

Geologic Disposal of Radioactive Waste in Perspective



General Information

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NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

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- to assist its Member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes, as well as
- to provide authoritative assessments and to forge common understandings on key issues, as input to government decisions on nuclear energy policy and to broader OECD policy analyses in areas such as energy and sustainable development.

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In these and related tasks, the NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has a Co-operation Agreement, as well as with other international organisations in the nuclear field.

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FOREWORD

Today, nuclear energy provides 25 per cent of all electricity produced in OECD countries (17 per cent world-wide). The technology is mature, performance is improving and operating costs are falling. Nuclear power, provided that it is properly managed, provides economic and environmental benefits; in particular, it can make an important contribution to what is likely to be the dominant environmental imperative of the 21st century – limiting emissions of greenhouse gases, particularly carbon dioxide.

The challenge now facing the nuclear industry is to address a number of issues which may affect the continued availability of nuclear power, including improved competitiveness, maintenance of the current high levels of safety, a more stable regulatory framework and broader public and political acceptance. A key requirement is to ensure the safe, environmentally acceptable and economic disposal of all types of waste, a requirement which must be shared by all technologies. But this requirement is not related only to the future availability of nuclear power – solutions would be needed even if all nuclear power operations were to cease immediately, because of the backlog of wastes from past operations and the further wastes that will inevitably arise when nuclear power stations and other facilities are decommissioned.

There has been significant progress in developing and implementing technologies for processing, conditioning, storing and transporting all types of radioactive waste, and many relatively short-lived wastes (those whose radioactivity decays to harmless levels within a few decades or, at most, centuries) have been routinely disposed of for many years. For the longer-lived waste, which must be isolated from the human environment for many thousands of years, the preferred option since at least the 1950s, on ethical as well as technical grounds, has been disposal in repositories deep underground in well-chosen, stable geological media.

There is a broad scientific and technical consensus that geologic disposal is an appropriate and safe means of long-term waste management. There has been significant progress in understanding how deep geologic disposal facilities will function over very long periods, and methodologies have been developed for assessing the performance of the entire disposal system, including the

engineered structures of the repository as well as the geological formations between it and the surface, to attain optimal safety assurance and ensure compliance with regulatory requirements. There have, however, been setbacks in the disposal programmes in many countries – primarily due to the failure of the waste management community to win sufficient public and political support – and some groups are advocating postponement of disposal and further reviews of alternative waste management options.

From a purely technical point of view, there is no urgent need to implement disposal of long-lived waste – the volumes from civil nuclear power programmes are relatively small, storage facilities can be built and operated to a very high level of safety, and an interim storage period of several decades allows adequate cooling of the most radioactive wastes before disposal.

However, those responsible for radioactive waste management in most countries are continuing to advocate careful, phased progress towards the implementation of disposal, in accordance with the current view of the international radioactive waste management community, as expressed in a Collective Opinion of the NEA in 1995, which concluded that:

- from an ethical standpoint, including long-term safety considerations, our responsibilities to future generations are better discharged by a strategy of final disposal than by reliance on stores which require surveillance, bequeath long-term responsibilities of care, and might in due course be neglected by future societies whose structural stability should not be presumed;
- after consideration of the options for achieving the required degree of isolation of such wastes from the biosphere, geologic disposal is currently the most favoured strategy.

Maintaining the current 25 per cent contribution that nuclear energy makes to OECD electricity requirements, let alone providing for any increased contribution that countries may wish to make in the context of their Kyoto commitments to limiting carbon dioxide emissions, would require the construction of new nuclear generating capacity during the decades to come. The extended time-scales for planning, licensing and constructing new nuclear facilities, and the common perception that the “problem” of radioactive waste disposal contributes significantly to the difficulty of gaining acceptance for a continuing role for nuclear power, makes it timely to review the progress that has been achieved towards geologic disposal of long-lived waste and the further steps that may be required to implement such disposal, taking into account both the technical and regulatory requirements and the need to achieve an appropriate level of societal acceptance.

This report provides such a review, reflecting the NEA goal to “assist Member countries in the area of radioactive waste management, particularly in developing safe management strategies for spent fuel, long-lived waste, and waste from the decommissioning of nuclear facilities”. It presents an assessment of progress and prospects for geologic disposal, based for the most part on two recent reports by the members of the OECD/NEA Radioactive Waste Management Committee, which includes representatives of policy makers, regulators and implementers.

TABLE OF CONTENTS

FOREWORD	3
1. INTRODUCTION.....	9
2. PROGRESS IN LEGISLATION AND REGULATION	13
Summary	13
International developments	13
National developments	15
3. SCIENTIFIC AND TECHNICAL PROGRESS	19
Summary	19
Disposal concepts	20
Waste conditioning and packaging.....	21
Engineered barriers.....	22
The geological barrier	23
Site characterisation	24
Underground rock laboratories.....	26
Natural analogues	28
Performance assessment.....	29
4. PROGRESS TOWARDS IMPLEMENTATION	35
Summary	35
5. PROSPECTS AND CHALLENGES	39
Summary	39
Confidence in scientific, technical and regulatory aspects.....	40
Achieving civil society’s confidence.....	44
The search for other management options.....	52
6. THE INTERNATIONAL DIMENSION.....	57
BIBLIOGRAPHY	61

Chapter 1

INTRODUCTION

The safe, environmentally acceptable and economic management of radioactive waste arising from the generation of nuclear power is an essential component of nuclear power programmes. Significant technical progress has been achieved and considerable experience of all stages of waste management has been accumulated in many countries. Waste processing, conditioning, storage and transportation have become routine and demonstrably safe activities. Disposal, too, has become a routine operation, in near-surface facilities or at depths of tens or hundreds of metres in various geological environments. Almost all disposals, however, have been of relatively short-lived waste.

A number of options for the disposal of long-lived wastes have been examined over the years. Studies have been performed on concepts such as disposal in oceanic sub-seabed sediments and ultra-deep boreholes, as well as on more exotic proposals such as disposal into geologic subduction zones, in polar icecaps and launching into space. All these have been found wanting in terms of costs or risks, or impractical because of political or legal restrictions. There has long been a broad consensus among the waste management community that deep geologic disposal represents the only feasible route for ensuring sufficient long-term isolation of long-lived waste from the human environment and thus “closing the nuclear fuel cycle”. Current debates within waste management programmes focus mainly on when and where disposal should take place, bearing in mind the need to fulfil ethical obligations, reduce present and future risks, ensure that other management options are given due consideration, and enhance societal participation in and ultimately acceptance of the disposal strategy.

There has been significant progress during the past ten years in the scientific understanding of, and the necessary technology for geologic disposal, including understanding the roles of the natural and engineered barriers, achieving site characterisation, assessing repository performance and demonstrating confidence in such assessments. There has also been progress in the areas of legislation and regulation. However, the time-scales envisaged for

implementing geologic disposal of long-lived waste were too optimistic. Only in the United States, and there only since March 1999, has there been an operating purpose-built geological repository for some waste from the United States defence programmes that contains significant long-lived components, although high-level, heat-generating wastes (HLW) are excluded. Elsewhere, and in the United States for most long-lived wastes, estimates of the time-scales for implementation of disposal range from several years to several decades, and in many countries there are considerable uncertainties about timing and the societal framework and processes required to enable disposal to be implemented.

In order to evaluate the current status of disposal programmes in its Member countries, monitor the evolving technical consensus and guide future activities, the Radioactive Waste Management Committee (RWMC) of the NEA has carried out a critical review of developments in geologic disposal of long-lived waste during the past decade (key documents are listed in the bibliography on page 61). A second RWMC report sets out the broad strategic areas for future work, reflecting the major challenges currently faced by national waste management programmes, including those related to the disposal of long-lived waste.

The *key questions* that the review addressed were:

- Is progress being made towards offering society a technically safe and suitable means for the management of long-lived radioactive waste?
- In particular, how has the technical case for geologic disposal progressed in the past decade and how has the acceptability of geologic disposal changed?
- What are the key current issues and concerns that will determine future developments and acceptability?

The *strategic areas* identified for the future, given here for completeness although they do not all relate to the disposal of long-lived waste, are:

- overall waste management issues, including: environmental concerns, safety and sustainable development; comparison of the regulation and impacts of radioactive and non-radioactive waste management; and economic concerns related, for example, to deregulation of electricity markets and the impact of waste management costs on the continued economic sustainability of nuclear power;

- the process of repository development for long-lived radioactive waste, including: the resolution of technical issues; the development of common understanding between implementers, regulators and policy makers on the goals to be achieved and respective responsibilities; and the generation of societal confidence on how to move forward at the various stages of a repository development programme;
- the management of materials from decommissioning and dismantling, and of very low-level waste;
- public perception and confidence, including: understanding the concerns of stakeholders; communicating effectively; sharing practical experience; and public decision-making processes;
- implications of, and participation in, international guidance and agreements;
- system analysis and technological advances: identifying emerging waste management and disposal technologies; considering their implication at the system level; and exchanging information.

The following three chapters discuss, in turn, progress in regulation and legislation, scientific and technical progress, and progress (in some cases, setbacks) in implementation and the vital concomitant – achieving societal acceptance. The next chapter considers what remains to be done to enable and implement sound, safe and economic disposal of long-lived radioactive waste. The final chapter discusses the role of international organisations and co-operation.

Chapter 2

PROGRESS IN LEGISLATION AND REGULATION

Summary

The regulation of radioactive waste management is unique in the scope and breadth of the international consensus on safety standards on which national legislation is based. The primary objective is to protect current and future generations from unacceptable exposures to radiation originating from the radioactive materials in the waste or their radioactive decay products.

In most countries with a need for eventual geologic disposal, regulatory guidelines set out principles and specific requirements for underground disposal. Several countries have also set site-specific requirements and issued guidance on demonstration of compliance with the regulatory requirements.

There is a trend towards the use of broader indicators of long-term performance than radiation dose and risk, and increasing recognition that the nature of performance assessments varies with the timescale being considered.

A number of countries have made institutional changes which confirm or reinforce the independence of nuclear regulators, give waste management issues a higher profile within government and provide for regular exchanges between regulators and implementers.

International developments

International Commission on Radiological Protection (ICRP)

Radiation protection is based on the recommendations of the International Commission on Radiological Protection (ICRP), an independent body of medical and scientific experts, which formulates fundamental radiation protection principles and criteria for world-wide application.

The most recent ICRP publications relevant to geologic disposal are ICRP 64 (1993), which is concerned with protection from potential radiation exposure, and ICRP 77 (1998), which sets out the way in which ICRP's general framework for radiation protection should be applied to radioactive waste disposal.

An ICRP Task Group has recently issued recommendations to be applied specifically to the disposal of long-lived waste (ICRP 81). The intention is to supplement ICRP's 1985 recommendations (ICRP 46) in the light of more recent developments, including ICRP 77.

International Atomic Energy Agency (IAEA)

Based on the work of the ICRP, the International Atomic Energy Agency (IAEA) has issued the Radioactive Waste Safety Standards (RADWASS), an internationally recognised non-binding set of standards. The leading document The Principles of Radioactive Waste Management was issued in 1995. It formed the technical basis for the Joint Convention of 1997 on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, which was signed by 41 States, out of which 19 were Contracting States as of May 2000. Efforts are now focused on formulating harmonised standards, with the next few years seeing the completion of the planned set of documents.

Nuclear Energy Agency (NEA)

An NEA International Workshop took place in Cordoba in January 1997, involving regulators and implementers from a wide range of national programmes. The participants examined waste disposal objectives and criteria, trends in performance assessment and the conduct of regulatory processes. In the specific area of regulatory issues, the key points agreed were:

- Single regulatory criteria such as dose or risk indicators had the appeal of being transparent and easily understood, but a more sophisticated approach that took multiple factors into account was more appropriate.
- Protection of the environment was an area that needed further clarification, notably because of current interest in the protection of the environment per se. The protection of humans against radiation may be generally sufficient to protect fauna and flora, at least at the level of living species which is probably the essential concern, but not necessarily at the individual level.

- There is no real justification, from a technical and scientific perspective, for a specific cut-off time or times for a performance assessment. An essentially quantitative approach will have to move to more qualitative considerations for the very long term (greater than 10 000 years).
- Communication, between regulators and implementers as well as with broader groups, needs improvement.
- Licensing requirements (“rules of the game”) should be framed well ahead of when they are to be applied – and can justifiably include simplified or stylised approaches.
- A phased approach to planning, licensing and implementation is valuable for implementers, regulators, decision-makers and the public.

European Union

EU Directives, which Member States are required to implement, cover basic standards of radiation protection, controls on the shipment of radioactive material, and environmental impact assessments (EIA) for new facilities, which must include public information activities. Recent developments of particular relevance to radioactive waste management are the 1996 revisions of the Basic Safety Standards Directive, which include lower radiation dose limits for workers and the public, and the 1997 amendments to the EIA Directive, which now requires assessments for radioactive waste storage facilities with a planned storage period of over 10 years as well as for repositories.

National developments

There have been significant developments in national legislation during the past ten years. Politicians and legislators in the United States have been particularly active in seeking to move disposal projects forward and new laws have been passed in the United Kingdom, Germany, the Netherlands, Hungary and the Czech Republic. In Canada, the government in 1997 passed laws streamlining and reorganising the regulatory structure and adding additional assurance that license applicants are adequately funded.

At the regulatory level, guidelines that set out principles and specific requirements for underground disposal are now in place in most countries planning geologic disposal. Several countries have also set site-specific requirements and more detailed guidance on how an organisation wishing to

dispose of radioactive waste would be expected to demonstrate compliance with the regulatory requirements. The United States Switzerland, Sweden, Finland, Spain and Japan have recently amended, are amending or are developing regulations specifically governing radioactive waste disposal while some countries, like Belgium and the Netherlands, do not, as yet, have such regulations. In many countries, there are regular exchanges between regulators and waste management organisations covering, for example, reviews of research activities and safety studies and iterative performance assessments.

There is a trend in national regulations towards the use of broader indicators of long-term performance than simple estimates of radiation dose or risk, for example environmental concentrations and biospheric fluxes of radionuclides. There is also increasing recognition that the nature of performance assessments varies with the timescale being considered. With increasing timescale, uncertainties increase and the results of assessments have to be regarded as indicators of performance rather than precise predictions of impacts. Such considerations have brought with them proposals to develop internationally agreed approaches to assessing long-term impacts. A common trend is towards advocacy of a phased approach at the regulatory level, to provide smaller steps in the societal decision-making process.

There is also a trend towards embedding national laws or regulations on radioactive waste disposal in a wider framework of environmental regulation. However, while many countries claim coherence between legislation affecting radioactive waste disposal and other environmental legislation, there is as yet little evidence that objective risk-based regulations are ensuring equitable treatment – and proof of treatment – of different potential hazards. For example, permits to allow injection of toxic materials into boreholes may in principle require the applicant to demonstrate that groundwater will “never” be endangered, but there are no requirements to submit and exhaustively review predictions of performance in the very long term, equivalent to those required for radioactive waste disposals. More generally, there is seldom any direct mention in environmental legislation or regulations of issues like sustainability or approaches to ensure a uniform degree of protection from a variety of radioactive materials and from non-radioactive hazardous wastes.

A number of countries are making changes to their institutional framework which confirm or reinforce the independence of nuclear regulators. For example, in the Czech Republic responsibility for regulation has been transferred from the Atomic Energy Commission to a new State Office for Nuclear Safety, In France the Institut de Protection et de Surete Nucleaire (IPSN) has been separated from the Commission Energie Atomique (CEA), and in Canada a new Nuclear Safety Commission is replacing the former Atomic Energy Control Board. In Spain and Sweden, structural changes within the

regulatory organisations are resulting in waste management issues having a higher profile within government.

Some countries have made organisational changes aimed at facilitating the contentious issue of siting. France has introduced a mediator who has had some success in identifying volunteer communities for underground laboratories and Sweden has appointed a National Co-ordinator to facilitate siting negotiations.

There have been few fundamental changes in the organisation of the implementing side of waste management. Dedicated implementer organisations have been in place in many countries for several years, and more recently set up in Finland, the Czech Republic, Hungary and Switzerland (GNK). Japan and Canada are considering similar action.

Chapter 3

SCIENTIFIC AND TECHNICAL PROGRESS

Summary

The past ten years have seen little fundamental change in the basic technological approach to geologic disposal. The approach makes use of engineered and natural barriers, working in conjunction to achieve the necessary long-term isolation of the wastes by preventing or limiting their movement away from the repository to the human environment.

There have been relatively few new concepts or technological breakthroughs but there has been significant progress on many of the components of geologic disposal systems, particularly in the development of robust engineered systems, the science and technology needed to underpin performance assessment, and the better integration of disposal system design, site characterisation and performance assessment. Work in an increasing number of underground laboratories and studies of natural analogues has continued to provide crucial data and increased confidence in geologic disposal. Natural analogue exercises are often performed co-operatively, with several organisations involved in each project. As a result, participating organisations have benefited through the development of international and interdisciplinary contacts.

The interdependencies of these different areas are now widely recognised and integrated project management structures have been established to encourage interaction between them. In particular, closer integration between site characterisation and system design is resulting in experimental and design work being more precisely focused on areas that promise to improve safety and confidence.

In general, the necessary technologies for geologic disposal are now available and can be deployed when public and political conditions are favourable. However, it is recognised that there is relatively little experience in

the application of some of these technologies, and demonstration and testing will therefore need to continue and further refinements made.

Disposal concepts

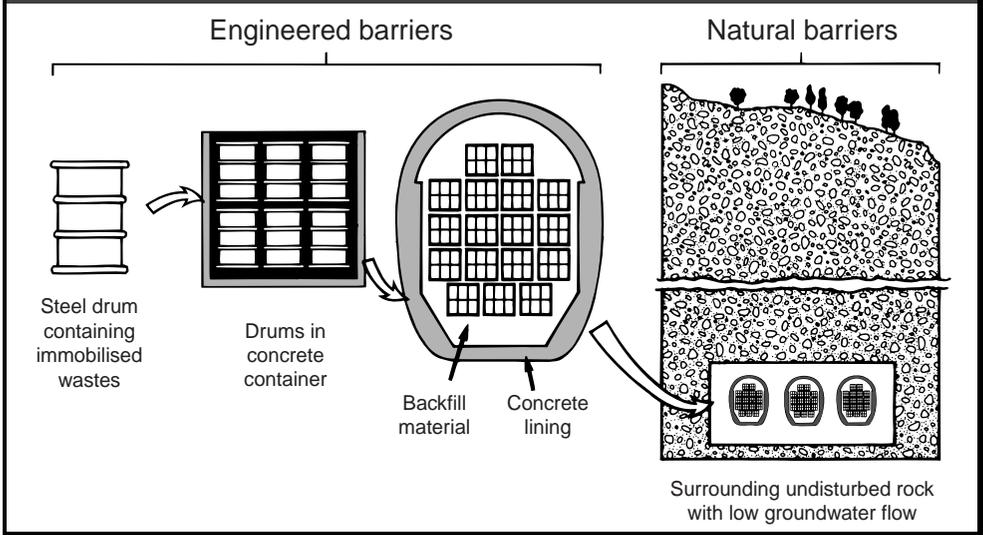
All the methods in use or under development for geologic disposal rely on a series of barriers to provide the necessary degree of long-term isolation of the wastes from the human environment. The barriers can be man-made, for example steel or concrete, or natural, for example thick layers of clay or hundreds of metres of rock. A key feature of the geological barrier is low groundwater flow, since dissolution and transport in groundwater is generally the most important pathway by which wastes may be carried away from a deep underground repository and to the human environment.

Progress has been achieved mainly through gradual improvements in repository designs and the technologies needed to implement them. There have been relatively few new concepts or technological breakthroughs, indicating that the key decisions taken more than ten years ago have not needed radical revision. One exception is the dramatic rate of development of computer technology, communication and control systems which will allow the use of remotely-controlled equipment for waste-package emplacement and related operations.

Partly in response to the perceived difficulty of adequately characterising certain geological environments, more attention has been focused in recent years on developing so-called robust engineered barrier systems. These are systems which, by a combination of physical barriers and chemical controls, can confidently be expected to provide a high level of long-term containment while making relative few demands on the characteristics of the host rock. In some cases, where actual sites have been investigated, a high level of refinement has been applied to adapt the engineered barrier design to the characteristics of the site.

Also of importance has been the increased emphasis on an integrated view of the multiple barrier system – a paradigm shift from a “Russian doll” picture of independent barriers to one of a complementary set of interlinked barriers.

Containment by multiple barriers



Waste conditioning and packaging

The overall performance of the engineered barrier system depends on the properties of the waste form itself, and these may be influenced through controlling the composition of the wastes or the conditioning process (the process used to convert waste into a form suitable for long-term storage or disposal). The most common material used for conditioning wastes other than HLW remains cement, using a range of formulations. Vitrification is well-established for HLW and is now being applied to some other wastes.

A number of possible container designs and materials have been or are still being considered, depending on the type of waste being packaged, with associated research on material properties and long-term corrosion performance. However, a single reference design is often adopted in feasibility studies and performance assessments. There is increasing emphasis on ensuring reliable fabrication and good long-term performance of containers, and this has fed back into development programmes. In Sweden, for example, full size copper canisters for spent fuel have been fabricated as prototypes, and in the US, full-diameter, quarter-length prototypes of the current dual metal design of containers for both spent fuel and HLW have been manufactured to demonstrate the feasibility of the fabrication process used.

Engineered barriers

The engineered barriers consist typically of steel containers for the wastes, grouted into concrete containers which are surrounded by a backfill material and possibly more concrete. In the case of HLW or spent fuel (when treated as a waste rather than being reprocessed), composite containers (for example a steel insert with an outer copper sheath) will be surrounded by a backfill material such as bentonite. A co-operative full-scale experiment at the Grimsel test site in Switzerland, under the aegis of the European Union, is examining the industrial fabrication, handling and emplacement of a bentonite backfill and its behaviour under realistic repository conditions.

The engineered barriers act together to delay access of groundwater to the wastes and subsequently limit the movement of groundwater containing dissolved radionuclides away from the repository into the surrounding rocks. Experimental results suggest that the engineered barriers should provide physical containment for several thousand years.

In some repository concepts, the engineered system also makes an important contribution to long-term containment within the repository by providing chemical conditions that ensure that many of the components of the waste dissolve only extremely slowly. For example, specially formulated porous cement-based backfills that have been developed in Switzerland and the United Kingdom create chemically alkaline conditions in which the solubility of many key radionuclides is many orders of magnitude lower than it would be in normal groundwater. Furthermore, these materials are porous and the pore surfaces are able to retain radionuclides that have been dissolved in groundwater by the process of sorption (attachment to surfaces), further delaying their release from the repository.

Several programmes, including laboratory studies and the development and validation of models, have led to increased understanding of the long-term chemical properties of the various forms of backfill that have been proposed. Under the low groundwater flow rates expected in a suitable host rock, the use of such backfills is expected to result in the persistence for over a million years of chemical conditions that ensure low solubility and high sorption of many important radionuclides.

The combination of the physical and chemical barriers provided by the engineered system should ensure that the vast majority of the initial radioactivity of the wastes will decay within the repository itself, and that any radionuclides that might be carried away from it do so only very slowly and at very low concentrations.

The geological environment has always been seen as a key component of the overall geologic disposal system, and in some formations, such as clays, the role of the engineered structures may be mainly to provide safety during the operational phase of the repository life. In others, such as fractured hard rock, there have been significant advances in the analysts' ability to understand and characterise the geological and hydrogeological features of the natural system and a greater awareness of the difficulties and uncertainties in providing a sufficiently complete characterisation for performance assessment purposes. Where such geological environments are being considered, there has been a trend towards the adoption of robust engineered systems in order to offset some of the difficulties inherent in assessing the performance of the natural systems and thus increase overall system confidence. Robust engineered components should be simple and conservative in their design and must be chemically compatible with and functionally complementary to the natural systems. The massive copper canisters being developed in Sweden for spent fuel are a prime example of the robust engineering approach.

The geological barrier

The geological environment provides a stable setting and isolation from inadvertent human intrusion or disruption by natural events, an environment favourable to the longevity of the materials of which the engineered system is made, and a chemical and physical buffer that is conducive to slow container degradation and very slow radioactivity releases thereafter. Ideally, the geosphere needs to ensure low groundwater flow into and through the repository and provide chemical conditions (particularly in the groundwater) that do not adversely affect the engineered system. Other important geosphere characteristics are a long groundwater travel time from the repository to the biosphere, spreading out (dispersion) of radionuclides dissolved in the groundwater and retardation of radionuclides relative to groundwater flow. A long travel time for radionuclides through the geosphere gives time for them to decay and disperse, thus reducing the amount of radionuclides released into the biosphere during any given time period.

The main types of formation that have been studied for geologic disposal are salt, sedimentary formations such as clay and shale, crystalline formations such as granite and gneiss, and volcanic formations such as basalt and tuff.

Salt formations are many millions of years old, and, since salt dissolves easily in water, their very existence indicates that there has been little flow of water for very long periods. Salt creeps under pressure, so any fissures tend to be self-sealing. The formations are mechanically strong, so the construction of large caverns and tunnels without roof supports is straightforward.

The main advantages of formations such as clays and shales are their favourable sorption properties. In clay formations, for example, strong sorption results in many important radionuclides moving up to one million times more slowly than the groundwater in which they are dissolved. The rate of water movement through these formations can be very slow, and virtually zero in plastic clays. However, even in clays and shales, fracture zones can occur and, as with hard rocks, these can be areas of faster groundwater flow.

Crystalline rocks in the unfissured state have very low permeability to water flow. In addition, they have good sorption properties, and good structural and chemical stability. While formations tend to be highly fissured near the surface, and considerable water movement can occur through these networks, fissures generally decrease with depth. A major requirement of the site characterisation process in such rocks is to explore and understand the groundwater flows within and around the repository area.

Basalt has low permeability and moisture content and is very hard and strong. Tuff can be of two types: high density, when it has a low porosity and moisture content, or low density, when it has good sorption properties.

Site characterisation

Ten years ago, the lack of site-specific data was a major limitation when assessing the long-term performance of repository designs and the feasibility of their construction. Few data were available from potential sites and data-collection strategies and methods were far less developed. Much work has now been carried out to rectify these deficiencies, for example at Sellafield in the United Kingdom, Yucca Mountain and WIPP in the United States, Gorleben in Germany, Mol in Belgium, Wellenberg in Switzerland and at the potential deep disposal sites in France.

A more integrated strategy for site characterisation has been developed in several national programmes. For example, probabilistic techniques to optimise site-characterisation strategy have been developed, and the United States, as well as others, have performed formal system evaluations to focus experimental and design work on areas that promise to improve system safety and confidence. The need for an interactive project management structure has also been recognised. This should enable more effective co-ordination of the planning and implementation of site investigations, project-specific evaluation of site properties, development of performance-assessment methods and application of these methods in comprehensive assessments.

One lesson from recent experience in site-characterisation work is that conflicting data can emerge, implying that yet more data may be required to understand the system - i.e. to reduce the uncertainty in a system that is more complex than originally believed. This happened, for example, at Yucca Mountain in the United States where measurements that suggested the existence of heretofore unmodelled faster flowpaths led to a restructuring of the models used to calculate groundwater flow.

Recent technical developments in site characterisation

Techniques for measurement and interpretation of data have been refined and tested at potential sites and underground research laboratories. Recent advances include:

- detection of small groundwater flows in deep boreholes;
- extraction of undisturbed groundwater samples from low-permeability media;
- the use of environmental isotope sampling methods to identify pathways for past and potential future rapid recharge of water into unsaturated media;
- determining the depth of more saline water by electromagnetic methods.

The interpretation of data is benefiting from:

- three-dimensional visualisation techniques for integrating interdisciplinary data (e.g. geological, hydrogeological and geochemical data);
- better numerical modelling tools for representing heterogeneity, including probabilistic modelling tools to take account of incompletely characterised natural variability;
- the use of hydrochemical data to indicate patterns of groundwater flow.

Better processing and interpretation codes are enabling field data (e.g. from seismic surveys) to yield more relevant information than previously.

In summary, there has been significant progress during the past ten years, through improved understanding of the natural system, technical developments and extensive studies at various sites, which has enabled site characterisation to develop from a relatively unstructured collection of geological data into a

focused technical activity, aimed at gathering the key data needed to assess the performance of a disposal system.

Underground rock laboratories

Research has been carried out at sixteen underground rock laboratories (URLs) in nine countries. Of these, eleven are “generic” URLs, at locations that are not foreseen as repository sites, and five are “site-specific”, forming an integral part of the investigation and development of a candidate site whose choice must be confirmed by detailed underground analysis. There are plans for further URLs, at Meuse in France, Příbram in the Czech Republic and Horonobe in Japan.

These laboratories provide an environment for developing and proving underground engineering methods and invaluable data for the testing of the scientific and mathematical models used in performance assessment. They can also provide practical demonstrations that can help to improve confidence of all those who are involved in or observe their operation, and they have acted as centres for promoting international co-operative research projects. They have been used for:

- further development and testing of excavation techniques;
- quantification of impact caused by excavation (regional and local scale, physical and chemical perturbations);
- application of site-exploration strategies and strategies to adapt underground systems as more information is acquired;
- integration of results to derive conclusions, conceptual models and predictions regarding groundwater flow (and 2-phase flow);
- testing of models, exploration methods and processes potentially relevant to radionuclide transport through rock;
- simulation of effects caused by emplacement of radioactive waste (heat, nuclide release, mechanical impact);
- demonstration of engineered-barrier systems (feasibility);
- experiments related to long-term processes, post-operational phases, geochemical corrosion, geomechanical stability, etc.

Underground rock laboratories and other underground research centres

Country	Host rock	Laboratory
Belgium	Boom clay (plastic clay)	Mol/Dessel Underground Research Facility. Site-specific URL, 230m. Operating since 1984.
Canada	Granite	Lac du Bonnet. Generic URL, 240-420m. Operating since 1984
France	Granite	Fanay-Augeres. Galleries in uranium mine. Generic URL. Operated 1980-1990.
	Granite	Tournemire facility. Former railway tunnel and adjacent galleries. Generic URL. Operating since 1990.
Finland	Granite	Olkiluoto research tunnel. Site-specific URL, 60-100m. Olkiluoto repository operating since 1992.
Germany	Salt dome	Asse R&D programme. Generic URL, closed down 1995.
	Salt dome	Gorleben*. Potential repository site, >900m. Shafts constructed 1985-1990, galleries under construction since 1997.
Japan	Sediments	Tono. Galleries in former uranium mine. Generic URL. Operating since 1986.
	Granite	Kamaiishi. Galleries in former Iron/Copper mine. Generic URL. Completed in 1998
	Granite	Mizunami URL. Generic URL. Borehole drilling under way.
Sweden	Granite	Stripa mine. Galleries in former Iron mine. Generic URL, 360-410m. Operated 1976-1992.
	Granite	Aspo hard rock laboratory. Generic URL, <460m. Construction started 1990.
Switzerland	Granite	Grimsel Test Site. Gallery from a service tunnel of a hydroelectric scheme. Generic URL, 450m. Operating since 1983.
	Opalinus clay (hard clay)	Mont Terri Project. Gallery from a highway tunnel. Generic URL, 400m. Initiated 1995.
USA	Salt (bedded)	WIPP, Carlsbad, New Mexico. Site-specific URL, 650m. Operating since 1982.
	Welded tuff	Yucca Mountain Exploratory Studies Facility. Site-specific URL, 300m. <i>In situ</i> testing began in 1996, construction of an exploratory side tunnel completed in 1998.

* Gorleben has been selected for underground investigations aimed at demonstrating site suitability.

Natural analogues

Natural analogues, processes occurring in nature similar to those which would determine the long-term behaviour of a repository, can be used to complement the data obtained from site characterisation studies and measurements in underground laboratories. They can be especially valuable in the building of confidence, since they allow a check of our understanding of processes which are too slow, or too large in scale, to be directly measured in the laboratory or in the field. Data from natural analogues have rarely been used directly in repository performance assessment because their interpretation is complicated by lack of information regarding, for example, the initial conditions of the analogue system. They can, however, support the qualitative and (less commonly) quantitative understanding of key processes. They can also provide evidence that no potentially significant long-term processes or phenomena have been overlooked, and may be used to gain general confidence in the behaviour of the geological aspects of a repository.

Particular advances during the past ten years include:

- insights into the oxidation of uranium and the migration of uranium dioxide, from studies of analogue sites in Mexico and Greece;
- better understanding of the processes controlling the performance of spent fuel in a repository in plutonic rock, in a reducing environment and protected by clays, from work at the Cigar Lake uranium deposit in Canada;
- evidence from studies of natural clays that, under repository conditions, the swelling capacity, permeability and ion-exchange capacity of bentonite will be retained over a very long period;
- evidence for the stability of cement gels, the absence of colloids and organic complexants and very low levels of microbial activity, from studies at the Maqarin site in Jordan;
- the observation of rock matrix diffusion of uranium in granite at El Berrocal in Spain and in crystalline rocks at the Grimsel Test Site in Switzerland;
- validation of thermochemical data used to model rock-water interactions, from studies of geochemical data from wells at the Wairakei geothermal field in New Zealand;

- Pocos de Caldas, a major international study looking at solubility and transport of radionuclides in and around natural uranium and thorium ore bodies and testing models of these processes;
- evaluation of performance assessment methodologies in the Palmottu natural analogue project in Finland;
- work on bentonite properties at a deposit of that material in Saskatchewan.

Performance assessment

Developing geologic disposal systems and assessing their performance requires data, understanding and modelling at several levels:

- Establishing the feasibility of the use of geological formations to provide isolation of the waste from the human environment requires a general understanding of the relevant physical, geochemical and hydrogeological properties of the wide range of geological formations in which a repository may be sited and the ways in which these, and the properties of the surface environment, may change with time.
- Developing and assessing generic repository designs for different types of waste in different geological environments requires more detailed understanding of processes such as groundwater movement, retardation and dispersion of radioactive material as it is carried in solution through the rocks by flowing groundwater, and processes by which such material can move through the biosphere and reach humans.
- Finally, establishing whether or not a particular repository design at a particular site can be built and operated in full accordance with the regulatory requirements requires detailed characterisation of the site and an exhaustive analysis of the likely performance, short and long-term, of all the components of the disposal system, engineered and natural.

Many decades of work in the field, in laboratories, including underground laboratories, and at natural analogue sites, often under international auspices, have resulted in a substantial body of data and understanding relevant to this challenging area of science and technology, much of it based on the most advanced measurement and analytical techniques. Advanced data processing

and interpretation methods are allowing the data to yield more and more detailed and accurate information. Mathematical techniques, using powerful computers, are allowing detailed predictions to be made of the performance of complex systems and the possible consequences of any remaining uncertainties in the data.

Much of the research on the natural system during the past ten years has been directed to improving the understanding of water-conducting features and groundwater flow in potential host geologies. Other factors important to performance assessment, such as hydrogeochemical analysis and the analysis of the roles of colloids, organics and potential microbial processes, have also received attention.

Advances have been made in the specification of safety-relevant technical criteria for the acceptability of potential host rocks (including, in the case of Sweden, acceptance criteria for individual deposition holes). Such technical criteria are valuable, particularly if developed in advance of an exploration programme, in that they not only serve to guide that programme, but may favour public acceptance, by demonstrating transparently that an implementer would be prepared to abandon a site, should it prove unacceptable. On the other hand, setting unrealistic or over-simplistic criteria may lead to the abandonment of a site that is, in fact, adequate in terms of its ability to satisfy the regulatory requirements.

One of the most important developments during the past ten years has been in integrated performance assessment – the integration of performance assessment and site selection, characterisation and repository design. The need for effective communication between those involved in performance assessment and those involved in site characterisation has been widely recognised and there is close integration of the work of geologists, hydrogeologists, designers and performance-assessment modellers in most disposal programmes. For example, several organisations are using the results of performance assessment for optimising their site characterisation and laboratory investigation programmes and for evaluating and improving repository layout. Such integration helps to focus site characterisation on safety-relevant issues and avoids the selection of sites and designs and the development of models for which the data needed to demonstrate safety are unlikely to be attainable.

Overall, there is growing confidence that performance assessments can now provide a reliable basis for judging the acceptability of a repository site and design from the point of view of safety.

Progress in understanding of system components

Analysing the performance of an integrated repository system requires an adequate, quantitative understanding of the behaviour of the waste form itself, the engineered structures around the waste, the host rock and the biosphere. Each of these elements has one or more safety functions associated with them. The geological barrier, for example, functions both as a barrier to nuclide release and transport and as a complement to the engineered barrier by providing a stable, protected environment for the engineered system over long times.

Individual barriers may also have different safety functions at different times. For example, a steel canister can provide complete containment of radionuclides for an initial period, while, at later times, canister corrosion products give rise to chemical conditions that favour retention within the backfill. The various elements of a repository are increasingly being viewed as complementary, rather than independent, contrasting with the traditional picture of multiple series of independent barriers, like a “Russian doll”. It is clearly important that the elements are compatible, e.g. geochemical compatibility between backfill materials and the geological environment. Many national and international programmes have sought, through performance assessment, to enhance their understanding of these safety functions and their relative importance.

At the level of individual barrier performance, there have been significant advances in:

- understanding waste-form degradation processes;
- more realistic modelling of the processes that may lead to canister degradation and failure;
- modelling early canister failures;
- more sophisticated use of geochemical codes and data to simulate chemical processes in pore-water;
- understanding the effects of the thermal history of the repository;
- three-dimensional modelling of groundwater flow, including density and transient effects, and the use of spatially-variable models of hydrogeological media, based on site data;
- modelling geosphere transport in fractured and unsaturated media and testing models against available field data;
- better-founded models of the stability of the geosphere with respect to climate change, seismicity or volcanism, effects of colloids and gas-mediated releases and interactions between repository components.

An NEA Working Group reviewed a selection of these assessments completed during the period 1991-1996 and concluded:

- that the NEA/IAEA/CEC Collective Opinion of 1991 remained valid, i.e. that safety assessment methods are available today to evaluate adequately the potential long-term radiological impacts of a carefully designed radioactive waste disposal system on humans and the environment;
- that while the increased use of data from actual sites and the increased detail in the specification of repository designs presented new challenges and required more resources than expended in earlier performance assessments, no new insurmountable problems in the use of performance-assessment methods had been encountered;
- that particular progress had been made in understanding the performance of system components and their respective roles, the treatment of uncertainty, the presentation of assessment findings and feedback to site selection, characterisation and repository design.

Increasing confidence

Overall, confidence in the models used to assess the performance of the engineered and geological barriers, and the level of realism that such modelling can achieve, have increased over the past decade. Large-scale experiments that test models of the engineered barriers and hydrogeological aspects of the geosphere have been performed in underground laboratories. There have been significant advances in modelling of the geological barrier, including a more realistic incorporation of natural variability in models of geosphere transport and a better understanding of the nature of water-conducting features over a range of scales and of the interface between the engineered system and the geosphere. More reliable modelling of this interface is being carried out as a result of studies of the excavation-disturbed zone in underground rock laboratories.

Nevertheless, there are still significant uncertainties associated with modelling all aspects of the performance of a geologic disposal system. Problems include the natural variability of repository host rocks, the difficulty in assessing how groundwater flows and rock properties may change over very long times, and the difficulty of testing models at appropriate spatial and temporal scales.

Sources of uncertainty in performance assessment, and the main ways in which they are addressed, can be classified as:

- uncertainty in the data, addressed through the well-established technique of sensitivity analysis;
- uncertainty in the models, addressed through validation and verification, for example by using the models to make predictions which can be tested against observations and by intercomparison with similar but independent models and with direct calculations that do not use computer codes;
- uncertainty over the long-term evolution of the repository, the environment and human behaviour, addressed by examining a broad range of evolution scenarios, taking account of the probabilities of the different scenarios occurring.

Although the repository developer may contribute suggestions on how to treat such uncertainties, it is up to the regulator and other relevant decision-makers to judge whether the treatment is acceptable or not if the results are intended to be used for comparison with regulatory criteria.

Presentation of assessment findings

The presentation of results poses a number of problems to the organisations involved in performance assessment, associated, for example, with the long time-scales over which assessments are performed. Presentation is a particular problem where probabilistic assessment methods are used: the large amounts of results generated by such methods must be distilled in such a way that the key findings are clearly shown.

Although the exact contents of a performance-assessment report will depend on a number of programme-specific and practical constraints, there is a broad consensus about the elements that such a report should contain. Of particular importance are:

- traceability: an unambiguous and complete record of the decisions and assumptions made, and the models and data used, in arriving at a given set of results;

- transparency: the clear reporting of a performance assessment, so that the audience can gain a good understanding of what has been done, what the results are, and why the results are as they are.

Aspects of presentation where progress has been made during the past ten years include:

- the graphical representation of assessment results, illustrating the performance of system components as well as overall performance;
- methods that illustrate where radionuclides reside within the system, as a function of time;
- the use of “insight” models, which capture and explain the behaviour of key radionuclides, based on simple physical and chemical principles;
- the production of specific reports tailored to different audiences;
- the placing of assessment results in perspective with the risks associated with other human activities;
- the need for a statement of confidence in the findings of a performance assessment (with supporting arguments);
- the recognition that appropriate caveats should be placed on the conclusions of a performance assessment, acknowledging the technical limitations of the assessment and the potential impact of these limitations on the analysis.

Despite these advances, however, several organisations recognise that the presentation of results, especially in view of the diverse audience, is an area where further work is required.

Chapter 4

PROGRESS TOWARDS IMPLEMENTATION

Summary

Significant progress towards implementation of geologic disposal has been made in several countries, but the rate of progress has been slower than expected ten years ago, and serious set-backs have occurred in some countries.

Geologic disposal has been implemented for many types of radioactive waste, the main exception being long-lived waste, particularly used nuclear fuel and high-level waste.

- In Germany, low-level radioactive waste was disposed of in the Asse salt mine between 1967 and 1978, as a demonstration project, and a deep repository for low and medium-level waste has operated in a salt dome at Morsleben since 1981, although this operation has now been interrupted. Both facilities are at depths exceeding 500 m. The licensing procedure to permit the disposal of non-heat-emitting waste in a disused iron ore mine at Konrad, at a depth of 1 000 m, is in its last stages.
- In Sweden, a repository at intermediate depth for the disposal of low and medium-level waste has been operating at the Forsmark nuclear site since 1988. The disposal caverns are excavated in granitic bedrock, offshore, about 60 m below the bed of the Baltic Sea, and accessed by a tunnel from the land. In Finland, a facility for disposal of low and medium-level waste was opened in 1992 at the Olkiluoto nuclear site and in 1998 at the Loviisa site. These consists of caverns excavated in granitic bedrock at depths of around 100 m below ground. In Norway, the Himdalen facility for low-and medium-level waste has started operation in 1999. It consists of four caverns under 50 m of bedrock cover.

- Most notably, in the United States, the necessary permits were granted in 1999 to start disposal of waste from the US defence programmes at the Waste Isolation Pilot Plant (WIPP), in south-eastern New Mexico. The waste to be disposed contains significant long-lived radioactive components, although high-level, heat-generating wastes are excluded. The waste is being placed in caverns excavated at depth of 650 m below ground in a bedded salt formation. The first shipment of waste was placed in the repository on 26 March 1999, making this the first operating, purpose-built, deep geologic repository for long-lived wastes in the world.

Programmes for the geologic disposal of long-lived waste appear to be most advanced in the United States and Scandinavia.

- In the United States, comprehensive surface-based investigation have been completed, and access and experimental tunnels have been constructed at 350 m below ground, at the Yucca Mountain site in southern Nevada. A comprehensive “Viability Assessment” was submitted to Congress in December 1998. It is expected that a site recommendation will be made in 2001 and, if Yucca Mountain is recommended as the national repository site, that a license application could be made in 2002.
- In Finland, one local community has agreed to host a national repository and a governmental siting “decision in principle” should be made in the year 2000.
- In Sweden it is planned to start investigations at two sites a few years into the 21st century.

Programmes in Belgium, France and Japan are on track but remain far from implementation.

In some other countries, setbacks have been experienced or there is uncertainty about the future of geologic repository projects.

- In Canada, an independent panel reporting to the government on its review of the concept of geologic disposal of nuclear fuel waste concluded in 1998 that, from a technical perspective, the safety of the concept had, on balance, been adequately demonstrated. The panel also observed, however, that, at this stage, the concept had not been demonstrated to have broad public support and did not, in its present form, have the required level of acceptability to be adopted

as Canada's approach for managing nuclear fuel waste. In particular, organisational reforms and fuller consultation processes were recommended.

- In Germany, the investigation of the suitability of a large salt dome at Gorleben to house a repository for all kinds of wastes, including used nuclear fuel and high-level waste, is well advanced, and vertical shafts have been sunk to 960 m depth. However, the present federal government in Germany has declared the intention to end nuclear power production and to re-evaluate options for long-term waste management. Whereas the eventual need for deep disposal facilities is acknowledged, there is considerable uncertainty in timing and in the political attitude to progressing with disposal projects.
- In the United Kingdom the rejection in 1997 of the planning application for the construction of a rock characterisation facility at Sellafield, as a step towards the possible development of a deep repository, left the United Kingdom with no practical plan for the disposal of long-lived radioactive waste. A subsequent inquiry by a Select Committee of the Parliament upper chamber has since endorsed geologic disposal as both feasible and desirable, while noting that public acceptance is required. As in Canada, widespread consultation and organisational reforms are recommended.
- In Switzerland, the proposal to develop a geologic repository for low and medium level waste at Wellenberg was rejected in a public cantonal referendum. The option of resubmitting the proposal with a modified design and implementation process is being considered.

Chapter 5

PROSPECTS AND CHALLENGES

Summary

Substantial progress during the past ten years has strengthened the confidence of the waste management community in geologic disposal as the most appropriate option for the disposal of long-lived wastes. Although there is a need for continuing high-quality scientific and technical work, the technology for constructing and operating repositories is mature enough for deployment.

The slow progress in implementing this technology may be partly attributable to an earlier technical optimism, e.g. related to the difficulties of geological characterisation and developing adequate understanding of real sites. In addition, the burden of regulatory compliance – demonstrating with a high degree of confidence that very challenging safety standards will be met over long times into the future, and ensuring adequate traceability and transparency in the demonstration – has only become apparent as programmes enter the phase of developing specific proposals, and submitting them for regulatory examination.

More significant are the setbacks that have arisen mainly from an underestimation of the political, public and regulatory dimensions of disposal projects. The public does not, in general, share the high level of confidence of the scientific and technical community.

Confidence in decision making for geologic repository development requires confidence in the technical safety case, in the ethical, economic and societal aspects of the appropriateness of geologic disposal, and in the organisational structures, legal frameworks and regulatory review processes.

It is increasingly recognised that a phased approach to planning, licensing and implementation, which recognises public aversion to large irreversible steps, provides a way forward that should strengthen public and political confidence in the safety of a disposal facility, in the competence of the regulators and the implementers, and in the appropriateness and acceptability of the decision-making process.

Options such as long-term storage and partitioning and transmutation may be components of an overall management strategy, but they do not remove the need for some final disposal route.

Confidence in scientific, technical and regulatory aspects

Substantial scientific and technical progress towards implementation of geologic disposal has been made during the past ten years, resulting from extensive work in national and international programmes. In spite of the setbacks that have occurred, and although some countries have delayed their repository siting programmes or questioned the wisdom of a selected location, no nation has rescinded its decision to pursue geologic disposal.

The confidence of the waste management community in the concept and feasibility of geologic disposal has been enhanced by:

- the improved understanding of safety-relevant processes through site characterisation and research, including work in underground laboratories and on natural analogues;
- the development of detailed repository concepts in many countries;
- the demonstration of the safety of repository concepts through the application of rigorous performance assessment methods;
- independent reviews of these assessments by national and international groups of experts;
- the development, and in some cases demonstration, of technologies necessary for implementation of deep geologic repositories.

However, while the technology is well developed, there is a need for continued high-quality scientific and technical work, including further refinement of the basic concepts, testing, demonstration, implementation, monitoring and quality control. Further research is needed to reduce

uncertainties, characterise a wider range of sites and geological formations, optimise and improve the economics of site characterisation, and facilitate the application of existing knowledge to new geologic media, waste streams and disposal concepts. These challenging tasks will probably extend over decades. The following sections summarise future challenges and possible trends in a number of areas.

Site characterisation

Further development is needed of measurement techniques that do not perturb the characteristics of the rock being studied. For countries approaching a systematic siting process, such as Canada, electronic tools for geological mapping and methods for integrating data from remote sensing and land-based sources are priorities. Other areas requiring further work include:

- understanding the possible effects of infrequent, but highly-transmissive pathways for radionuclide transport;
- determining infiltration and groundwater recharge (e.g. in the case of the Yucca Mountain Project in the United States);
- the influence of gas generated in the repository on the barrier properties of the host formation;
- characterising naturally occurring colloids;
- quantifying the effects of organic matter as complexants for migrating radionuclides;
- assessing the effects of natural and induced changes to the geosphere;
- establishing those characteristics of the site that are relevant to the optimisation of repository design.

Underground rock laboratories

The emphasis of research in generic underground rock laboratories is shifting from basic feasibility studies and the accumulation of fundamental geological data towards optimisation of methodologies and testing of key performance-assessment models. Most work at site-specific underground laboratories is aimed more directly at modelling of system performance at that location. Plans are being developed for full-scale demonstration experiments on

engineered-barrier systems for high-level waste and spent fuel. This may reflect the increased emphasis being placed on the engineered barriers in some performance assessments.

Performance assessment

Future work on performance assessment, on which the technical safety case is based, is likely to include:

- studies of sorption of radionuclides on canister corrosion products, which may contribute significantly to the safety of some repository concepts, but is not, as yet, supported by sufficient data to be included quantitatively in performance assessments;
- further consideration of climatic and geological events and changes, following some advances in the quantitative assessment of the impact of climatic, volcanic and seismic events on system performance;
- the treatment of coupled phenomena (thermal, chemical, mechanical and hydrological), that may affect, for example, the characteristics of the backfill, and also influence its long-term performance;
- further work on the impact of gas generated by repository materials, including waste, on system performance;
- further work on the potential for the enhanced transport of radionuclides by colloids.

Whereas progress in these various aspects will obviously help to build confidence in the safety of a repository, the question arises as to when that confidence is sufficient. A degree of uncertainty is inevitable in any quantitative evaluation of repository performance, particularly over very long time periods of hundreds of thousands or millions of years. It has therefore become increasingly recognised that a performance assessment in which there is overall confidence must be built on both of the following principles:

- The repository system must exhibit intrinsic robustness with respect to safety which is achieved through simple but robust design features, and suitable siting, i.e. the long-term performance must be relatively insensitive to uncertainties in the characteristics of any specific components.

- The performance assessment must exhibit the required degree of quality and reliability. This can be achieved, for example, through the use of well-tested, performance-assessment models and databases traceable to verifiable measurements that incorporate conservative assumptions where there is uncertainty.

When advanced, more complex engineering systems are proposed to provide additional assurance and safety, consideration will have to be given to whether the extra safety margins which should result from such systems compensate for the additional uncertainties in evaluating their behaviour and their interactions with other system components. One example of such a problem is the use of a complex, multi-component engineered barrier system, including composite containers, specially treated bentonite buffers and intermediate layers of other materials, for wastes emplaced in a saturated environment. Such a design must be weighed against designs with simpler physical and chemical behaviour.

Natural analogues

Observations of natural analogues play an important role in enhancing confidence since such systems have evolved over extremely long time periods. The main thrust of future work on natural analogues is likely to be on more quantitative comparisons of model predictions with observations, and the better integration of natural analogues into performance assessments. There are plans in the USA to use supporting data from natural analogues during the licensing and subsequent phases of repository development, for example from further studies at Pena Blanca, Mexico. Observations of archeological artefacts can be used to demonstrate the durability of some of the materials used in the engineered structures of a repository. Studies of copper and steel, bentonite and various types of cement and concrete have strengthened confidence in the ability of these materials to provide long-term containment under repository conditions.

Co-disposal

In some countries, repository design concepts have broadened to include disposal of HLW together with spent fuel and possibly other long-lived waste streams. The range of different waste types considered has increased to include wastes which may have been in store for many years and wastes from decommissioning programmes. In the United Kingdom, for example, there is

now an active programme to recover, condition and encapsulate waste from early nuclear research programmes, and in the United States there is a massive programme aimed at dealing with the nuclear and chemical wastes resulting from over 50 years of nuclear weapons production and nuclear research, some of which may need disposal in a HLW repository. In the United States there is also a need to treat and dispose of surplus weapon materials resulting from reducing the nuclear arsenal.

Regulatory aspects

An important basis for confidence is the establishment of stable national policy and legal frameworks which set out the decision-making processes over the long time scales associated with the development of geologic disposal. Such frameworks exist in several countries, e.g. Finland, France and the United States, but, at this stage, are less clear in some other countries. The 1997 Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, developed under the administration of the IAEA, may give added impetus to the establishment of national policies where these are not already in place.

Achieving civil society's confidence

Opinions expressed by a wide cross-section of waste management experts confirm the consensus view that, at present and for the foreseeable future, geologic disposal represents the only truly available option for ensuring safety and security over several tens of thousand years and more.

In recent years, however, the waste management community has become acutely aware that technical expertise and confidence are insufficient, on their own, to justify geologic disposal as a waste management solution to a wider audience, or to see it through to successful implementation. Partly due to public sensitivity on all matters connected with protection of the environment, nuclear power and especially nuclear waste, and partly because of the required longevity of the disposal concept, a decision on whether, when and how to implement geologic disposal needs a thorough public examination and greater public involvement in decision making.

The acceptability of a long-term management strategy such as geologic disposal has ethical, economic and political as well as technical dimensions and can only be decided at a societal or government level, after consultation with a

range of relevant organisations and taking account of public views. Confidence in the ethical, economic and societal aspects of the appropriateness of the geologic disposal concept cannot be achieved in isolation, but requires a review of the concept within a wider context, including evaluation of other possible strategies.

The judgement must be taken with a broad view of the options, but must also take practical constraints into account. In no society will a complete consensus ever be reached. Ultimately, governments are responsible for making decisions that meet with an appropriate level of public support and providing the framework within which the necessary actions can be taken.

In addition to confidence in the technical safety case, as judged by decision-makers within implementing and regulatory organisations, implementation of geologic disposal also requires:

- public confidence that the organisational structure, legal framework and regulatory review process provide a well-defined, logical and credible decision-making path;
- confidence, on the part of the wider technical community and the public, in the social and ethical aspects of the appropriateness of the geologic disposal;
- confidence in the availability and adequacy of funding for all stages of disposal.

The phased approach to planning, licensing and implementation

The planning, technical development and associated research, siting, construction and eventual licensing of a geologic disposal facility is expected to take place over a period of several tens of years. It has long been recognised that during this period there will be a phased, incremental development of a safety case for the repository as the design is refined, the understanding of safety-relevant phenomena is developed, and data are accumulated.

It is now increasingly recognised that the decision to commit resources to each stage of repository development should be accompanied by an appropriate level of confidence in the safety case. Phased development of the facility and its safety case also provides an opportunity for a phased regulatory and societal review process. Discrete, easily overviewed steps facilitate the traceability of decisions, allow feedback from regulators or the public and promote the

strengthening of public and political confidence in the safety of a facility and trust in the competence of the regulators, as well as the implementers. The increased confidence that comes with a phased approach can also, to some extent, derive from observations of system behaviour over longer time periods.

Confidence in decision making for repository development

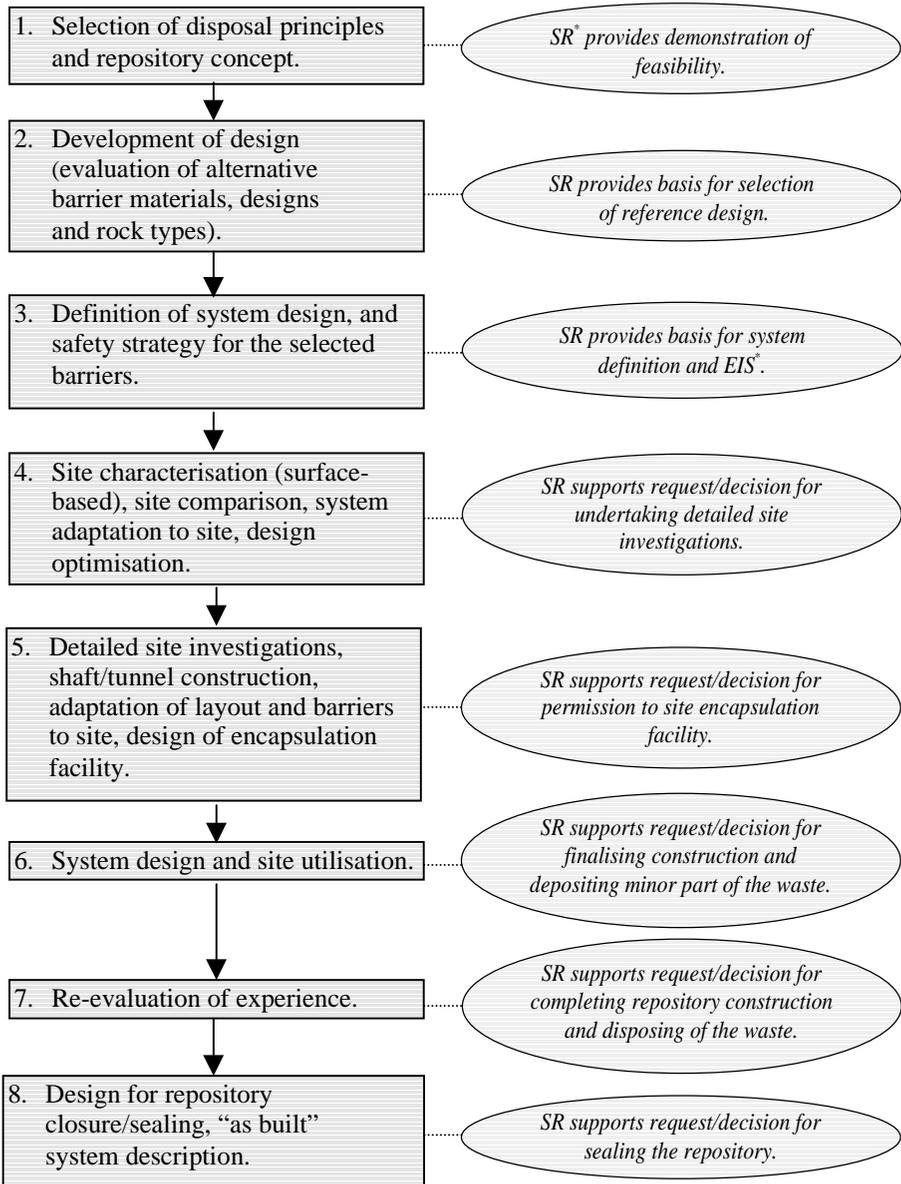
Confidence in decision making for repository development rests on these basic elements:

- general agreement regarding the ethical, economical and political aspects of the appropriateness of the underground disposal option;
- confidence in the practicality and long-term safety of disposal (including safety case and statement of confidence);
- confidence in organisational structures, legal and regulatory framework for repository development, including agreement on development stages.

The phased approach can also be applied to the operation of the facility, with progress towards the final configuration, with all waste in place and the repository sealed in such a way as to provide maximum passive safety, being implemented in a staged or flexible manner which postpones steps that are difficult to reverse. In Sweden, for example, it is proposed to dispose of only 10% of the spent nuclear fuel wastes, initially, and then pause for a number of years in order to evaluate the experience gained and monitor the emplaced waste. In other countries, the possibility of emplacing waste, but delaying the final backfilling or closure of the underground tunnels, has been considered (e.g., in Switzerland, the United Kingdom and the United States). This creates an underground store from which wastes could relatively easily be retrieved, if necessary, but could also be easily closed when and if that decision is taken.

The overall approach is illustrated in the diagram, which shows the sequence of events envisaged in Sweden.

The incremental process of developing a deep repository system (an example from Sweden)



* SR = Safety report; EIS = Environmental impact statement.

The phased approach reflects the clear public aversion to large irreversible steps. In Switzerland, for example, a prime reason for the negative result of a public referendum at the Wellenberg site was that the public would have preferred to give an initial permit only for the construction of an exploratory tunnel, rather than directly for the final repository.

An open, phased, regulatory review process, led by a respected regulator, has the advantage that the implementer's proposals are subject to detailed technical scrutiny on behalf of the public. At certain key milestones, more direct public consultation may be required. This may include widespread consultation with national organisations on matters related to strategy, full discussion with directly affected communities and their representatives when considering developments at a specific site, and parliamentary debate in order to judge progress to date and make specific forward-looking decisions.

Reversibility and retrievability

An important message that the waste management community has problems in getting across is that waste would never be placed in a underground facility if safety were in question and, furthermore that the geologic disposal concept is reversible. Reversibility can be an aim throughout waste management:

- wastes should not, as far as possible, be conditioned into a form which precludes taking advantage of future technological developments;
- sites should not be definitively nominated until options have been explored;
- designs should not be frozen too soon;
- commissioning, operation and closure of a repository should all be in small steps each of which allows commitments to be fully considered.

Reversal of the entire disposal process by retrieving previously emplaced wastes is perhaps the most challenging and contentious issue. At a practical, technical level easy retrievability can conflict with maximal isolation; in the area of disposal economics, planning for possible retrieval leads to the need for financial provisioning for subsequent alternative disposal technologies. Nevertheless, in view of the increasingly widespread desire to keep future

options open, there is a corresponding increased interest in evaluating retrievability.

The degree of difficulty and the cost involved in retrieving waste safely from a repository depend on the details of the disposal concept, including the materials that are used. In the United Kingdom and Switzerland, for example, the low strength of the cement-based backfill material referred to above may facilitate retrievability, should this be required.

For long-lived waste, governments in the Netherlands, France and the USA have either recommended, or require consideration of, retrievability or reversibility (for a limited time after emplacement). Implementers in countries like Sweden, Switzerland, Canada and the United Kingdom have read the signs given by the public and politicians, and have themselves built in features assuring longer term retrievability than originally envisioned. The periods explicitly considered run through the whole operational period and over a period of the order of a hundred of years beyond.

The predominant technical view, however, remains that disposal implies emplacement without intention to retrieve, and that allowing for retrievability must not be allowed to compromise the long-term performance of a repository. Retrieval is currently judged to be an extremely unlikely scenario, and the implications of doing so would have to be weighed against the benefits when a decision on whether or not to retrieve is being taken.

The question of reversibility and retrievability, with its ethical, sociological, security, safety, economic and technical aspects, certainly represents, in the words of the EC respondent to an NEA questionnaire, “an issue which has aroused increased attention” in recent years, and it would justify a clear statement of its implications by the international community.

Social issues

The social issues raised when considering geologic disposal demand that the public be as fully informed as possible about the issues at stake and take the greatest possible part in the decision-making process. While ultimate responsibility for public and political affairs lies with society and government, waste management specialists must be willing to engage in activities at the interfaces of technical, public and political affairs, and to recognise that the ensuing exchanges must be two way. That is, technical specialists must give

information on practical requirements, constraints and options, but also listen to, and attempt to satisfy, public and political concerns, which may include non-technical issues.

An example of societal involvement in decision-making relates to the implementation of long-term institutional controls, including protection of the site and monitoring. Although geologic disposal is conceived as a passively safe arrangement, with no requirement for long-term control, the concept does not preclude monitoring and maintenance of a repository by this and future generations. It is up to the implementers of disposal to ensure that any such measures that may be needed are in place and functioning satisfactorily, but it will be up to future societies to decide whether and for how long such measures should be maintained. These actions can certainly enhance confidence, but a key objective of geologic disposal is to ensure that even if such controls were to fail, human health and the natural environment would still be protected.

The level of public consultation which should be built into the development of policy or the decision-making path is a matter for national consideration. All countries should be aware, however, that the debate on radioactive waste and other environmental issues is becoming increasingly internationalised. Scientific and public debate will occur in international fora, whether or not provision is made within national frameworks, and such debate has the capacity to affect national views.

There is, internationally, a heightened awareness of the wider context of waste disposal. Discussions in and around national and international bodies point to the need to give greater attention to issues such as sustainability, which is a much larger societal question that requires a comprehensive look at energy production and use, as well as at waste disposal and treatment.

Ethical concerns

Geologic disposal addresses the ethical concern that the generation that has benefited from nuclear power and other uses of radioactivity should provide a means for the safe and permanent disposal of the resulting waste. This is the principle of inter-generational equity. More recently, an equally valid ethical concern has been raised that this generation should not foreclose options to future generations, or hinder their ability to make decisions. It has been suggested, by some critics, that geologic disposal limits the choices open to future generations. Those engaged in waste management, on the other hand, point out that there is an overriding need to ensure the availability of a passively

safe solution that does not place a burden of care on future generations, and that a phased repository development process keeps options open for very long times.

There also exists an issue of intra-generational equity, in particular the need for society to identify an ethical approach to the handling of resources within current generations, and to public involvement in the decision-making process. Thus, when considering resource allocation, expenditure on ensuring the safe disposal of radioactive wastes should be kept in perspective with competing projects in the area of human health and environmental protection. Also relevant in this context is the consideration of equity and fairness for communities which are judged to be affected by the construction and operation of a centralised national facility such as a geologic repository.

The predominant views among the waste management community remain as expressed in the 1995 Collective Opinion of the NEA Radioactive Waste Management Committee, in which the Committee members:

- confirm that the geological disposal strategy can be designed and implemented in a manner that is sensitive and responsive to fundamental ethical and environmental considerations;
- conclude that it is justified, both environmentally and ethically, to continue development of geological repositories for those long-lived wastes which should be isolated from the biosphere for more than a few hundred years;
- conclude that phased implementation of plans for geological disposal leaves open the possibility of adaptation, in the light of scientific progress and social acceptability, over several decades, and does not exclude the possibility that other options could be developed at a later stage.

Economic issues

There is continuing growth in the application of the "polluter pays" principle to the funding of waste management. This requires that the costs of managing radioactive waste, including final disposal, are met by the organisations whose activities produce it. The principle was incorporated in Swedish legislation in the 1970s and, more recently, in the Swedish Financing Act of 1992 and the financial reforms of 1996. The United States has long had a system by which a fee is levied on nuclear electricity to fund the work done by

the Department of Energy on management of commercial wastes from reactors. Germany, Canada, Hungary and the Czech Republic have all joined the extensive list of countries which already have the principle legally anchored. In other countries, such as Belgium and Switzerland, formal governmental measures have been taken to assure that sufficient funding is available to close the back end of the fuel cycle.

A recent EC study, however, has found considerable divergence in the financing schemes adopted by different countries. These fall into one of two categories: those which rely on a levy on electricity generation, and those which rely on payments based on the characteristics of the waste. Each individual scheme, however, has unique characteristics. The EC study found that there were three criteria against which all schemes should, in principle, perform well – financeability, fairness and efficiency – but that there were, in practice, some contradictions between these that made it impractical to formulate an ideal system.

Overall, the study concluded that all the countries studied had established funds which aimed to provide adequate funds for future radioactive waste management. In general, schemes based on an electricity levy gave the best assurance of the availability of money when it was needed but tended to give the least efficient economic signals. Schemes which took account of different characteristics in setting tariffs for different types of waste tended to be fairer but more complicated to operate than those based on a single parameter such as volume. All the countries studied were found to have adopted a very cautious investment policy.

The search for other management options

For long-lived waste, the concept of deep geologic disposal offers a solution that is both safe and resistant to malicious intervention. The concept does not preclude monitoring, maintenance and reversibility/retrieval, but these are principally measures to enhance confidence and should not be required to ensure safety. Similarly, society may choose to use long-term institutional controls as a management tool but, even if such tools were to fail, human health and the natural environment should still be protected.

Geologic disposal thus represents a waste management end-point providing security and safety in a manner that does not require monitoring, maintenance and institutional controls. Despite the confidence in geologic disposal on the part of the waste management community, there is, nevertheless,

a continuing pressure to identify and assess other possible management routes which may be more politically and socially acceptable.

Several exotic disposal routes were fairly extensively studied in the seventies and are no longer the subject of serious consideration, at least within the waste-management community. Sub-seabed disposal has also been evaluated (e.g. in the PAGIS study of the EU) and found to be promising from the point of view of safety, but implementation would depend on international acceptance and development of an appropriate international regulatory framework. Currently, most countries would interpret their obligations under the London Dumping Conventions as precluding the disposal of nuclear waste under the seabed.

The most common management alternatives currently raised in public debate on waste disposal, as well as by implementers and regulators striving for completeness in the range of options considered, are extended or indefinite storage and partitioning and transmutation of long-lived radionuclides in wastes. However, although these options may be components of an overall management strategy, and extended storage over a few decades is already planned in some countries, neither can be regarded as complete alternatives to disposal.

In France, legislation requires that disposal, storage and transmutation are studied in parallel, and in the Netherlands underground repositories must be designed in such a way that waste can be retrieved if this is deemed necessary at some future time. The recent review of the Canadian programme by an independent panel recommended a study of options for spent fuel management other than the geologic disposal concept that was the subject of the review.

Extended surface storage

In virtually all countries, some period of interim surface storage to allow decay of radiation and heat generation has always been recognised to be necessary or valuable. This interim storage is often at a centralised location, but can also be at individual facilities. The choice of location may reflect political and social acceptance problems more than technical or economic developments. Storage differs from disposal in that monitoring, maintenance and institutional controls are necessary to maintain the safety and security of a storage facility.

More extended storage has been accepted as unavoidable because of delays in implementing disposal for both HLW and spent nuclear fuel. There are, in addition, arguments that favour extended (though not indefinite) surface storage:

- Postponement of disposal is advocated by some scientists and decision-makers who believe that more time is needed to prove the geologic disposal concept more completely and/or to allow public confidence to increase. Sweden, for example, is explicitly looking at the “zero option” of continued surface storage, in order to allow a broad-based comparison of options for the next decades, in response to public interest and Swedish legislative requirements.
- Electrical utility waste producers are under increasing economic pressures, due to the opening of the electricity supply market. Storage may be attractive for some utilities, largely because it can postpone large investments in expensive repositories. Whether the storage route is more economic on the intermediate timescale also depends on financial considerations such as whether utilities are required to establish segregated funds for future disposal facilities.
- Increased reserves of uranium ores and decreased demand for recycled fissile materials have tended to make direct disposal of spent fuel more attractive. However, the fuel still represents an energy resource and, particularly in an age of sustainability, it can be argued that long-term storage keeps this resource easily available. Of course, other arguments concerning non-proliferation of fissile materials can lead to the conclusion that this availability is not a positive feature.

Indefinite storage, though advocated by some outside the waste-management programmes, is not considered to represent a real alternative to deep geologic disposal, partly because indefinite human surveillance of such a storage site cannot be guaranteed, with inevitable safety implications. Continued surface storage therefore appears to be rationally viewed not as a solution, but only as a postponement of disposal. Continuing investment in the construction, long-term monitoring and periodic replacement of surface stores when there is a suitably safe and acceptable disposal route would divert resources that would be more cost-effectively spent on disposal. In some countries the continued storage of wastes on the surface is viewed as presenting low, but not insignificant, risks that can be avoided by placing the wastes in a more stable environment, deep underground.

Partitioning and transmutation

An approach which has been claimed to have the potential to change the future of geologic disposal is partitioning and transmutation (P&T). The process involves two stages. The first is to separate the long-lived radionuclides in the waste from those which have shorter half-lives and therefore do not present as serious a challenge to the isolation capacity of repositories. The second is to transmute the separated radionuclides by converting them into shorter-lived radionuclides, generally by neutron bombardment in a nuclear reactor or an accelerator. The potential advantage of this approach is that it reduces the need for very long-term isolation of the wastes. However, complete conversion would require many stages of separation and transmutation, which would in turn give rise to other types of risk.

P&T is being actively studied in Japan, Spain, France and the United States and (in a minor research-oriented way) in Belgium, Germany and Sweden. P&T approaches are in the early stages of development. Most of the work is analytical and prototype research with the intent to evaluate the merit of further development. P&T may be an option for well-characterised, concentrated wastes, but is unlikely to be a practical option for the treatment of heterogeneous wastes with dispersed contamination. Pressure to devote efforts to this subject often appears to come from government or advisory levels rather than from the technical radioactive waste-management community. The most pronounced expressions of technical attitudes towards P&T come from the United States and the EC, which do not view the technology as a replacement for geologic disposal. At best, it provides a disposal inventory with less long-lived radionuclide content.

Chapter 6

THE INTERNATIONAL DIMENSION

There has been a growing realisation over the past few decades that the safe management of wastes that could pose a threat to the environment or human health is seldom purely a national problem, since pollution is no respecter of frontiers. This clearly applies to atmospheric pollutants like sulphur dioxide and nitrogen oxides, to some gaseous and liquid discharges of radioactive effluents and to materials released in extreme accidents such as Chernobyl. There is no possibility, however, of radioactive material from the geologic disposal of radioactive waste reaching the surface more than a few tens of kilometres from the repository, even after very long periods, so no trans-boundary problems are likely to occur unless the repository is sited very close to a national frontier. The time-scales involved in geologic disposal, however, are far longer than the periods for which national frontiers are likely to remain stable.

Nevertheless the issue of geologic disposal does have some international dimensions. One relates to the possibility of developing international repositories, another to the transport of spent fuel for reprocessing in another country and the return of the resulting waste for eventual disposal in a national repository. While such transport has resulted in some protests and public concern, there is a comprehensive system of national and international transport regulations, designed to ensure that any associated risks are minimised, and experience indicates that a very high level of safety is being achieved.

The way geologic disposal programmes are planned and implemented depends primarily on the national situation – the legal and regulatory framework, cultural considerations, the available geological settings and the inventories of radionuclides in the waste. Each country will have its own approach to the development of procedures and methods, to the training of staff and to funding. International contacts, the international exchange of ideas and experience, and co-operative programmes such as underground laboratory,

natural analogue and other technical projects can, however, contribute significantly to the progress of national programmes.

International repositories

The most direct way in which geologic disposal may become a significant international issue would be in the context of an international repository, available for the disposal of waste from a number of countries, which has been discussed in some circles. The quantities of waste needing geologic disposal, particularly from countries with small or no nuclear power programmes, are small enough to make the concept of one repository serving several countries attractive in principle. The idea may well be attractive to countries which lack the resources needed for a proper disposal project (e.g. some of the former East Block states) and to those with difficult geological or environmental situations. The studies that have been carried out suggest that there are unlikely to be any significant technical or economic obstacles to the development of an international repository. However, the ethical and political problems associated with siting and the likely public opposition to accepting another country's waste are expected to pose major obstacles, at least in the near future.

The sharing of insights and resources in co-operative projects has proved valuable to legislators and regulators, as well as implementers, by:

- demonstrating the wide consensus that exists at the technical level;
- helping to optimise the use of technical and financial resources;
- clarifying the understanding of key concepts in repository development;
- ensuring that the process of repository development is transparent, and perceived to be so, by those outside the waste-management community;
- rationalising differences between national regulatory guidelines;
- working towards harmonisation of regulatory requirements across different types of environmental risks.

The role of international organisations has been discussed in Chapter 2. The activities of the NEA, especially of the Radioactive Waste Management

Committee, have led a gradual building of confidence among OECD Member countries, and others, in the scientific understanding of waste disposal processes, and in the evaluation of the performance of disposal systems based on this enhanced scientific understanding. A characteristic feature of the NEA's work on radioactive waste management has been its support for the discussion of technical, policy, and strategic issues in fora which include policy makers, regulators and implementers. Such fora are likely to continue to play an important role in the future for all those involved in waste management and also in communicating to wider audiences. Of particular importance have been the Collective Opinions organised and published by the NEA – an extensively cited series of international documents which have made a major contribution to the debate on geologic disposal.

All of these international activities of the NEA, especially the expression of a common opinion which reflects the views of policy makers, regulators and implementers, are expected to continue to play a vital role in radioactive waste disposal.

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