelihood of the consequence arising.* Institutional control measures, such as the construction and maintenance of fences and other physical security measures, markers, land use controls and archives, can all be seen as means to reduce the likelihood of the wastes being disturbed. It is important not only to reduce the likelihood of radiation exposures being received, but also to reduce the likelihood of engineered barriers being impaired.

(c) *Monitoring of sites.* Post-closure monitoring can serve several functions [58]. It can provide an early warning of system malfunctions that might lead to unacceptable impacts on individuals and the environment. It can also help in verifying the intended overall performance of the disposal system. The content and duration of the monitoring programme will depend on local conditions and societal considerations (see Section 2.6). Satisfactory monitoring results over an extended period of time will probably be essential for improving the confidence in the satisfactory performance of the disposal system and may support the decision to discontinue institutional controls. The time needed to achieve this cannot be stated in advance; such a decision will inevitably fall on future generations. The responsibility of the repository developer is to ensure that any monitoring that is required can be undertaken and to ensure that such activities do not impair the integrity of the multiple barrier system.

2.5. DEVELOPING A SAFETY CASE

There is an international consensus that the long term radiological safety of a disposal facility can be assessed by comparing the estimated radiological impacts with established standards [59]. A further consensus has been achieved on methods for developing a safety case. A rigorous assessment, based on methods that have been justified scientifically and technically and which include quantitative as well as qualitative arguments, provides the basis for any safety case for a disposal facility [60, 61]. Assessment approaches and details of the methods available for assessing safety are described in numerous national and international documents, in particular Refs [59–76] and the references therein.

Developing a safety case will normally include performance and safety assessments, but it may also require supporting information on the robustness and reliability of the assessments and the underlying assumptions. Performance assessment involves an analysis to evaluate the performance of a system or subsystem, followed by a comparison of the results of such an analysis with appropriate standards or criteria. Hence performance assessment plays two major roles: it provides an evaluation of how the different components of a disposal system contribute to its overall performance and it allows comparison of the assessment results with specific performance criteria.

The term safety assessment is used in this publication to denote the assessment of all aspects of the siting, design and other stages of repository development that are relevant to safety, including performance assessment. In a safety assessment, the output is in a form suitable for comparison with relevant safety criteria. IAEA recommendations on the development of a safety case for a near surface disposal facility are summarized below; this summary is based on various IAEA reports [74, 75].

Developing the repository safety case is a continuous and iterative process carried out at different levels of detail and making use of the information available at the various stages of repository development. At an early stage, safety assessments are used to determine the feasibility of disposal concepts, to direct site investigations and to assist in initial decision making. Screening calculations may be performed in order to evaluate the proposed concept and to focus on the most important safety relevant radionuclides, migration pathways and release mechanisms. Screening calculations require only limited data on waste package characteristics and radionuclide pathways. These data can be obtained from a number of sources: literature searches, material specifications, laboratory studies, studies of natural analogues, pre-operational monitoring in the surrounding area and preliminary site investigations.

Assessments, following concept development and site selection, can contribute to system optimization and facility design by comparing the performances of different combinations of waste packaging, engineered barriers and closure measures. Performance assessment can be used to identify the components that are most important to overall safety and to show how the other parts of the system affect the performance of those components. For example, the source term (i.e. the rate at which radioactive species are released from the disposal units) will be affected by a number of processes. First, water enters the disposal units and gains access to the waste package; the waste container then degrades, allowing the waste form to be exposed to water. The waste form, in turn, degrades, resulting in the release of radionuclides. The release rate will depend upon radionuclide transport in water, taking into account processes such as radionuclide solubility and sorption. Performance assessment describes how all of these processes interact to result in a source term, and helps to define which processes are the most important in determining the source term characteristics. A result of the application of performance assessment might be, for example, the finding that it is important to control water chemistry and that cement based materials should be used to condition the near field chemistry, thereby exerting solubility constraints on the concentrations of some radionuclides.

The completeness and robustness of the safety assessment depend on the availability of data on waste and site characteristics, waste package performance and properties of the engineered barrier system. Close co-ordination of the safety assessment and the supporting data acquisition programme is therefore necessary, with the safety assessment serving as a valuable tool for identifying and prioritizing supporting research and development work. The process continues with the acquisition of additional data, for example by field and laboratory investigations and appropriate modelling, as the design is developed and optimized, until it can be reasonably assured that the repository meets the relevant safety requirements.

The development of the safety case plays a key role in the licence application and approval process. Safety assessments may be required at various stages of the licensing process, including the approval to construct, operate and close the repository, and whenever there are significant changes in the state of the repository. For this reason, the safety assessment is usually updated at each stage of repository development. This updating may require supporting studies and additional data collection that can help to reduce uncertainties in modelling.

Developing the safety case includes the identification of possible radionuclide transfer routes, known as pathways, and relevant scenarios (descriptions of a sequence of future events). Scenarios deal with natural phenomena and gradual or abrupt changes in conditions that may lead to changes in disposal system performance over time. These scenarios are usually assessed by analysis of features, events and processes (FEPs). Recently the information on FEPs relevant to the near surface disposal of radioactive waste has been assembled at the international level within the ISAM Project [74]. Experience with safety assessments of near surface repositories shows that it is usually reasonable to assume normal evolution scenarios during the period when institutional controls are in effect and to consider also intrusion scenarios after the termination of institutional controls. The typical normal evolution scenario results in mobilization of radionuclides by infiltrating water and transport by groundwater to some accessible points, such as a spring, a body of surface water or a water well. Intrusion scenarios, while defined in detail on the basis of repository design and local environmental conditions, consider activities such as drilling, construction and farming at the site of the repository.

Consequence analysis involves the development and application of transport and exposure models and the evaluation of uncertainties. Models usually consist of submodels addressing processes such as infiltration and leaching, gas generation, near field transport, gas and groundwater transport, surface water transport, atmospheric transport, uptake by plants and animals, and exposure of humans. For the near field, the source term used in the models needs to be a reliable representation of potential releases of radionuclides from various waste forms under anticipated disposal conditions, and with account taken of the progressive degradation of the engineered barriers. For geological repositories, assessments may need to consider impacts that might take place over very long time periods (potentially in excess of 10^4 years). For near surface repositories, the timescales of relevance in assessments are generally much shorter because of the preponderance of short lived radionuclides.

Uncertainty is inherent in any safety assessment. One source of uncertainty is the degree to which models represent the real system; additional uncertainties are due to the inherent unpredictability of future human actions and of the evolution of the facility and its environment over long periods of time. Sensitivity and uncertainty analyses play an important role in understanding and, where possible, reducing uncertainties (see Section 6.2.2).

In the development of the safety case, the results of the assessments, including the identification of uncertainties, are compared with the design goals and regulatory criteria. Account can also be taken of other lines of reasoning that contribute to arguments for the acceptability of the repository. Examples of such supporting arguments might include relevant observations of natural systems and archaeological analogue studies, evidence of a robust design with defence in depth, and the use of limiting or bounding analyses. Communicating the arguments for repository safety to the various interested parties is an important component of overall confidence building, and the presentation of the results of safety assessments requires careful consideration, as discussed further in Section 6.

2.6. MONITORING AND SURVEILLANCE

Monitoring and surveillance of existing disposal sites have provided valuable data on the performance of near surface disposal facilities [58, 77]. Most of the recently developed near surface repositories have involved interactions between safety assessment and monitoring and surveillance programmes, resulting in the strengthening of confidence in safety. This section addresses some of the technical issues involved in monitoring and surveillance activities undertaken in the pre-operational, operational and post-closure phases, related mainly to environmental monitoring and the collection of data used in safety assessments. It makes use of the information contained in relevant documents [58, 77, 78] and employs the following terms and definitions.

Monitoring means the continuous or periodic observation and measurement of radiological, environmental, engineering and other relevant parameters. Monitoring helps in the evaluation of the behaviour of the different components of the disposal system, and of the impacts of the repository on the environment. For example, periodic measurement of contamination levels in the local groundwater may provide assurance that there have been no significant releases of radionuclides.

Surveillance is periodic inspection to verify that structures, systems and components relevant to the safety of the repository continue to function or are in a state of readiness to perform their functions. For example, periodic inspection of installed monitoring equipment will increase confidence that the equipment is working correctly.

Environmental monitoring covers a broad range of media, including air, surface waters, soils, and flora and fauna that may be part of the food chain. Groundwater and vadose zone (i.e. unsaturated zone) monitoring, on the other hand, can provide an early warning of the release of contaminants, especially the ones that are highly mobile. The broad nature of environmental monitoring provides reassurance that significant exposure pathways have not been overlooked or underestimated.

Pre-operational environmental monitoring of the site involves the collection of data, particularly those that are expected to vary with time, for the characterization of the site and definition of ambient conditions that will eventually serve as a baseline for comparison with measurements taken during the subsequent phases of repository development. These data are used in initial safety assessments and are useful in engineered barrier design, evaluation of construction impacts and identification of preferential water flow pathways. They can also serve as a benchmark for the testing of mathematical models.

The following are examples of repository features, processes, parameters and characteristics that can be monitored on an ongoing basis.

- Meteorological conditions: precipitation, temperature, wind, evaporation.
- Geomorphological aspects: erosion mechanisms and their rates.
- Hydrological conditions: runoff, flow characteristics of existing water streams, lakes and wetlands.
- Hydrogeological conditions: infiltration and evapotranspiration, permanent and temporary springs, depth and oscillation of the water table, preferential flow pathways, direction and rate of groundwater flow in both vadose and saturated zones, travel times to existing and potential outflow and extraction points.
- Geochemical conditions and environmental quality: water quality, concentrations of naturally occurring radionuclides in a variety of environmental media, retention of radionuclides by soil and geological materials.
- Geotechnical conditions: rock stress, response of the geological media to excavations and load of support structures.

Operational monitoring and surveillance data, besides being important in achieving radiation protection and physical security objectives, may indicate deviations from predicted conditions. Therefore many of the monitoring activities initiated in the pre-operational phase are likely to continue during the operational phase. Some near surface repositories may allow the discharge of solid, liquid or gaseous effluents, as a result of leachate collection, waste treatment or conditioning activities. Specific monitoring activities are generally planned for the sampling and control of effluent discharges [7].

The potential exists for changes to the local environment, induced by the construction and operation of the repository, that can affect the performance of the system. For example, increased water infiltration can be caused by the disturbance of the ground surface, the loss of native vegetation over the disposal units, the drilling of boreholes or the channelling of runoff water. Another example is the potential generation of preferential pathways for the migration of groundwater, and any released radionuclides, that may result from the construction of rock cavity repositories. Any such induced changes are likely to require specific modifications to the monitoring programme to determine their potential impact on the future performance of the system.

The main objective of surveillance activities during the operational phase is to detect any degradation or anomalies in the engineered barriers. Visual inspections and physical surveillance of disposal unit covers are conducted to determine if their integrity has been affected by erosion, cracking, subsidence, deflation, the action of burrowing animals or any other processes. The covers may also be monitored to detect minor changes that can affect performance, such as increases in water content or permeability.

Technical requirements for the monitoring programme during the post-closure phase are not expected to differ significantly from those relevant to the operational phase, with specific monitoring being required to ensure the performance of additional barriers installed at closure. The basic objectives of post-closure monitoring are to verify the absence of unexpected levels of waste derived radionuclides at various locations and to provide confirmation of system performance. National programmes do not commonly plan to use post-closure monitoring data to provide confirmation of estimated doses. This is because estimated radiological impacts are generally small and may occur far into the future [75]. Some other safety indicators, such as environmental concentrations and fluxes of long lived radionuclides, can be monitored [79]. This is the subject of an ongoing IAEA co-ordinated research project.

The details of the measurements to be undertaken will depend on the specific features of the site and of the repository design. For example, infiltration through engineered covers may be monitored and compared with predicted values. Other examples of measurements to comply with the post-closure monitoring objectives would be the collection and analysis of water samples taken from a leachate collection system, measurements of moisture distribution in low permeability covers and in unsaturated materials underlying the disposal units, and the collection and analysis of water samples taken below or immediately downgradient from disposal units.

Post-closure monitoring may last for a long period of time. The size of the monitoring programme and the frequency of measurements can be expected to decrease with time after closure. Decisions on any changes in monitoring schedules, including their termination, that will obviously be the responsibility of future generations will need to be based on the interpretation of accumulated monitoring data (see Section 2.4.3).

Post-closure surveillance is needed mostly for repository components that have a barrier or monitoring function. It includes the inspection of the repository cover, drains, leachate collection and monitoring systems. Fences and warning signs prohibiting access to the site also need to be maintained. Periodic inspections ensure that land use restrictions and prohibitions are being complied with. Surveillance of rock cavity installations, if carried out, would focus on the inspection of accesses to the underground openings and areas above the excavations. However, as mentioned earlier, for this particular disposal concept, adequate safety in the post-closure phase might be achieved with minimal active institutional control measures.

The level of effort expended on post-closure monitoring and surveillance, and indeed in the preceding phases, should be commensurate with the potential hazards of the repository [58].

3. NEAR FIELD

Evaluation of the source term involves consideration of the degradation of the engineered structures to the extent that fluids, air and water contact the waste and result in the release of radionuclides from the waste form and subsequent transport out of the disposal facility. The characteristics of the near field environment, such as the physical properties of the surrounding geological media, the hydrogeology and groundwater chemistry and their evolution over time, are clearly important in determining the nature, rate and extent of the various near field processes that control the source term. Mechanisms for the degradation of waste packages and other engineered barriers, mobilization of radionuclides in the near field and the generation of gases are discussed in this section. Modelling aspects of the near field are discussed in this section and in Section 6.

3.1. NEAR FIELD ENVIRONMENT

Various environmental settings and geological media selected for the location of near surface disposal facilities, and their interactions with the waste and the engineered barrier system, taking into account the relevant hydrogeological and geochemical conditions, have been extensively studied and discussed in numerous publications [12, 13, 17, 20–23, 42, 50, 51, 76–95].

3.1.1. Host geological environment

The ‘host rock’ consists of the geological medium in which the disposal units are located. The main functions of the host rock are to provide isolation of the waste from the accessible environment and to limit the migration of radionuclides from the repository. The vadose zone may show favourable features for the location of near surface repositories, such as allowing disposal unit designs that are intrinsically capable of minimizing the contact of infiltrating water with the waste. For disposal in the saturated zone, candidate host media are generally low permeability materials in which radionuclides can be sorbed, resulting in limited radionuclide transport. Some examples include relatively unfractured clay, clayey till and mudstone.

Ideally, for a shallow facility in the vadose zone, the preferred host rock is one that has a low unsaturated moisture content at field capacity and that provides effective drainage for water percolating through the facility, for example a sandy host medium. For disposal in the saturated zone, a host medium is preferred that has a low groundwater flow into and through the repository, for example a clay rich host medium that also provides ample sorption capacity, contributing to retardation of radionuclide migration. Rock cavity and borehole facilities, depending on the nature of the host rock and on local climatic conditions, may have the disposal units either in saturated rock or in the vadose zone.

For shallow disposal units that, during the initial period of repository construction and operation, are exposed to the risk of water inflow, for example after episodes of high intensity precipitation or snow melting, careful consideration needs to be given to the potential impacts of such events. If such impacts are judged to be unacceptable, adequate provisions need to be included in the design and operation procedures to avoid or minimize the probability of water inflow during the pre-operational and operational phases of the repository.

For disposal in the saturated zone, the disposal units will be excavated, drained and exposed to atmospheric air. In addition to mechanical disturbances caused by the construction and operation activities, exposed rock surfaces may dry out or be oxidized. Some unlined excavations may crack and require support. After closure, the groundwater that has been drained during construction and operation is expected to re-enter the disposal zone and gradually fill the disposal units. These processes may need to be monitored and their effects accounted for.

In rock cavity type facilities, if ventilation air were to flow from warmer to cooler sections of the repository, condensation of moisture would be likely to occur. Steel support systems could corrode and might require maintenance, and cement might be partially carbonated as a result of exposure to atmospheric carbon dioxide.

3.1.2. Hydrogeological conditions

The depth of the water table depends on climatic conditions, the characteristics of the geological media below the surface and surface morphology. In an arid climate, the water table is usually at a depth of hundreds of metres, but in other climatic zones the water table may be only a few metres below the surface, particularly if near surface layers are rich in clayey materials having low permeability.

For many sites and geological media currently being used or considered for near surface repositories where the waste is emplaced below the water table, hydrogeological conditions are the most significant factor affecting the performance of the near field barriers. The design of the waste isolation system, the characteristics of engineered barriers and solute transport are influenced by the local hydrogeology, while the regional hydrogeological conditions determine the far field migration of radionuclides released from the repository. Hydrogeology and geochemistry control two key aspects of the near field: (a) the rate at which water can enter the disposal units and the rate at which it can transport released radionuclides away, i.e. the dominant mass transfer process; and (b) the chemistry of the water entering the near field. For some extremely low permeability host rock formations, or low energy hydrogeological environments, where diffusion is the dominant mechanism controlling solute transport, it is probably more accurate to say that it is the chemistry of the pore water that determines the near field conditions.

In the vadose zone, the water content generally exhibits considerable variability in the first few metres below the surface and can be used to estimate infiltration. Infiltration is influenced by the highly transient processes of precipitation, runoff, drainage, evapotranspiration and snowmelt. Water movement within the vadose zone is mainly in the vertical direction, but there may be significant lateral flow if the geological profile includes layers of variable permeability, which may allow the formation of perched water. The dynamics of water movement through the vadose zone will depend on the permeability of soil layers, precipitation rate, extent of runoff and amount of evapotranspiration. When perched water layers are present, careful consideration needs to be given to protecting the disposal units from water inflow, not only from above but also laterally. This can be achieved by the construction of vertical capillary barriers, consisting of coarse grained walls surrounding the disposal units and underlain by a high permeability layer. This would prevent perched water from reaching the waste.

For near surface repositories in rock cavities, careful consideration needs to be given to the potential impact of the zone disturbed by excavation on water inflow into the disposal units and on the performance of the various engineered barriers.

3.1.3. Chemical conditions

Chemical conditions in the near field are determined by the chemical properties of the repository materials and the processes of mass and energy transfer into and out of the repository. The major chemical and physicochemical processes in the near field that can adversely affect the repository components include oxidation, which can cause degradation of some waste forms and packages, the corrosion of waste containers, and leaching processes leading to the mobilization of radionuclides. Microbial activity could affect the waste package, depending on the local conditions, in either an adverse or a beneficial manner.

The transport of gases, including air and water vapour, directly into the near field of the disposal units, located either above the original ground surface (mounds) or underground in the vadose zone, will lead to oxidation and, in the presence of moisture, also to corrosion. The transport of chemical species by inflowing water, while to be expected to a certain extent for disposal in the saturated zone, should be minimized or prevented for disposal units located above the water table. While this can be achieved by proper repository siting and design of the barrier system, it is conceivable that extreme events, such as abnormal weather conditions or other natural phenomena causing unforeseen variations of the water table, might lead to water entering the disposal units.

For disposal below the water table, groundwater moving towards the disposal units is likely to carry chemical species from the adjacent hydrogeological system. Mobilization of certain chemical species and their transport in natural waters may be enhanced by the presence of complexing agents or colloids, and by microbial activity. Although solutes and colloids can certainly be transported by moving water (advection), diffusion might also need to be considered. Ultimately, depending on the sources and the transport routes and mechanisms, a variety of chemical species and compounds that can affect waste package performance may be present in the repository near field environment.

Waste packages can contain a wide variety of chemical species. In most cases, the contents and components of waste packages exert more influence on the near field chemical conditions than the chemical species transported in groundwater. Some of the components in a waste package may act as complexing agents and subsequently reduce the capacity for sorption of radionuclides in the near field. With high concentrations of radionuclides in the waste, it is possible that solubility limits may restrict the mobilization of some radionuclides, which in turn will reduce the source term.

There are many chemical processes that can affect repository performance. These include oxidation, corrosion, dissolution, solubility limitation, diffusion and sorption. These processes can in turn be affected by the near field temperature and pressure, pH, redox potential, ionic strength (total dissolved solids), buffer capacity, chemical composition, speciation and complexation. Processes of importance for near field performance depend on waste characteristics, repository design, and the location of and materials used in the engineered barriers and in waste packages. Consideration of the near field chemical environment is important specifically in defining the retardation properties of the materials within the disposal units.

In a high pH environment, both the mobilization and the transport of certain long lived radionuclides, specifically ^{14}C and actinides, could be limited because of solubility considerations. The important point here is that it is the chemical buffering property, not the physical integrity, of the cementitious engineered barrier (waste form, structural components, etc.) that provides constraints on the solubility of certain radionuclides, thereby reducing the potential for mobilization and transport. This is particularly important in consideration of the fact that a high pH environment can be maintained in the near field for a long time.

The chemical composition of groundwater depends on its origin (meteoric water, formation water, etc.), climatic conditions and water–rock interaction processes. Meteoric water is characterized by low concentrations of dissolved solids (mainly Na, K, Ca, Mg, HCO_3, SO_4, Cl, Si), positive redox potentials and slightly acidic conditions. In areas where the water table is close to the surface, the occurrence of fresh meteoric waters is typical in the upper, more dynamic zones of the groundwater system, and in deeper regions of the geosphere, which are more heavily weathered or fractured. Slow groundwater movement over long periods of time results in geochemical equilibrium with the host rock minerals. In near surface disposal concepts which involve placing disposal units below the water table in impervious host rocks or at sites with low hydraulic gradients, groundwater chemistry is likely to be controlled by host rock mineralogy. Repositories located in coastal regions may be subject to ingress of saline sea water into the disposal units.

Groundwater chemistry can also be influenced by the activity of microbes that thrive in nutrient rich groundwaters. The action of microorganisms, in particular the biodegradation of waste forms, could be a negative factor in repository performance (see Section 3.4). On the other hand, the results of some studies [92, 93] indicate that, under certain conditions, microbes in the geosphere may also be capable of protecting the host rock and repository materials from oxidation by consuming oxygen while using available reductants. In a microbial process, some chemical by-products, such as iron, manganese, carbonate and sulphide compounds, that can lower the redox potential of groundwater are also generated. This may lead to strongly anoxic conditions and supersaturation of repository water with respect to such species, resulting in their precipitation. In addition, some evidence has been gathered that microbial activity may accelerate rock weathering and induce the formation of clay minerals that would favour the retention of radionuclides through sorption [93].

3.2. WASTE PACKAGES

As indicated earlier, the key features of waste package performance are durability and radionuclide containment. Information on important properties of waste packages, as well as on processes that need to be investigated and understood to assess radionuclide containment and durability characteristics, is provided in Refs [22, 23, 37, 43–55, 76, 95–98]. Radionuclide release mechanisms and the performance of waste packages under repository conditions are discussed below.

3.2.1. Waste form performance

The waste form itself may provide waste containment to some degree. Once the container degrades, radionuclide release is determined primarily by the performance of the waste form. The effect of cementitious material on the near field chemistry has already been mentioned. Cementitious material buffers the pH of groundwater so that the mobilization of certain radionuclides is reduced as a result of solubility constraints on their concentrations [43]. The long term stability of cement based products used in waste packages and other engineered barriers is a function of very slow setting reactions influenced by the movement as well as the chemical composition of water, and the sorption of corrodants (see Section 3.3.2). In contrast, bitumen is not affected as much by interaction with water and, provided it is not oxidized, can exhibit stability over a long period.

The physicochemical properties of the waste form, including the types of contaminant, will determine the nature and extent of radionuclide release. Depending on the type of waste form, radionuclide release mechanisms can vary significantly. For example, cement solidified wastes exhibit diffusion controlled release for many radionuclides. Radionuclides present as surface contamination on metal or other surfaces are likely to be released by dissolution. A good understanding of the underlying release mechanisms and rates can be important in predicting waste form leaching behaviour or in developing source term release models.

The radionuclide release mechanisms for organic matrices, in particular bitumen, are not well understood. Although there is a significant amount of leaching data for a variety of bitumen waste products, the available information is not amenable to modelling to predict waste form behaviour, because the underlying release mechanisms have not been fully investigated.

In the discussion presented above on radionuclide release from waste forms, it has been assumed that the waste form retains its physical integrity during the entire leaching period. Therefore it is important to test waste forms under realistic repository conditions both during operation and after closure (immersion, freeze–thaw, compressive strength, etc.). Furthermore, degradation induced changes in waste form properties over time are likely to affect long term leaching behaviour. Therefore, in order to predict waste form performance, it is important to establish the degradation induced changes in release mechanisms, rates of changes and the mass transport properties of the degraded waste forms.

In addition to contributing to waste containment, waste form stability is also important for the overall integrity of the waste package. For example, the waste form, together with the container, must have sufficient mechanical strength to withstand the load due to stacking of containers and backfill. Loss of waste package integrity could contribute to instability of the disposal unit and cover. Impact resistance and compressive strength are important properties that are normally tested to ensure that waste forms possess sufficient physical strength to maintain structural integrity during handling and under anticipated repository conditions.

Standardized leach test methods, such as the American Nuclear Society/American National Standards Institute test [96], are commonly used to assess the radionuclide release behaviour of solidified waste forms that exhibit diffusion controlled release. However, with the progressive degradation of the cementitious matrix, resulting in an increase in porosity and permeability, development of cracks, etc., the release mechanism can change over time to yield higher rates of release. These changes in waste form properties as a result of degradation over time need to be taken into consideration for modelling waste form behaviour and the corresponding evolution of the source term. Depending on the sensitivity of the safety assessment results with respect to the temporal evolution of the source term, these issues could be the subject of further scientific investigations or demonstrations.

3.2.2. Container performance

Waste containers can contribute to overall waste package performance by delaying the contact of the waste form with water, thereby allowing the short lived radionuclides to decay to acceptable levels. Typically, LILW containers consist of carbon steel drums, steel liners, concrete boxes, etc. (see Section 2.2.2). Materials used to fabricate HICs include HDPE, stainless steel, metallic fibre reinforced concrete and polymer impregnated concrete. Plastic container materials (HDPE, etc.) are not susceptible to corrosion. However, because of problems related to the mechanical stability of plastic containers, HDPE containers are often placed in concrete overpacks to provide additional containment and durability lasting for hundreds of years. Because the container in some cases is important with respect to providing physical containment of short lived radionuclides, estimation of the container lifetime is necessary to establish how much credit should be assigned to the waste package for radionuclide containment relative to the other barriers of the disposal system.

Container performance and durability depend upon factors such as container material and design, and environmental conditions. For metallic containers, corrosion performance is an important factor affecting container durability. It is important to identify the corrosion mechanisms that contribute to container failure for the various types of container material and to estimate corrosion rates under anticipated disposal conditions. In estimating container durability, repository specific conditions may be critical. For example, a high pH environment is beneficial for reducing corrosion. Therefore a cementitious near field environment will result in lower corrosion rates and hence longer container life. A high chloride, sulphate or carbonate content in the wastes or in ambient groundwater, on the other hand, can lead to conditions that accelerate corrosion; specifically, stress and pitting corrosion can be enhanced in stainless steel and other metals by the presence of chlorides. Other environmental factors, including ambient redox conditions, can also affect container corrosion performance.

For concrete containers, the performance characteristics, including the degradation of concrete, have also been the subject of detailed studies. It has been established that the amount of water needed to hydrate cement phases is usually smaller than that used for mixing the concrete raw materials. This excess water remains inside the materials after setting and hardening, thus producing a network of capillary pores that results in a more permeable concrete matrix.

Properties determining the water ingress and radionuclide transport for concrete containers, such as permeability, radionuclide diffusivities and sorption coefficients, can be measured by standard, well established test methods. Resistance to thermal cycling is another important criterion for waste package integrity and acceptability. Standard freeze–thaw tests are normally performed on containers as part of container qualification and quality assurance requirements. Changes in mechanical stability and mass transport properties as a result of container degradation need to be taken into consideration in deriving estimates of radionuclide transport in partially degraded concrete containers.

In summary, the performance and durability of waste containers under repository conditions are affected by degradation processes which depend on exposure to atmospheric fluids and/or groundwater, waste constituents and other chemical species present in the repository. Some specific processes that can affect waste package durability include:

- Concrete dissolution and crack development (in the case of cementitious waste forms, concrete containers);
- Corrosion (metal containers);
- Chemical attack by waste constituents and water transported species;
- Ageing and, in some cases, radiation effects, especially for plastic containers.

For assessing container performance, in addition to standard testing used to determine a container's mechanical and structural integrity, it is necessary to consider the chemical and physicochemical mechanisms of container degradation.

3.3. ENGINEERED BARRIERS

Engineered barriers are features of the disposal system made or altered by humans during the construction, operation and closure of a repository. Engineered barriers are intended to contribute to the overall performance of the disposal system by providing the level of containment required while the waste remains hazardous. In cases where the selected site or geological environment is not ideally suited for disposal, the repository can be heavily engineered so that, for meeting safety targets, reliance is placed primarily on the engineered barriers. Because engineered barriers can play an important role in the overall performance of near surface repositories, many Member States are now considering the use of engineered barriers in the development of new repositories. Engineered barriers are described in detail in many publications, some of which have been referred to in previous sections. Information on the long term performance of engineered barriers can be found, in particular, in Refs [20, 22, 23, 37, 41, 43, 52, 53, 82, 96, 98, 99].

3.3.1. Functions and materials

To predict the performance of engineered barriers over the required assessment period, it is important that information be available on the physical and chemical properties of the materials, including radionuclide retention and water transport, as well as on the physical and chemical processes controlling degradation of the barrier materials. In this regard, two co-ordinated research projects [37, 97] sponsored by the IAEA have focused on the performance of engineered barriers in near surface disposal facilities and on waste package performance under disposal conditions.

In contrast to natural barriers, the behaviour of the engineered system and its components is amenable to optimization and control. This is particularly true when one considers that cement based engineered barriers can be used to condition the near field chemical environment. Given the availability of relevant geochemical codes and associated thermodynamics databases, this type of chemically conditioned engineered barrier system can be modelled to establish the source term, which in turn is needed to assess the overall safety of the repository.

With regard to the physical barrier functions of engineered barriers, it is important to recognize that cement based materials allow a great deal of flexibility with respect to their mass transport properties. Flexibility in their formulation means that the design can be optimized and an engineered barrier selected to provide control of water ingress or facilitate escape of any gases that might be generated in the disposal units.

Besides being used to fabricate waste containers and as waste conditioning matrices, cement based materials are widely used as structural components in many repository designs, especially in vault type facilities. A vault consists of a reinforced concrete basement with a thickness of several tens of centimetres, reinforced concrete walls and a roof. The roof can be directly concreted over the waste packages when the structure is filled, or alternatively can consist of reinforced concrete slabs put in place and jointed with cement and/or bitumen. The vault can also be designed as a large concrete box where the bottom and the walls are sufficiently linked to result in a monolithic structure.

Backfill can provide stability to the disposal units and surrounding geological media and can reduce the potential for subsidence. To this end, besides backfilling the inside of the disposal units to fill voids between waste packages, backfill can also be emplaced outside the disposal units to fill in excavations. In both cases, it enhances the integrity of the disposal zone.

Backfill may also be used to limit the access of any infiltrating water to the waste packages. If disposal units are located below the water table, low permeability backfills offer the best protection against infiltrating groundwater. Clay based backfill material performs an additional function of retarding the transport of radionuclides leached from the waste. Depending on the nature and the physicochemical characteristics of the radionuclide content of the waste, low permeability cementitious backfill can also be used to retard radionuclide migration. If the disposal units are in the vadose zone, high permeability materials that facilitate drainage, such as gravel, sand or crushed rock, are most effective. Highly permeable backfill material also facilitates gas transport and escape from the disposal units.

The cover of the disposal units is the outer barrier for near surface disposal facilities. Its main function is to limit the quantity of rainwater infiltrating into the disposal units. The efficiency of the cover is expressed as the volume of water per unit surface area per unit time that could pass through the system (of the order of $L \cdot m^{-2} \cdot a^{-1}$). The permeability of each cover layer has to be determined. The cover also protects the disposal units against intruding animals, for example by including a graded cobble layer, and against the harmful effects of freeze–thaw cycles. It also protects to some extent against human intrusion. It generally consists of alternating layers of impervious and pervious materials, capped with earth and planted with shallow rooted vegetation and grass. This top layer is important for maintaining an acceptable level of evapotranspiration and erosion. The impervious materials used are generally clay based, HDPE liners and bituminous or geotextile membrane. The pervious materials used are usually high permeability gravel or sand.

Sealing of near surface repositories is usually applied in rock cavity and borehole disposal concepts and is performed partly in the near field and partly in the far field. If disposal units are located in the vadose zone, the purpose of sealing the repository is in principle the same as that of placing a cover on a near surface disposal facility. It reduces water infiltration into the disposal units and thereby limits the release of radionuclides. Potential sealing materials include clays, cement, chemical grouts and bitumen.

3.3.2. Degradation processes

Material properties in a near surface repository environment will change in the course of time. As discussed above, a number of factors can bring about changes in material properties. An obvious one is sharp changes in temperature such as freeze–thaw cycles encountered under particularly extreme climatic conditions, which can be an important cause of progressive or episodic material degradation. Freeze–thaw effects are usually taken into consideration in the design of the engineered barrier system, for example by using air entrapment additives. Other degradation processes include the action of microorganisms and gas formation inside the structure, in particular in the waste packages, resulting in pressure buildup and subsequently leading to the development of cracks and loss of integrity. Many of the degradation processes in concrete depend on its permeability. The permeability of concrete is also influenced by the formation and propagation of cracks. Depending on the composition of the dissolved species in the infiltrating water, cement based materials are subject to different degradation processes. These include the following:

Corrosion. Corrosion of the reinforcing steel bars is a complex physicochemical process dependent on the availability of oxygen and the presence of other chemical species, for example chlorides. The chloride ion acts as a catalyst for the oxygen in the reaction. Once corrosion starts, it may proceed to completion in less than a hundred years. To prevent the collapse of the concrete structural components, one conservative approach would be to design them to withstand the applied loads and movements even in the absence of the reinforcing steel bars. Another process relevant to concrete degradation is crack development and propagation caused by the accumulation of corrosion products. Carbonation can also adversely affect the integrity of concrete structures, as a result of the enhanced corrosion of the reinforcing steel bars.

Acid leaching. This is basically a bulk material degradation process which, in extreme cases, may induce progressive leaching of the cement phases, selectively removing calcium and leading to the total disaggregation of the material. The most conservative assumption would be to assume that sufficient acidic water contacts the surface of the concrete barrier to continually leach out calcium hydroxide, ultimately resulting in the loss of integrity of the barrier.

Sulphate degradation. Any sulphate ions carried by infiltrating water may react with calcium and aluminium compounds. The resultant products are new hydrated mineral phases, including gypsum and ettringite, whose molar volumes differ significantly from those of the original constituent materials. This can lead to the buildup of internal pressure and cleavage, causing spalling of one thin surface layer after another and exposing new layers to chemical attack. Since sulphate transport through concrete is diffusion controlled, the determination of sulphate diffusion rates can be important in evaluating this degradation process.

Alkali–aggregate reactions. This process involves reaction of soluble silica in the aggregate material with sodium and potassium ions in the pore solution, leading to in situ precipitation of hygroscopic gels that expand and fill in the pores. The positive effect of this process is the reduction of diffusion rates and hence the rates of other degradation processes. However, just as in the case with products of corrosion of reinforcing steel, the precipitation of gels creates internal stresses that result in the development of internal cracks, ultimately increasing permeability and hence the rate of concrete degradation.

Degradation of concrete structures can also affect the properties of buffer and backfill materials. One mechanism is backfill self-sealing through filling in of the pore spaces by degradation products such as iron hydroxides from steel and calcium hydroxide from cement. The self-sealing phenomenon, caused by deposition of material from precipitation reactions driven by differences in pH and/or Eh and solubility constraints, may decrease the permeability of the backfill, thereby reducing its drainage effectiveness and affecting its mass transport properties. Evaluation of the interactions between waste packages, concrete structures and backfill materials should also take into account the swelling and shrinkage properties of the materials.

After a few hundred years, usually at the end of the institutional control period, it can be assumed that the disposal units, including all engineered barriers, are totally degraded. This means that the concrete can be assumed to have completely lost its structural integrity. Under such conditions, safety assessments generally take into consideration the sorption properties of the degraded barriers with regard to radionuclide retardation.

3.4. GAS GENERATION

Gas, particularly hydrogen, carbon dioxide and methane, can be generated in the near field as a result of a number of processes, depending on the availability of reactive materials and the existence of favourable physicochemical conditions. The content and amounts of waste package materials, such as metals (Fe, Al, Zn, etc.) and organics (bitumen, cellulose, polymers, etc.), as well as temperature, radiation field, microbial activity and the presence of nutrients in the groundwater, are all important factors. Different gases, including gas phase radionuclides such as ^{3}H, ^{14}C, ^{85}Kr, ^{129}I and ^{222}Rn, may be produced owing to a variety of processes, for example: (a) production of hydrogen from anaerobic corrosion of metals, (b) production of methane and carbon dioxide from microbial degradation of organic materials, (c) failure of sealed sources of ^{85}Kr, (d) release of gaseous radionuclides contained in the waste, and (e) radioactive decay of ^{226}Ra to ^{222}Rn.

If disposal units are located below the water table, corrosion of iron based containers can initially occur in aerobic conditions, without generation of any gases. However, after a period of time (typically tens of years), following the depletion of all available oxygen, anaerobic conditions will develop in the disposal units and will generally prevail for the remainder of the post-closure period. Anaerobic corrosion of iron and some other metals can then result in the generation of large amounts of hydrogen gas. This may have an adverse effect on repository performance. Volatile radionuclides such as ^{3}H and ^{14}C could escape from the repository in association with hydrogen generated from metal corrosion. Pressure buildup inside the containers or in the repository as a result of gas generation could have an adverse impact on the integrity of the containers, the backfill and/or the host geological environment. Biodegradation of organic waste materials and waste forms is another potential mechanism for gas production. The by-products of biodegradation of organic materials are primarily carbon dioxide and methane gases. Microbially mediated production of gases can be significant. Associated with the microbial generation of gases is the potential for the direct release to the biosphere of ^{3}H and ^{14}C in the form of carbon dioxide, methane and other hydrocarbons.

If disposal units are located in the vadose zone, gas generation is much less of an issue as anaerobic conditions are not expected to develop and engineered barriers are generally not designed for tightness but rather to facilitate drainage. On the other hand, the potential impact of gas generation on the integrity and durability of waste packages would still need to be considered.

The potential consequences of gas generation can be the loss of waste package or repository integrity and the subsequent release of volatile radionuclides to the accessible environment. If the rate of gas generation exceeds the rate at which gas can dissipate out of the disposal units, gas overpressure may develop, leading to the physical breakdown of barriers and the potential release of contaminated fluids. Although much has been done in this area recently [100–105], further work is needed to understand fully the possible impacts of gas generation on the performance of disposal facilities, particularly when disposal units are located in the saturated zone.

3.5. TRANSPORT OF RADIONUCLIDES

Once the waste container has degraded, numerous chemical species contact the waste form, resulting in the mobilization of radionuclides. Water is expected to be the main transport medium, but, particularly in the vadose zone, some transport may take place also in gaseous form. For near surface disposal concepts where the backfill is designed to have a high permeability (see Section 3.3.1), advection may be an important transport process. For disposal below the water table, where low permeability engineered barriers contribute to radionuclide isolation, diffusion may be the principal transport process.

The transport of radionuclides through the near field is strongly dependent on the chemical speciation of the contaminants, as affected by local Eh/pH conditions, the availability of complexants, and possibly the generation and behaviour of colloids, as well as groundwater flow. Colloids may be generated by a number of processes that occur in the near field, for example by waste form and barrier degradation or by precipitation reactions at sharp geochemical discontinuities such as redox fronts. However, the actual production of colloids in a cementitious near field is not well established, and therefore their role in the source term remains unclear. When generated, colloids, like dissolved chemical species, have the potential to migrate, interact, sorb onto surfaces, precipitate or dissolve.

The main process likely to control radionuclide concentrations and their fluxes out of the near field is sorption from solution onto sorbents such as cementitious materials and additives (sand, clays, zeolite, etc.). In general, sorption is governed by the specific or effective surface area of the material available for sorption, and the chemical form and concentration of dissolved species or colloids. An extensive body of literature shows that many radionuclides are strongly sorbed by clays and zeolites. Sorption by cement has also been studied extensively and is summarized in Ref. [99]. Care must be taken to distinguish experimentally between sorption and precipitation.

4. FAR FIELD

This section discusses the main functions of the far field, i.e. the natural barrier system, and the processes that control its performance, including the transport of radionuclides. The focus is on the information that is required for assessing the performance of the natural barriers. The standard safety assessment methodology (see Section 2.5) includes pathway analysis in which the transport of radionuclides away from the disposal facility to the accessible environment and humans is assessed. As radionuclide release from the near field provides input to far field modelling, radionuclide fluxes through the geosphere–biosphere interface provide input to biosphere modelling. Groundwater is usually the most important vehicle for radionuclide migration in the geosphere. Work carried out in this area has greatly contributed to a good understanding of the role of the far field in the safety of both geological and near surface disposal of radioactive wastes [20–23, 36, 40, 41, 83–91, 106–117].

4.1. GEOLOGY

Locating a suitable site for a near surface disposal facility involves careful consideration of technical, social, infrastructural and planning factors [55]. The acquisition of geological and environmental data is the most extensive activity in the site selection process. Detailed guidance on this particular activity is given in Refs [54, 106, 107].

When considering the type of information that is needed, it is important to recognize that actual data needs depend on the existing databases and are design and site specific:

- The characteristics of a specific candidate site may affect the relative importance of different kinds of data. For example, for a site located in an arid zone, less groundwater information may be required.
- The design of the disposal facility may reduce the need for some data. For example, use of a particularly robust engineered barrier system may minimize the need for seismic information.
- Performance assessment may identify data that are relatively unimportant with respect to the outcome of the safety assessment. For example, if it is demonstrated that groundwater travel from the facility to the accessible environment takes thousands of years, geochemical phenomena affecting radionuclide retardation may be unimportant, at least for exposure scenarios that do not include the creation of short-circuit pathways, for example from the drilling of water wells.

Technically, locating a suitable site means finding a physically and chemically stable geological environment that will provide the required degree of containment for the desired period. Major functions of the natural barriers are to limit the ingress of fluids to the waste and to retard, dilute and disperse any radionuclides that are released from the repository.

Several types of geological environment may satisfy these requirements and may therefore be used for siting near surface repositories, as discussed in Section 3.1.1. Geological media that can be used for hosting near surface repositories are widely distributed in many regions of the world. They generally consist of unconsolidated sedimentary sequences (alternating interlayers of sand, gravel, clay, clayey till, etc.). For near surface disposal at depths of tens of metres, as in rock cavity repositories or intermediate depth boreholes, a wide variety of host rocks can be considered and their suitability evaluated on the basis of the safety assessment results.

To evaluate the impact of the geological features of a candidate site on the development of an acceptable safety case and on the likelihood of successful licensing, information on the following is typically required:

- Geological history.
- Stratigraphic, lithological, mineralogical and structural geological conditions of the region and the site, including the geometry and distribution of geological features.
- Recent evidence of active faulting, evidence of active tectonic processes, the occurrence of quaternary faults at the site and the age of recent movements, historical earthquakes, and an estimate of the maximum potential earthquake within the geological setting.
- Evidence of volcanism, history of volcanic activity near the site.
- Topography of the site, including actual drainage features, the location of existing and planned surface water bodies, and definition of areas containing poorly drained materials; data on the flood history of the region, upstream drainage areas, precipitation and the potential for extreme weather phenomena, such as hurricanes, tornadoes and severe winter storms.
- History of subsidence; records of past and present drilling and mining operations in the vicinity of the site, including groundwater extraction and use.
- Occurrences of energy and mineral resources, including groundwater, and estimates of their present and projected quality and value, and of their potential for use.

State of the art geological data acquisition, recording and interpretation methods can be employed. Techniques for measurement and interpretation of data have been refined during the last decade. Examples of recent technical developments in data interpretation are three dimensional visualization techniques for integrating interdisciplinary data, such as geological, hydrogeological and geochemical data, and probabilistic modelling tools to take account of poorly characterized natural variability.

Application of modern methods and extensive studies of various sites have contributed to a better understanding of the anticipated performance of the natural barriers.

4.2. HYDROGEOLOGY

This section discusses hydrogeological conditions, which are also partly described in Section 3.1.2. It reviews factors controlling groundwater flow in the far field. The relevance of groundwater flow in the far field for deeper disposal systems, such as rock cavities, is similar to that for geological repositories described in Refs [36, 86].

In general, groundwater flow is controlled by such features as geological structure, sediment texture, pore space, fractures and climate. Groundwater flow in any near surface geological environment is part of the hydrological cycle and is determined by the hydraulic conductivity, flow porosity and hydraulic gradients between higher head recharge areas and lower head discharge areas. As water infiltrates into the ground, the pore spaces can be filled either partially (vadose zone) or totally (saturated zone). The basic law of groundwater flow in the saturated zone, known as Darcy's law, establishes the relationship between the hydraulic parameters discussed above. Flow in the vadose zone is also a function of moisture content.

4.2.1. Saturated zone

In nature, there are no known regions where the ground is totally devoid of liquid water. Even the unsaturated zone is always partially saturated and portions of it may be fully saturated (that is why the term vadose zone is preferable). Most near surface hydrogeological systems are characterized by active hydrodynamic regimes where groundwater is always in motion. However, the velocity of groundwater flow varies greatly as a function of hydraulic gradient and conductivity, which is the most variable hydraulic property of the rocks, spanning a range of ten or more orders of magnitude. For example, for gravel, the hydraulic conductivity may exceed 10^{-2} m/s while for clays it can be less than 10^{-12} m/s. Usually, in low hydraulic conductivity materials, the flow porosity is also quite low. Hydraulic gradients can vary greatly, spanning a range of several orders of magnitude, depending on topographic, groundwater recharge and drainage conditions. Hydraulic gradients can also vary as a function of time in response to the fluctuation of hydraulic heads (water table variations). Accordingly, in areas where the water table is close to the surface, gravel and sands can yield groundwater residence times of months or years, while pore water in clays can have a residence time of many thousands of years. This means that pore water in clays is practically stagnant.

Ideal hydrogeological conditions for a disposal site would be 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 and low hydraulic conductivity of the host geological medium and/or surrounding formations. In arid areas, it is comparatively easy to find such conditions, for example in closed hydrogeological systems in which the hydrological balance is at a steady state, i.e. evapotranspiration balances the water supply, so that there is no lateral flow of water and no outlet except towards the atmosphere. Such situations, although generally advantageous for near surface disposal, may not be simple to assess in the long term, as it may be difficult to predict climate change, and consequently the stability of the system, for the period of concern.

Definition of groundwater flow in a hydrogeological system requires information on:

- Distribution of hydraulic parameters, including hydraulic conductivity, porosity and storativity;
- Spatial and temporal variation of the hydraulic head;
- Geometry of the flow domain;
- Recharge and discharge areas;
- Recharge and discharge rates, including infiltration, evapotranspiration, water balance and extraction volumes;
- Groundwater system boundaries, including rivers;
- Relationship between the different hydrogeological units;
- Flow velocity and residence time of groundwater in the system.

As noted in Section 3.1, construction of the disposal facility will change some of the conditions influencing groundwater flow at the site. Additional information may be required and special consideration may need to be given to such changes.

4.2.2. Vadose zone

In contrast to the saturated zone, large air filled voids in the vadose zone impede water movement. Moisture content can vary with time in response to changes in recharge or climatic conditions. During periods of higher recharge, pores may fully saturate for short periods of time in some parts of the system. Because of the action of capillary forces that bind water to solids, fluid potentials are less than atmospheric. The lower the moisture content, the higher the suction and the lower the fluid potential and hydraulic conductivity. For the purpose of identifying water pathways in the vadose zone, it is important to note that, as long as the geological media remain unsaturated, water migration tends to occur in the pellicular water coating the soil particles. As a result, fine grained materials tend to transmit more water than coarse ones. This is the basis for the capillary barriers mentioned in Section 3.1.2.

During periods of abnormal water infiltration, when parts of the vadose zone may become saturated, water flow may be completely dominated by coarse grained, high permeability materials, resulting in the loss of the capillary barrier function. Where there are layers of different permeability materials, high infiltration events may cause the formation of temporary perched aquifers where the main water flow is in the horizontal direction. Such abnormal water flow conditions need to be taken into account for repository design and performance assessment.

In addition to the information needs mentioned above for the saturated zone, the following factors are relevant, particularly for the vadose zone:

- Variations in moisture content;
- Variations in fluid pressure (tension, suction);
- Hydraulic conductivity dependence on moisture content and fluid pressure.

The acquisition and interpretation of hydrogeological information have been facilitated by recent technical advances. These include: detection of small groundwater flows in boreholes, extraction of undisturbed groundwater samples from low permeability media, use of environmental isotope sampling methods to identify pathways for past and potential future rapid recharge of water into unsaturated media, determination of the depth of more saline water by electromagnetic methods, and the use of hydrogeochemical data and geochemical signatures to infer patterns of groundwater flow [40].

4.3. GEOCHEMISTRY

Besides playing a significant role in protecting the engineered barriers (see Section 3), geochemistry may affect the performance of the natural barrier system. Samples of groundwater obtained from water bearing layers and pore water from low permeability geological media can provide, through measurements of chemical and isotope composition, evidence of the age, flow patterns and groundwater residence times in particular formations. Standard analytical techniques for the main constituents of groundwater, including dissolved gases and a variety of isotopes, can be employed, provided that adequate samples of groundwater and pore water are obtained. These data on groundwater geochemistry need to be complemented by sampling and analyses of waters from springs and shallow wells.

The groundwater chemistry of trace substances can be applied to assess the geochemical behaviour of natural series radioisotopes and other chemically analogous radionuclides. The concentration and mobility of many trace elements are governed by the pH and redox conditions of the groundwater. Analytical techniques are now available to measure the concentrations of trace substances at levels commensurate with those expected in waters that have contacted waste materials. Current effort is focused on obtaining such data as site specific indicators of the mobility of key radionuclides, with the aim of eventually using the environmental concentrations and fluxes of those radionuclides in the vicinity of waste repositories as safety indicators, complementary to dose and risk.

Important organic substances in natural waters are typically humic acids, fulvic acids and low chain organic acids, for example citric acid. There are a large number of low chain organic compounds present in soil solutions, but the abundance of species is generally small and their complexation properties with radionuclides of interest are not yet fully understood. It can be important to understand the chemical composition, size distribution and stability of naturally occurring colloids in a given system. Finally, hydrogeochemical characterization includes investigation of the bacterial populations that are ubiquitous in natural waters of the Earth's crust down to depths of several kilometres. Although it is well known that bacteria can affect a number of important chemical processes, such as water–rock interactions and redox processes, the capability to account for microbiologically mediated processes in geochemical modelling is still rather limited.

Many chemical reactions occurring in natural water–rock systems take place at surfaces where water is in contact with both solid and gaseous phases. These reactions at interfaces fall into three categories: gas–liquid, liquid–solid and adsorption–desorption. In gas–liquid reactions, oxygen, carbon dioxide and nitrogen have the most influence and under some conditions represent the major control on water quality. Many of these reactions are microbiologically controlled. Liquid–solid interactions affect the water chemistry in many ways, for example through weathering reactions such as congruent dissolution of quartz and redox reactions with iron minerals. Absorption–desorption reactions include physical adsorption and absorption of ionic species. In natural water–rock systems, negative charges on the adsorbing surfaces exceed positive ones, and consequently cationic species are attracted more readily than anionic species.

The characterization of the mineralogical and geochemical properties of rocks, in particular the properties of secondary authigenic minerals in pore and fracture filling, and the properties of rock surfaces exposed to migrating radionuclides and water–rock interaction processes, is presently a fairly routine activity. Information that might be required, for example on the abundance and distribution of sorbing mineral phases (clay minerals, iron oxides, etc.), as well as the selection of appropriate geochemical codes, will depend on the site specific safety and performance assessments. For example, with respect to clay formations, one of the key areas of interest is developing an improved understanding of the complex interactions between geotechnical, hydraulic and geochemical properties, as all of them affect mass transfer rates.

In summary, the hydrogeochemical characterization of a site represents most of the required geochemical information and may include the determination of the following parameters:

- Variables: pH, Eh.
- Main components: Na, K, Ca, Mg, HCO_3, SO_4, Cl, Si and total dissolved solids (TDS), or the sum of the main components.
- Trace substances: Fe, Mn, U, Th, Ra, Al, Li, Cs, Sr, Ba, HS, I, Br, F, NO_3, NO_2, NH_4, HPO_4, rare earth elements, Cu, Zr.
- Dissolved gases: O_2, N_2, CO_2, CH_4, CxHx, H_2, Ar, He.
- Stable isotopes: ^{2}H in H_2O, ^{18}O in H_2O and SO_4, ^{13}C in dissolved inorganic carbon (DIC) and dissolved organic carbon (DOC), ^{34}S in SO_4 and HS, $^{86}Sr/^{87}Sr$, ^{3}He, ^{4}He, Xe isotopes, Kr isotopes.
- Radioactive isotopes: ^{3}H, ^{14}C in DIC and DOC, ^{36}Cl, $^{234}U/^{238}U$, ^{226}Ra, ^{222}Rn.
- Others: DOC, humic acids, fulvic acids, colloids, bacteria.
- Pore and fracture filling minerals: ^{18}O, ^{13}C, $^{86}Sr/^{87}Sr$, $^{235}U/^{238}U$, mineralogy, texture and sorption properties of deposited authigenic minerals.

The collection of complex geological, hydrogeological and geochemical data can involve a variety of analytical techniques and approaches. Consideration needs to be given to whether such data can be used effectively in performance assessment modelling.

4.4. MIGRATION OF RADIONUCLIDES

Radionuclides are likely to migrate from the near field engineered system to the far field and subsequently to the accessible environment via two major pathways. The most significant pathway involves migration in groundwater in the far field by means of diffusion, advection and dispersion. The second potential pathway, gas phase transport, is a more rapid route for gaseous radionuclides that can be transported directly to the accessible environment, as discussed in Section 3.4. The present section describes the main factors and processes governing radionuclide migration in the far field.

The extent to which a given radionuclide can migrate in the geosphere depends, first of all, on its solubility and speciation (i.e. the physical and chemical state of the soluble species) as affected by groundwater chemistry. The solubility and speciation of radionuclides are usually predicted by using equilibrium thermodynamic geochemical codes. In addition, almost all relevant radionuclides (see Section 2.3), with the exception of transuranium actinides, can best be studied in nature using the corresponding stable isotopes.

The reactions accompanying the dissolution of metal compounds in natural waters involve primarily hydrolysis reactions that produce monomeric, polynuclear and colloidal species. In natural aquatic media of near neutral solutions (pH = 5–9), many metal ions of higher oxidation state are very unstable to hydrolysis reactions and as a consequence display a lower solubility range. Groundwater usually contains dissolved heavy metal elements in amounts near the solubility concentrations of transuranium elements and some fission products. This can give rise to multicomponent competition for chemical reactions. Complexing anions, for example carbonate, sulphate, humate and fulvate ions, stabilize some radionuclides as monomeric ions. Because of the omnipresence in nature of CO_3^{2-} and its strong complexation properties, the carbonate complexation of uranium and transuranium ions is considered to be an important chemical reaction in groundwaters.

Apart from the normal chemical reactions associated with the dissolution of radionuclides, colloid generation is considered to be an important process in natural systems. Through hydrolysis reactions, the metal ions of higher oxidation state may produce their own colloids (called real colloids), or they can interact with and be sorbed on natural water colloids and thereby produce pseudocolloids. Natural water colloids differ in size and chemical composition from one system to another, and they can change appreciably according to the ambient geochemical conditions. Particularly important colloids in natural waters are those composed of authigenic clay particles. They sorb efficiently not only metal ions but also their complexes. Carbonato, sulphato and hydroxo complexes tend to be adsorbed more strongly on clay surfaces than do metal ions. Whenever colloid generation is the dominant process, solubility controls are difficult to assess. To ascertain the solubility defined in thermodynamic terms, the separation of colloid species from solution is necessary. However, colloids of ultra-small size (less than 1 nm) are always present in the solution, so it is still difficult to determine universally applicable solubility data for natural waters.

The dissolved radionuclides migrate from the near field at a rate determined by processes that include advection and dispersion, diffusion and retardation. While the first three processes are related to the hydrogeological processes discussed earlier, retardation of radionuclides is due to the chemical and physical interactions with minerals both in the host geological environment and in surrounding formations. Retardation represents one of the major barriers to radionuclide migration. The basic retention mechanisms include sorption on and diffusion into solid surfaces (matrix diffusion) and chemical reactions (redox processes) that may produce precipitates or colloids (see Section 4.3). Although the need to identify, understand and model the retardation processes has led to extensive studies internationally, the nature of these processes in complex geological media remains poorly understood.

For estimating the migration of radionuclides in the far field, it is common practice to use the retardation factor, defined as the ratios of groundwater flow rate to radionuclide migration rates. The distribution coefficient of a radionuclide between water and the sorbent involved (K_d, m^3/kg) is an important physicochemical parameter used in the calculation of its retardation factor. Besides some fundamental thermodynamic equilibrium issues involved, a major problem in using the K_d concept is the presence of colloids, which can play an important role in radionuclide migration in the far field.

In general, the information needed for assessing radionuclide migration in the far field, as discussed in the preceding sections, can be summarized as follows:

- Groundwater flow, including advection and dispersion processes: groundwater flow rate and patterns, codes to model groundwater flow, groundwater flux and velocity, flow patterns and pathways, migration behaviour of radionuclides, geochemical codes.
- Fracture flow (preferential and faster pathways for radionuclide transport): nature, characteristics and distributions of fractures, water flow rates.
- Diffusion: characteristics of the host geological medium, radionuclide–host rock interactions, effective diffusion coefficients.
- Solubility: groundwater chemistry, Eh and pH, geochemical codes to calculate concentrations controlled by solubility limits.
- Complexation (both organic and inorganic): nature and type of complexes, groundwater chemistry, geochemical codes to model complex formation.
- Colloid formation: colloid characteristics, colloid–radionuclide interactions, groundwater flow rate and pattern (advective transport of radionuclides as colloids, enhanced migration).
- Chemical reactions in groundwater: Eh and pH of groundwater, chemical species in groundwater, chemical stability of precipitates that may result from interaction of these chemical species with radionuclides, rates of reactions.
- Sorption: sorption coefficients in site specific groundwater, mineralogy of sorbing phases, groundwater chemistry, geochemical codes to model sorption.
- Gas phase transport in the vadose zone: groundwater chemistry, degree of saturation in the vadose zone, partitioning of contaminant between gas and aqueous phase, geochemical codes to model partitioning and transport, groundwater flux.

Considerable effort has been devoted to studying the speciation and behaviour of radionuclides in natural water–rock systems, including inorganic and organic complexation, colloid generation, sorption, diffusion, etc. The data from sorption studies use batch and column experiments in the laboratory and also field studies. Current research is focused on methods to quantify the sorption process, for example surface complexation, instead of using the K_d concept in transport modelling.

4.5. POTENTIAL IMPACTS OF CLIMATE CHANGE ON THE FAR FIELD

Knowledge about the past climate has improved considerably during the last few decades, although not to the extent that future climate changes can be confidently predicted. Major short term variations, which are relevant to the subject of this report, are superimposed on the well known long term glacial–interglacial changes in climate. Shorter cycles can also be identified. In addition to the well established variations in temperature and precipitation linked to the 11 year solar activity cycle, historical records for the last millennium indicate a periodicity trend in climate variations with time intervals of between 100 and 300 years [116].

Factors affecting the climate on short timescales include: variations in solar radiation; atmospheric concentration of water vapour, methane and carbon dioxide; volcanic dust; and changes in atmospheric and oceanic circulation. A significant uncertainty is related to the effect of human activities, especially the postulated trend towards global warming due to the introduction of carbon dioxide and other greenhouse gases into the atmosphere.

Much has been learned about the effects of past climate changes on natural systems. The results of palaeoclimatological, palaeogeographical and palaeohydrogeological studies have provided information on the way in which climate change has affected surface temperatures, precipitation, vegetation, the hydrological balance of surface water bodies, sea level, groundwater flows and groundwater chemistry [88, 117].

Climate change can clearly affect the groundwater flow regime. Changes in boundary conditions due to climatic variations may cause changes in infiltration, recharge to the aquifer and discharge to surface locations. These changes may result in the draining or saturating of disposal units and in changes of groundwater flow rates in both the near field and the far field.

Climate is also one of the major controls on the geochemistry of natural water systems, as it affects the chemical and physical processes controlling rock weathering, which in turn controls the pH, oxygen content and redox potential of the water environment. A well known example is the greater capability of CO_2 to dissolve in cold water, which makes it more acidic, than in warm water.

It can be concluded that possible climate change induced variations in the groundwater flow regime, groundwater chemistry and discharge points that could affect exposure pathways and fluxes of radionuclides should be taken into account in assessment calculations, at least in setting the ranges for variability and sensitivity analyses.

5. BIOSPHERE

The biosphere includes the atmosphere, soils, and surface water bodies, seas and oceans and their sediments, in which living organisms normally reside. The interface between the biosphere and the geosphere is often considered to be at the bottom of the near surface materials (soils, sediments and rocks) that are affected by human activities such as farming. For near surface repositories, the distinction between the biosphere and the geosphere can be somewhat arbitrary, but it is often convenient to retain this distinction in safety assessments.

The biosphere can be viewed as the last barrier in the multiple barrier concept and the receptor of radionuclides released from the repository. The biosphere comprises the accessible environment where the radiological impacts of concern are actually incurred. Contaminants can move between, and be diluted and dispersed or concentrated in, a large number of different environmental media.

This section describes the reference biosphere approach that is currently being developed for the identification and justification of biosphere systems in safety assessments. This is followed by a discussion of the important processes of radionuclide migration, dispersion and accumulation in the biosphere.

Examples of the different types of biosphere that are considered in safety assessments include: (a) a temperate biosphere, such as a flat forest ecosystem with lakes, streams and marshy areas, with a population living on small farms, assumed to provide a range of exposure pathways; and (b) an arid biosphere, such as a relatively densely populated and urbanized region with a drinking water well intruding into an aquifer. Descriptions of example biosphere types can be found in Refs [22, 23, 39, 41, 94, 118–124].

Radiological impacts may need to be assessed for different types of exposure scenario. A typical scenario assumes that water enters the disposal units and that radionuclides are mobilized and transported by the water to a point of possible utilization by humans or other organisms. Such a scenario is the main focus of this report. However, other release scenarios, for example releases due to transport in gas or erosion of the ground surface, may also be important. An additional scenario that is particularly relevant for facilities where the waste is emplaced at a limited depth and that is generally considered in the assessment of safety after the end of institutional controls is inadvertent human intrusion. Various intrusion scenarios have been defined for this type of assessment, including construction activities at the repository site or a farming community becoming established above the disposal units. Assessing the radiological consequences of all these scenarios requires assumptions about the conditions of the biosphere and an adequate modelling capability [73–75, 125].

Results from the modelling of the biosphere can also provide important inputs to the preparation of the Environmental Impact Analysis (EIA) and the Environmental Impact Statement (EIS). In the compilation of the EIA and the EIS, non-radiological issues need to be addressed as well, but these are outside the scope of this report.

5.1. REFERENCE BIOSPHERE CONCEPT

Once in the biosphere, radionuclides can enter food chains (terrestrial or aquatic) and the water supply, can irradiate humans externally, and can also be inhaled and ingested. Radionuclides released from near surface facilities may not enter the biosphere for a lengthy period, by which time the biosphere itself and the habits of humans living in it may have changed considerably. This represents a significant source of uncertainty in assessing radiological impacts and has been the primary motivation for developing stylized, reference biosphere concepts. The International Commission on Radiological Protection and the OECD Nuclear Energy Agency, as well as the IAEA through its Programme on Biosphere Modelling and Assessment Methods (BIOMASS) and the WASSC Sub-Group on Principles and Criteria for Radioactive Waste Disposal, are actively involved in this area [9, 11, 94, 118–124].

A stylized approach for describing biosphere systems for future situations, where human behaviour relevant to long term radiological safety assessment cannot be known with any certainty, is consistent with the approach adopted in other areas of radiological protection, for example where it is impracticable to establish the precise characteristics of exposed individuals. In fact, a stylized 'reference man' is used in calculating annual limits of intakes, and generic models of radionuclide behaviour are used to calculate dose coefficients. The concept of reference biospheres is intended to serve as a basis for the development of quantitative radiological assessments consistent with general safety principles and including, as one element, the definition of critical and other exposed groups.

In the reference biosphere methodology, the biosphere system is defined as a set of specific characteristics which describe the biotic and abiotic components of the accessible environment and their relationships that are relevant to safety assessment for radioactive waste disposal. The biosphere system, along with the associated chemical, physical and biological processes, forms the link between the geosphere system (and associated processes which affect radionuclide migration) and the ultimate radiological impact to be assessed. The boundary between the geosphere and the biosphere will be context specific and needs to be consistently defined within the assessment. Components of the biosphere system include human activities, climate, topography, site features (including location and geographical extent), flora and fauna, soils and near surface lithology, and water bodies [120]. Example reference biospheres that can be used as a basis for radiological impact assessments are currently being developed in international programmes.

Location, an important component of the biosphere system description, can be specified in relative terms. Thus, rather than specifying an exact geographical position, location may be expressed in terms of belonging to a certain climatic region, distance from the coast, altitude above mean sea level or some other factors that may be important in defining the biosphere system as it might exist now or in the future.

An example reference biosphere for a temperate location could be a biosphere system based on present day temperate conditions. Data for this type of environment represent the largest and most reliable database for radionuclide transport. The habits to be assumed for a hypothetical critical group of humans can be taken to be representative of subsistence communities living in these conditions. The reference biosphere and subsistence community hypothetical critical group can be applied in the period from around 100 to 10 000 years after repository closure, but for the period up to 100 years after closure the present day biosphere and critical group at the site (as used when considering operational releases) are considered applicable [94].

5.2. MIGRATION AND ACCUMULATION OF RADIONUCLIDES

Radionuclides transported in groundwater can be considered to discharge into a biosphere receptor at a geosphere–biosphere interface (a discharge zone or discharge point). Many different types of biosphere receptor and geosphere–biosphere interface can be envisaged. Examples of such interfaces include discharge directly to a surface water body (a lake or river) or through layers of sediment, discharge to soils, and discharge to an aquifer that is used as a source of drinking water.

To assess the migration and accumulation of radionuclides in a particular biosphere compartment, information is required on the characteristics of the interface between the biosphere and the geosphere, which is site specific and may be time dependent. For example, in the case of a discharge to a surface water body, estimation of radionuclide concentrations and transport through bottom sediments could be important because of their direct bearing on the rate of release into the overlying water column and also because sediments may later be converted into a substrate on which crops and other plants can grow.

Radionuclide residence times in soil will depend on the rate at which radionuclides can be transferred from soil back to groundwater or to other parts of the biosphere. Processes such as the infiltration of water into soil and radionuclide sorption on soil particles will be relevant. In general, high sorption in the geosphere tends to reduce impacts, but the opposite can be true in the biosphere.

More generally, radionuclide migration and accumulation in the biosphere can involve a wide range of processes. Radionuclides can be considered to migrate from the point of origin in the biosphere to humans or other living organisms of concern through various biosphere components (air, water, soil, plants, animals, humans) by means of transfer processes such as deposition from water or air to soil or sediments, uptake by plants or animals, and ingestion by animals or humans. Along the pathways, radionuclide transfer rates can be affected by advection and dispersion in water bodies, leaching from and sorption in soils and sediments, wind and water erosion and other geomorphological processes, biological activity in soils and sediments, and human actions. Uptake of radionuclides by biota is particularly important when it comes to calculating radiological impacts.

How these processes need to be treated in a safety assessment depends on the objective of the assessment and the calculation end points of interest, such as effective dose to the average member of the critical group and concentrations of radionuclides in the environmental media. However, particularly for near surface disposal facilities, the assessment of the biosphere cannot be undertaken in isolation from the other subsystems of the disposal system.

6. CONFIDENCE IN REPOSITORY PERFORMANCE AND SAFETY

The importance of the safety case in the development of a near surface repository has been emphasized in Section 2.5. To proceed with the disposal of radioactive waste in a near surface facility requires the confidence of many interested parties. Scientists, regulators, decision makers, concerned groups and the general public all need to have confidence in the safety of the disposal facility. Performance and safety assessments can play an important role in securing that confidence. This section deals with issues of confidence in the capability of near surface repositories to ensure the required level of isolation of the radionuclides from the accessible environment. The following discussion on building confidence in repository performance and safety assessments is based to a large extent on IAEA and other publications [4, 23, 36, 40, 44, 46, 48, 60, 75, 88, 126–135].

Performance and safety assessments generally imply estimating the evolution and performance of near field and far field barriers. The estimates, to be reliable and convincing, require an adequate scientific and technical basis, and satisfactory modelling capability.

It is also recognized that an important contribution to building confidence in a repository safety case comes from quality assurance programmes. A well designed and managed quality assurance programme is vital for developing a disposal facility, so it has been or is being introduced into many areas of radioactive waste management [46, 126, 127]. The content of a quality assurance programme that covers all activities related to the disposal of radioactive waste, from planning through siting, design, construction, operation and closure, including the various steps in the safety assessment process and institutional control activities associated with the repository, is described in Ref. [126].

6.1. CONFIDENCE IN WASTE ISOLATION

For the post-closure phase of disposal facilities, it is necessary to consider the protection of members of the public and the environment for as long as the radioactivity in the repository constitutes a significant hazard. Typically, for near surface repositories containing mainly short lived waste, the time to be considered is up to 300 or even 500 years. In some cases, even longer time periods may need to be considered. Requirements for safety and guidance on safety assessment for the post-closure phase of near surface repositories are given in Refs [4, 75]. Numerical safety criteria are usually expressed in terms of radiation dose or risk constraints and are intended to be applicable to assessments of both likely and unlikely events affecting a repository. Radiation exposure from such repositories is by no means certain to occur, since it is intended that the wastes will be adequately isolated from the biosphere, by a series of engineered and natural barriers, for a period allowing most of the radioactivity to decay.

As discussed in Section 2.6, monitoring of the site during operation and the post-closure period, when institutional control of the site is maintained, provides confidence that the radioactivity is adequately isolated.

This section discusses some of the key issues that provide confidence in the isolation of radioactive waste in near surface repositories, including the suitability of the site and the robustness of both the design and the safety assessment.

6.1.1. Suitability of the site

Generally, on scientific and technical grounds, the suitability of a site is approved if the safety assessment provides reasonable assurance that, on the basis of the characteristics of the site, the engineered barriers and the waste, the disposal system will provide adequate isolation of the radionuclides.

Particular features and processes that contribute to the suitability of a site, as well as associated data acquisition requirements, have been discussed in Sections 3.1, 4 and 5. In summary, the methodologies for site selection and evaluation are well developed and provide confidence in the scientific and technical basis for these activities. The range of suitable geological environments is very broad, and the selection of a particular type of site depends on factors such as waste disposal policy, the local climate and the types of geological environment in the country concerned.

In addition to site specific assessments, considerable benefits can be gained from generic, process oriented assessments that identify general system characteristics that help to ensure safety. Such assessments help to identify some of the features and processes that are important to the safety of the overall system. For example, in cases where the repository is sited in the saturated zone, low groundwater flow and reducing geochemical conditions are generally beneficial in all media and for all concepts. Depending on the specific circumstances, highly permeable features surrounding the disposal facility can also be beneficial since they reduce the hydraulic gradient across the disposal zone. Choosing a site that incorporates generically favourable characteristics contributes to the confidence that can be placed in its suitability.

6.1.2. Robustness of the design

In general, the design of a facility is more robust if it is based on multiple barriers, engineered as well as natural, where it is possible to achieve reasonable assurance that the system performance will remain satisfactory even if one of the barriers fails to function as expected. The design of the engineered barrier system (see Sections 2.2, 3.2 and 3.3) provides confidence in the reliability of waste isolation through the uniformity and testability of individual and assembled components. Together these factors allow the performance of a robust engineered barrier system to be predicted with high reliability for the near field, i.e. they provide assurance that the actual performance of the system will be at least as good as predicted.

Some uncertainties, for example those associated with the long term degradation of the engineered barriers, are unavoidable. To accommodate such uncertainties, repository design may incorporate some degree of conservatism. This may imply making use of designs and materials that are known to be resistant to a wider range of conditions than are actually expected. The thickness of materials used could be made greater than considered necessary to meet basic performance specifications. Robust designs are generally more costly, however, and thus a balance will need to be struck between the increased cost and the advantages in demonstrating safety.

6.1.3. Robustness of the assessment

Confidence in the isolation of the waste may be enhanced by incorporating some degree of robustness into performance and safety assessments. An assessment that demonstrates conformity with regulatory requirements and that is manifestly conservative would be regarded as robust. For example, reasonable conservatism built into models that can withstand scientific scrutiny would increase confidence in the safety assessment modelling. A simple modelling approach is likely to be efficient and transparent, and consequently more easily understandable and justified. Accordingly, assumptions should be formulated on the basis of available data and knowledge of the system or similar systems, taking uncertainties into account. An approach that balances simplicity, conservatism and realism is likely to be the best starting point for assessments [75]. Additional, more complex modelling for particular parts of the disposal system may provide useful supporting information.

6.2. BUILDING CONFIDENCE IN THE SAFETY CASE

The fundamental aim in the disposal of radioactive waste is to contain the radionuclides until they decay to an acceptable level or to limit their release so that the potential long term radiological impact on humans and the environment is within acceptable limits. It is possible that radionuclides could be released into the biosphere as a result of abnormal events, such as inadvertent human intrusion into the waste, or owing to natural events that may disturb the repository. During the period of institutional controls, intrusion events are considered to be very unlikely and it is usually possible to remediate the impacts of natural disruptive events; nevertheless, both need to be considered in the safety assessment.

Safety assessments provide a basis for rational and technically sound decisions in developing a radioactive waste repository. As discussed in Section 2.5, assessments may be undertaken at different levels of detail and complexity at different stages in the programme. Safety assessments are vital for the definition of waste acceptance criteria on a repository specific basis. This section discusses the main scientific and technical considerations that contribute to building confidence in the safety case.

6.2.1. Structuring the safety assessment

To ensure that all relevant features, events and processes (FEPs) have been properly considered and that the basis for the judgements that are made is clear and documented, the internationally recommended approach is to carry out a well structured, integrated performance assessment. This involves considering all relevant FEPs and analysing their combined impact on various components of the disposal system in an integrated manner. For the sake of transparency and flexibility, a modular system approach is used in the construction and application of models.

The modular approach is compatible with the multiple barrier concept that is fundamental to the repository design. Separate modules simulating the performance of different parts of the system will often correspond to or encompass identifiable engineered or natural components. For example, it is helpful to use a set of submodels to model the potential release and transport of radionuclides via selected environmental pathways to humans. This will ensure that individual submodels can be made available for inspection to assist in understanding how estimated impacts were determined.

The modular approach allows flexibility, and effort can be concentrated on those parts of the system that are most important for overall safety and that may require the most sophisticated modelling. The overall modelling of the system will include modules for radionuclide transport through the different parts of the system, together with one or more modules for radiological exposure calculations.

For each part of the system that is modelled, conceptual models of the relevant FEPs need to be developed into numerical models. Examples of commonly used models for the near field, far field and biosphere are included in some of the references cited in Sections 3–5. For example, methods that are currently being used for biosphere modelling are described in Refs [123–125].

6.2.2. Uncertainty management

Sensitivity and uncertainty analyses are powerful tools for managing uncertainty. They can help improve understanding of the most important sources of uncertainty and direct attention to obtaining better information for key parameters. Sensitivity analysis is used to identify those parameters, system components or processes that produce significant effects on the predicted disposal system performance. Uncertainty analysis quantifies the uncertainties in the calculated impacts of interest that arise from the uncertainty in the models and parameters that are used. Sensitivity and uncertainty analyses are valuable not only for determining the significance of various uncertainties in any particular line of reasoning, but also for judging which are the most robust arguments in the overall process of gaining confidence in safety.

Sensitivity and uncertainty analyses determine how and to what degree the predicted behaviour of the near surface disposal facility depends on:

- The conceptual models used,
- The scenarios considered,
- The parameters used in the models.

Conceptual model uncertainty arises when there are alternative ways to represent a process. Typical examples of areas where alternative conceptual models can exist are the description of groundwater flow and the description of radionuclide sorption. An example of scenario uncertainty is the possibility that boundary conditions, as well as the driving forces, rates and mechanisms of some processes, or their relative importance, may change with time.

If the results are sensitive to initial and boundary conditions, then more extensive data may have to be generated. The process should look at the sensitivity of the model to different scenarios and exposure pathways. If it is determined that the assessment is sensitive to these parameters, further evaluation should be considered, assuming a greater degree of conservatism.

Another important approach to managing uncertainty and building confidence is peer review. Although peer review can be regarded as a part of quality assurance, it has its own scientific and technical value. Peer review is brought to bear on the areas of the work where an independent technical appraisal is judged to reduce uncertainty and confer significant added confidence. Efforts to find the best way of representing processes at different spatial scales may give rise to different modelling approaches. Identifying alternatives is a matter of expert judgement and it is thus important for a safety case to include a wide range of expert input and peer reviews.

6.2.3. Testing models

During the development of conceptual models, in the transition from conceptual models to numerical models, and finally in their application, errors and uncertainties may be introduced that are due to the modelling assumptions, simplifications, approximations and/or mathematical approaches used. Therefore models used in a performance assessment need to be tested, and if necessary updated, to remove any errors and to increase their accuracy. For example, in the early stages of a site specific performance assessment, there may be many alternative conceptual models identified for different parts of the system, and it is normal practice to reduce these options through an iterative process of model testing.

As far as possible, modelling output should correspond to quantities that can be measured. Therefore, wherever possible, model testing should not be restricted to verification, but should include calibration and validation processes. A judgement will eventually have to be made about when it is sensible to stop the process of data collection and model testing.

Verification is used to address the question of whether the method of calculation solves accurately the mathematical equations that constitute the model. This can be achieved by solving test problems. Calibration and validation based on different data sets are used to address the question of whether the model can reproduce field and/or experimental results with sufficient accuracy. Calibration aims at reducing uncertainty by comparing model calculations with field observations or experimental measurements, whereby a set of site specific input data is used to compare predictions and observations at the site. In contrast to calibration, which is a site specific model adjustment process, validation is concerned with producing credible results at a variety of different sites or under a wide range of conditions. Although full validation of models for the long term evolution of a specific site is not possible over the relevant timescales, limited validation may be achieved through the use of data from natural analogues or by addressing specific aspects of the assessment. Model testing can in most cases help to define the limits of validity (conceptual or numerical) of the models used.

Models used in performance assessment can be tested and updated not only on the basis of comparisons of their outputs with empirical data, but also through peer review, inter-code comparisons, comparisons with other performance assessments, using results of experiments carried out to test specific aspects of conceptual and numerical models, and comparisons with cases for which analytical solutions exist.

6.2.4. Natural and archaeological analogues

Natural systems where processes occur that are assumed to be similar to those in a repository environment are generally termed natural analogues. Numerous publications are available and the scope of the studies is so broad that natural analogues can be used alongside other methods, such as field and laboratory experiments, which are designed to provide data and to increase confidence in the validity of a safety case. Closely linked to the studies of natural analogues are studies of ancient human made materials, provided the processes and conditions to which they have been subjected are natural. Studies of archaeological and historical artefacts, ancient buildings and anthropogenic sources of radionuclides such as nuclear weapons fallout can all be included in the field of analogue studies. Detailed information on analogue studies can be found in Refs [130–133] and the publications referred to therein.

Analogies between natural or archaeological systems and a radioactive waste repository are inevitably imperfect and consequently it is difficult to apply the results of analogue studies directly in a quantitative way, for example to perform quantitative validation of models or to provide values for parameters used in these models. However, some processes, such as degradation of waste package materials, radionuclide transport by groundwater and the transfer of elements from soil to biota, can be investigated using suitable analogues. Analogues can therefore play a useful role in building confidence in the understanding of processes and material properties relevant to disposal systems.

As indicated in Section 4.5, palaeohydrogeological analysis is conceptually similar to natural analogue studies. Groundwater flow patterns and groundwater chemistry have been affected by climate change and tectonic movements at many sites [117, 134, 135]. While palaeohydrogeological analysis is generally applied to the characterization of the long term evolution of groundwater systems and is thus potentially useful in the assessment of geological disposal systems, valuable data in support of water flow interpretations regarding near surface disposal systems have been obtained in some cases.

6.2.5. Documentation and maintenance of records

The need to generate confidence in the safety of LILW disposal requires that all activities in the development, operation and closure of near surface repositories be adequately documented. Records will include documents with safety implications, such as design and construction documentation, operating records, radionuclide inventories, closure data and documentation of the quality assurance programme. This information may be supported by a variety of other records and regulations, including site investigation and monitoring data, laws and criteria governing waste disposal, licensing documentation, safety assessment results and land use controls.

The long term maintenance of records in a manner consistent with regulatory and other applicable requirements represents a significant technical challenge. Records need to be stored in a suitable form under appropriate environmental conditions and in a safe place, and to be protected, in particular, from fire, flood and theft. Records need to be readily retrievable.

Some of the technical problems for different storage media are the following. In the case of paper and microfilm media, for a records management system to be effective, there will be a need to develop a database containing details of all the documents and their locations. In the case of records existing only in digital form, the system will be completely reliant on the use of electronic tools for the management of records that will need to be maintained over long periods of time. These and other technical issues of record keeping for radioactive waste disposal are further discussed in Ref. [129]. Because of the need for long term record keeping, participation in international co-operative activities for maintaining duplicate records in diverse locations may be beneficial.

7. SUMMARY AND CONCLUSIONS

Low and intermediate level radioactive waste is being generated in increasing quantities in many countries as the demand for nuclear applications in medicine, research and industry, including nuclear power, is continually increasing. In countries with reactor operations, waste arisings from that source are generally greater than those from institutional producers. Decommissioning of nuclear facilities is another potential source of large volumes of LILW.

Near surface disposal is an option suitable for short lived LILW that contains mainly radionuclides which decay to radiologically insignificant levels within a few decades or a few centuries. Limited concentrations of long lived radionuclides may also be present in LILW placed in near surface disposal facilities.

Near surface disposal of LILW has been practised for over half a century, and there are more than 80 near surface repositories around the world. During the past 50 years, there have been many examples of successful repository development and operation, but also of failures in repository performance. The lessons learned from these experiences have led to the adoption of improved concepts and technologies. It is anticipated that many new near surface facilities will be constructed and many existing facilities will be upgraded in the next few decades, especially in developing countries, eastern European countries and the Newly Independent States of the former USSR.

Disposal options include shallow facilities, with disposal units located either above or below the original ground surface, and facilities where the waste is emplaced at greater depths in rock cavities or boreholes. In the first case, the thickness of the cover over the waste is typically a few metres; in the second case the layer of rock above the waste can be some tens of metres thick. Rock cavities can be either natural or excavated in various geological formations. The borehole concept has been developed for the disposal of disused sealed radioactive sources and LILW exceeding waste acceptance criteria for shallow disposal.

In shallow facilities, the basic disposal units, typically trenches or vaults, are often located in the vadose zone, i.e. above the water table. However, in some countries, local conditions require the disposal units to be constructed in the saturated zone. In both cases, the disposal units have to be designed, constructed and maintained to limit the flow of water through the waste.

This report discusses, in a generic sense, the scientific and technical knowledge considered to be relevant for the design and safe operation of a near surface disposal facility, and for providing a convincing safety case that also covers the periods following repository closure and the end of institutional controls. As a result of the generic nature of the discussion, the described scientific and technical basis is quite comprehensive. For a specific repository, depending on the quantities and characteristics of the waste, the nature of the engineered barriers and the features of the site, the relative importance of the different scientific and technical elements is subject to change. As a consequence, the detailed scientific and technical basis relative to a specific repository depends on the various features of the disposal system.

The fundamental safety concept for the near surface disposal of radioactive waste is to isolate the waste from the accessible environment for a period sufficiently long to allow substantial decay of the shorter lived radionuclides and, in the longer term, to limit releases of residual radionuclides into the accessible environment by relying on multiple barriers.

For shallow repositories, a period of institutional control is needed after repository closure to provide assurance of waste isolation. The duration of post-closure institutional controls can be expected to be up to a few hundred years; a period of 300 years, for example, would correspond to around ten half-lives of radionuclides such as ^{137}Cs and ^{90}Sr. The anticipated duration of institutional control is an important strategic decision, since it affects both the definition of waste acceptance criteria and the required planning for surveillance, maintenance and monitoring of the disposal facility. If disposal takes place at greater depths, in rock cavity repositories or boreholes, less reliance may be placed on institutional controls.

Engineered barriers are features of the disposal system, made or altered by humans during construction, operation and closure of a repository. Because engineered barriers may play an important role in the performance of near surface repositories, many Member States are now considering the use of engineered barriers in the development of new repositories. Even after engineered barriers have degraded, they can continue to limit radionuclide releases through physicochemical processes such as sorption and solubility limitation.

The development of a near surface repository requires that a safety case be produced. Scientists, regulators, decision makers, concerned groups and the general public all need to have confidence in the isolation of the radioactive waste, and safety assessments can play an important role in demonstrating how the scientific and technical issues have been managed in order to ensure safety. The safety case can be developed as the repository programme proceeds, and it plays a key role in determining the types of waste that can be disposed of in any particular near surface facility.

The definition and effective application of waste acceptance criteria constitute an essential prerequisite for the safety of the repository. Waste acceptance criteria need to be based on considerations addressing the safety of the repository during the operational phase and in the post-closure period, both when institutional controls are still in effect and after their termination. For the period following the end of institutional controls, waste acceptance criteria address mainly the levels of long lived radionuclides that would be compatible with the safety targets even in the event of degradation of the isolation barriers or inadvertent human intrusion. Consequently, rationally justified waste acceptance criteria are important elements of a successful safety case.

Because of the extensive experience that has been gathered from operational near surface facilities, there is a wealth of information available on the key processes affecting the evolution of disposal systems and the behaviour of radionuclides in respect of their mobilization and subsequent migration through both engineered and natural barriers. This understanding is reflected in models for system performance.

A modular approach to system modelling is compatible with a multiple barrier design concept. Separate modules simulating the performance of different parts of the system can correspond to or encompass identifiable engineered or natural components of the disposal system. The modular approach allows flexibility, and effort can be concentrated on those parts of the system that are most important for the overall safety of the system. The overall modelling of the system needs to include modules for radionuclide transport through the different parts of the system, together with one or more modules for radiological exposure calculations. A simple modelling approach is likely to be efficient and transparent, and consequently more easily understandable and justified.

All activities in the development, operation and closure of a near surface repository should be adequately documented. The long term maintenance of records during the institutional control period in a manner consistent with regulatory and other applicable requirements represents a major technical challenge.

Key contributions to confidence in the safety of a near surface repository come from:

— A repository design based on the use of multiple barriers, engineered as well as natural, where it is possible to obtain reasonable assurance that the system performance can remain satisfactory even if any single barrier fails to function as expected.

- A well designed and managed quality assurance programme that covers all activities related to the disposal of the waste, from planning through siting, design, construction, operation, the various steps in the safety assessment process, closure and institutional control activities, including the maintenance of records.
- Studies of natural systems and of archaeological and historical artefacts, ancient buildings and anthropogenic sources of radionuclides such as nuclear weapons fallout. Such studies can all play a useful role in building confidence in the understanding of processes and material properties relevant to disposal systems.
- A well structured safety case that uses multiple lines of evidence as well as performance and safety assessments incorporating sensitivity and uncertainty analyses to address the inevitable uncertainties inherent in the representation of the evolution of the disposal system and the resulting potential radiological impacts.
- Monitoring and surveillance of the site as a part of active controls after repository closure.

Finally, there must be a long term commitment of Member States and international organizations to the demonstration and transfer of suitable technologies, to support for research and development, and to the exchange of scientific and technical information and expertise related to the near surface disposal of radioactive waste.

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