The disposal of radioactive waste is a major issue in the nuclear debate. This report provides a concise and accessible overview of the methods available for evaluating the long-term safety of radioactive waste disposal systems, particularly those to be built in deep geological formations.

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DISPOSAL OF RADIOACTIVE WASTE:

REVIEW OF SAFETY ASSESSMENT METHODS

NUCLEAR ENERGY AGENCY

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DISPOSAL OF RADIOACTIVE WASTE:

REVIEW OF SAFETY ASSESSMENT METHODS

A Report of the

Performance Assessment Advisory Group
of the Radioactive Waste Management Committee
OECD Nuclear Energy Agency

NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

Paris, 1991

Pursuant to Article 1 of the Convention signed in Paris on 14th December 1960, and which came into force on 30th September 1961, the Organisation for Economic Co-operation and Development (OECD) shall promote policies designed:

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- to contribute to sound economic expansion in Member as well as non-member countries in the process of economic development; and
- to contribute to the expansion of world trade on a multilateral, non-discriminatory basis in accordance with international obligations.

The original Member countries of the OECD are Austria, Belgium, Canada, Denmark, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The following countries became Members subsequently through accession at the dates indicated hereafter: Japan (28th April 1964), Finland (28th January 1969), Australia (7th June 1971) and New Zealand (29th May 1973). The Commission of the European Communities takes part in the work of the OECD (Article 13 of the OECD Convention). Yugoslavia takes part in some of the work of the OECD (agreement of 28th October 1961).

The OECD Nuclear Energy Agency (NEA) was established on 1st February 1958 under the name of the OEEC European Nuclear Energy Agency. It received its present designation on 20th April 1972, when Japan became its first non-European full Member. NEA membership today consists of all European Member countries of OECD as well as Australia, Canada, Japan and the United States. The Commission of the European Communities takes part in the work of the Agency.

The primary objective of NEA is to promote co-operation among the governments of its participating countries in furthering the development of nuclear power as a safe, environmentally acceptable and economic energy source.

This is achieved by:

- *encouraging harmonisation of national regulatory policies and practices, with particular reference to the safety of nuclear installations, protection of man against ionising radiation and preservation of the environment, radioactive waste management, and nuclear third party liability and insurance;*
- *assessing the contribution of nuclear power to the overall energy supply by keeping under review the technical and economic aspects of nuclear power growth and forecasting demand and supply for the different phases of the nuclear fuel cycle;*
- *developing exchanges of scientific and technical information particularly through participation in common services;*
- *setting up international research and development programmes and joint undertakings.*

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

FOREWORD

The management of radioactive waste and, in particular, the safety assessment of radioactive waste disposal systems, are areas of high priority in the programme of the OECD Nuclear Energy Agency. Although a general consensus has been reached in OECD countries on the use of geological repositories for radioactive waste disposal, analysis of long-term safety, using performance assessment and other tools, is required prior to implementation. In response to this need, recent national and international programmes have significantly improved the quality of performance assessment methods.

In October 1989, nearly 300 scientists attended a major symposium on the safety assessment of radioactive waste repositories organised by the OECD/Nuclear Energy Agency in co-operation with other international agencies with active programmes in the area of radioactive waste management: the Commission of the European Communities (CEC) and the International Atomic Energy Agency (IAEA). The proceedings of this symposium were published recently by OECD/NEA. They provide an authoritative description of the scientific and technical state-of-the-art in the field of long-term performance assessment. They form the main basis for this report which reviews for a wider audience the current status of development in this area.

Presentations at the symposium confirmed the confidence of the scientific community in the safety of repositories for the disposal of radioactive waste. Areas of uncertainty and debate in the performance assessment field were recognised, and will be the subject of further research. This effort will help to refine performance assessment methods, and improve the underlying foundation on which such methods are based.

This report is published under the responsibility of the Secretary General of the OECD and it does not in any way commit the countries of the OECD.

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EXECUTIVE SUMMARY

Engineered disposal systems are necessary to isolate radioactive waste from humans and the environment. Such systems have generally been built at or near the surface for low-level and short-lived wastes, and are widely envisaged to be built deep underground in geological formations for high-level and long-lived wastes. These systems, commonly referred to as repositories, are designed to ensure that the risks for harmful release of waste to the environment are so low that they are acceptable to the regulatory authorities and the public. This report is concerned with the methods available to assess the safety of engineered disposal systems for radioactive waste. Its main objective is to present a concise summary of performance assessment methods and their uses within radioactive waste disposal programmes.

The General Approach

The long-term safety of any hazardous waste disposal system must be convincingly shown prior to its implementation. For radioactive wastes, safety assessments over timescales far beyond the normal horizon of social and technical planning have already been conducted in many countries. These assessments provide the principal means to investigate, quantify, and explain the long-term safety of a selected disposal concept and site. A safety assessment consists of a number of interrelated elements, each of which is thoroughly documented:

- broad identification of the possible future evolution of the selected disposal system. This process is called scenario development;
- development and application of appropriate models;
- evaluation of potential radiological consequences in an integrated assessment;
- uncertainty and sensitivity analyses;
- validation and review of all components of the assessment; and
- comparison of the results with criteria.

Feedback between these elements and iteration through the full set of elements are important aspects of safety assessment.

Although wide international consensus exists on this general approach, it is important to note that different specific techniques are being used depending upon the purpose of an assessment and the type of safety criteria to be met. In addition, the models and data being used for safety assessment differ depending upon waste-specific, concept-specific, and site-specific conditions. Finally, identification and characterisation of the wastes to be disposed of, and of the disposal system as a whole, are necessary bases for meaningful safety assessment.

Scenario Development

Scenario development, the starting point for safety assessments, is concerned with defining the broad range of possible futures to be considered in the subsequent modelling and consequence calculations. Human imagination and scientific judgement coupled with existing knowledge of natural systems and man-made barriers form the basis of scenario development. Over the last few years, scenario development methods have been substantially improved by the use of approaches that are systematic and transparent. Extensive lists of phenomena (for example, faulting, seismicity, or erosion) that have to be initially considered in safety assessments have now been developed, and only a few new phenomena have been identified as potentially important in recent years, and these on a site-specific or concept-specific basis.

One particular area that has received greater attention recently is assessment of human intrusion scenarios. Work on the basic approach for consideration of human intrusion, and on the preservation of information about the site and the content of the repository is being undertaken.

If required by regulation or otherwise undertaken, the estimation of the likelihood of occurrence of the final set of scenarios chosen for detailed consequence analyses can be a particularly difficult element of safety assessments. Although several different techniques are used, depending on the type of future events and processes being considered and the data available, all of them rely at least to some extent on the use of expert judgement.

Model Development and Application

The necessity of using predictive models to assess potential radiological consequences in safety assessments is well recognised, and the general procedures for development of models are well accepted. Predictive models have been developed for the more important aspects of waste isolation systems. Substantial improvements toward more realism and detail have been made over the years. There are models available, at different levels of detail and realism, to evaluate and quantify the effects of the key processes determining the performance of radioactive waste disposal systems. Further development is still justified in some areas because better modelling could clarify or reduce uncertainties associated with assessment results. It could also contribute to further improvements in disposal system design.

In recent years, special attention has been given to the interdependence between model development and corresponding data gathering efforts. In addition, a

main area of ongoing work is the coupling of models for specific processes into larger integrated models and the simplifications needed to make them practical tools for safety assessments. A sound basic understanding of the relevant physical and chemical properties of the system's constituents and their evolution remains a main prerequisite for successful modelling.

Integrated Assessments

The ultimate goal of data gathering, scenario development, and predictive modelling is an integrated assessment describing the characteristics of the disposal system and quantifying the performance of the overall system in terms of radiological safety as a function of time. Several integrated assessments of high-level waste conceptual repositories in various host formations have been made over the years. Licensing assessments for low-level waste (near-surface and deep repository) facilities have also been completed. Results from these assessments suggest that it is possible to site and build repositories that can be considered safe for the human environment today and in the future.

Safety assessment models tend to be of two complementary types: detailed research models and simplified system models. The detailed research models and their results are needed to evaluate design and engineering options, and are used to provide a defensible basis for excluding processes not important to safety in the simplified system models. Simplified system models may be used to conduct a more robust or bounding analysis. In the robust bounding approach, scenarios, models, and parameter values are chosen conservatively (that is, pessimistically). Thereby, the assessments are simplified and discussion of some uncertainties not significant to system safety are avoided in the licensing procedure.

Uncertainty and Sensitivity Analysis

Uncertainties are, and always will be, associated with assessment results. Uncertainties can be partly reduced by additional model development and by collecting additional and more accurate data. However, uncertainties will persist reflecting the variability in present and possible future states of systems. Statistical methods are being increasingly relied on when extensive measurements of the needed data are not feasible. In some cases uncertainties can also arise from a limited understanding of controlling processes.

As part of integrated safety assessments, sensitivity studies provide guidance on which areas uncertainties most need to be reduced. This guidance is specific with regard to disposal site and concept, and is being used to direct national resources for research and development to areas where they are most needed. In addition, the information on uncertainties is being provided to those responsible for repository design, enabling possible improvements to the design and siting of the repository.

Confidence Building

The ultimate objective of safety assessments is to provide a basis for well-founded decisions about radioactive waste disposal systems. To this end, it is necessary that scientists, safety assessors, regulators, and those involved in or concerned with the decision-making process have confidence in the information, insights, and results provided by safety assessments. The importance of this topic is reflected in the main text, and only a few additional remarks concerning model validation are given here.

Model validation is the process of assuring that models adequately represent real system behaviour; efforts in this area have been intensified during recent years. Validation of long-term predictions must focus on the adequacy of modelling the processes that may define system performance under a reasonable variety of possible futures. There is no way to validate system performance predictions over long times, but the adequacy of specific aspects of modelling may be supported through a variety of laboratory, field, and natural analogue studies. Several international co-operative projects have been established to investigate the possibilities for validation of the models used within safety assessments.

Validation needs depend upon the disposal concept. For some concepts, satisfactory validation can be done only with the help of in situ studies at the potential disposal site. Increasing co-operation is apparent between those designing the repository and the relevant engineered barriers, and those studying the possibility of validating the models to be used in assessing the safety of the disposal system.

Regulatory Criteria for Disposal

In a final licensing assessment, the results of safety assessments are evaluated in the context of the established regulatory standards and criteria. International criteria for the radiological protection of individuals and populations have been used as the basis for development of national long-term safety criteria for radioactive waste disposal systems in practically all countries. Some countries currently have detailed regulations in place for radioactive waste disposal, whereas others have specified general radiological protection objectives, without necessarily having established specific requirements for final disposal of wastes. Both on a national and an international basis, further work is underway to develop specific criteria for the long-term safety of radioactive waste disposal systems, in particular in order to have such criteria available in due course for the licensing of high-level waste repositories.

The details of safety assessment approaches, methods, and data requirements are dependent upon and influenced by the detailed criteria applied. Yet even where the detailed formulation of specific safety standards may differ between countries for legal or historical reasons, it is evident that the same general type of safety assessment work is needed and is undertaken at some stage of the regulatory process.

The safety of a waste disposal system is judged, therefore, only after a clear presentation of the information obtained in an integrated assessment, after due consideration of the uncertainties associated with assessment results, and after a critical review by the regulatory authorities and others involved in the decision-making process. In view of the need for critical reviews by regulators and others, the need for a clear presentation of safety assessment results, as well as underlying assumptions, data bases, and modelling approaches is evident. This challenging task is being addressed, largely through the experience that is being gained from the presentation and publication of assessment results in scientific conferences and symposia, and from expert reviews of documents describing preliminary assessments in detail.

Conclusion from the report "Disposal of Radioactive Wastes - Can Long-Term Safety be Evaluated?" OECD/NEA, Paris 1990.

The NEA Radioactive Waste Management Committee and the IAEA International Radioactive Waste Management Advisory Committee have carefully examined the current scientific methods for safety assessments of radioactive waste disposal systems, as briefly summarised in this report. The Committees have also reviewed the experience now available from using safety assessment methods in many countries, for different disposal concepts and formations, and in the framework of both nationally and internationally conducted studies, as referenced in this report. Following this review, the NEA Radioactive Waste Management Committee and the IAEA International Radioactive Waste Management Advisory Committee

- **Recognise that a correct and sufficient understanding of proposed disposal systems is a basic prerequisite for conducting meaningful safety assessments,**
- **Note that the collection and evaluation of data from proposed disposal sites are the major tasks on which further progress is needed,**
- **Acknowledge that significant progress in the ability to conduct safety assessment has been made,**
- **Acknowledge that quantitative safety assessments will always be complemented by qualitative evidence, and**
- **Note that safety assessment methods can and will be further developed as a result of ongoing research work.**

Keeping these considerations in mind, the two Committees:

- **Confirm 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; and**
- **Consider that appropriate use of safety assessment methods, coupled with sufficient information from proposed disposal sites, can provide the technical basis to decide whether specific disposal systems would offer to society a satisfactory level of safety for both current and future generations.**

This Collective Opinion is endorsed by the CEC Experts for the Community Plan of Action in the Field of Radioactive Waste Management.

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1. INTRODUCTION

This chapter describes the purpose and scope of the report and provides definitions of performance and safety assessment.

1.1 THE PURPOSE AND SCOPE OF THIS REPORT

The focus of this report is on the different elements of performance assessment and their integration into overall assessments of the safety of radioactive waste disposal systems. The report has three principal objectives:

- to present a concise, clear, and up-to-date summary of performance assessment methods;
- to underline the degree of international consensus on performance assessment activities and methods; and
- to provide an overview of the most important aspects and uses of performance assessment to a non-specialised audience.

This report is divided into six chapters. Chapter 2 consists primarily of background information on the generation and disposal of radioactive waste. It provides the non-specialist with an understanding of the sources of radioactive waste, the waste types produced in the nuclear fuel cycle, and the basic principles of waste disposal systems. Chapter 3 provides a summary of the approach and roles of performance assessment and safety assessment methods. It presents information neccessary to understand the general considerations affecting the performance assessment task and its role in the development of a repository programme. Chapter 4 discusses the analytical and methodological tools used to conduct safety assessments. These tools are used to understand disposal system behaviour and to assess the effects of events and processes that might affect the system during its lifetime. This chapter includes sections on scenario analysis, modelling, data requirements, consequence calculations, and uncertainty analysis. Chapter 5 discusses measures that can be taken to assure that safety assessments address relevant issues and provide results that can be used as a basis for decisions. These measures are discussed in four areas: verification and validation of models; quality assurance; critical review; and, international co-operation. Chapter 6 discusses the expected development of performance assessment methods and their use. It also outlines the expected focus of research needed to improve assessments.

This report does not discuss the safety or acceptability of particular waste disposal systems or practices. However, reference is made to studies of the safety of radioactive waste disposal in order to illustrate how the assessment methods have been applied in integrated assessments, and their results. The report deliberately excludes judgement on the non-technical issues that help form the basis for decisions on radioactive waste disposal policies.

1.2 WHAT ARE PERFORMANCE AND SAFETY ASSESSMENTS?

In simple terms, performance assessment is an analysis to predict the performance of a system or subsystem, followed by comparison of the results of such analysis with appropriate standards or criteria. A performance assessment becomes a safety assessment when the system under consideration is the overall waste disposal system and the performance measure is radiological impact or some other global measure of impact on safety. Thus, performance assessment can be used to describe the analysis and comparison of systems at a variety of levels and requirements while the term safety assessment is normally reserved for the overall system and its impact. It is important to note that safety assessment is not just a calculational framework for producing numerical predictions of system behaviour. Performance and safety assessment are to be understood as a broad activity aimed at the following major goals:

- developing a sufficient understanding of the physical and chemical behaviour of a disposal system;
- quantifying this understanding in order to allow predictions of future system behaviour;
- assessing the uncertainties in the predictions; and
- convincing all relevant groups (project staff, regulators, and the public) of the adequacy of the analyses.

The intent of this report is to provide the reader with an understanding of the performance assessment methods used to help ensure the safe disposal of radioactive waste. This report covers a range of methods or tools that can be used for such assessments. For some types of radioactive waste, use of the full range of tools addressed in this report may not be necessary.

This report draws heavily on the results of an International Symposium held in October 1989, as well as scientific and technical work previously presented and reviewed at the international level, notably within expert groups and committees of the CEC, IAEA and OECD/NEA. Performance assessment has evolved considerably over the last ten years and this report reviews the progress made to date. At the same time, it is important to recognise that although this report represents the state-of-the-art upon entering the 1990s, performance assessment is a discipline which will continue to improve through the development, testing, and application of what has been learned so far.

2. THE GENERATION AND DISPOSAL OF RADIOACTIVE WASTE

This Chapter provides background information on the generation and disposal of radioactive waste. It is intended to give the non-specialist an understanding of the sources of radioactive waste, the characteristics of the wastes produced in the nuclear fuel cycle, and the principles of waste disposal systems. This knowledge will be valuable for understanding the methods used to evaluate the safety of radioactive waste disposal systems. Although details of the waste type and disposal system are important in the evaluation of individual disposal systems, they are not necessary for a basic understanding of performance assessment methods.

2.1 SOURCES OF RADIOACTIVE WASTE

Radioactive waste is generated from the use of nuclear material in a wide variety of applications. These applications include the generation of electricity and heat, use within industry and research, and medical diagnosis and treatment. A flow chart depicting these applications and the generation of waste is shown in Figure 1. In countries with nuclear energy programmes, the majority of waste is generated by

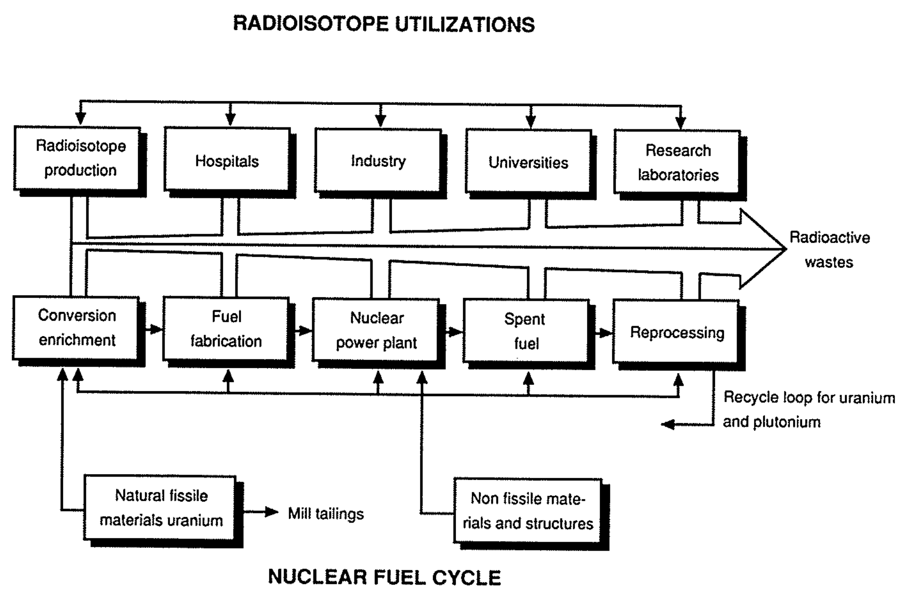

Figure 1: Radioactive wastes are generated in the nuclear fuel cycle and from the use of radioisotopes in hospitals, industry, and research. Spent fuel can enter the waste stream directly or it can be reprocessed to recover uranium and plutonium.

power plant operation and fuel reprocessing. In a few countries, radioactive waste is also generated from the production of nuclear material for weapons. It is recognised that the waste produced from these different applications must be managed and disposed of in an environmentally safe manner.

2.2 RADIOACTIVE WASTE PRODUCTION IN THE NUCLEAR FUEL CYCLE

This report is primarily concerned with radioactive wastes produced in the nuclear fuel cycle. The nuclear fuel cycle is a term used to describe the activities necessary for the production and use of uranium as a fuel source. Radioactive waste from the nuclear fuel cycle is generated during: (1) the mining of uranium ore and the preparation of the ore for use as fuel in a nuclear reactor; (2) operation of the reactor; and (3) reprocessing and recycling of the used fuel or management of spent nuclear fuel elements.

The radionuclides in waste from mining operations and from initial fuel preparation arise from naturally occurring radioactive elements. These radionuclides, present in the original ore body, consist primarily of uranium and the elements formed from its radioactive decay.

A wide range of radionuclides are generated during reactor operation. Some of these, such as plutonium, do not exist in any substantial amounts in the natural environment. During reactor operation, nuclear reactions occur in the fuel, the materials comprising the core of the reactor, and in the cooling agent that is circulated through the reactor core. The radionuclides generated from those reactions follow one of four possible paths:

- they may decay within the nuclear plant;
- they may be released directly into the environment if produced in environmentally insignificant quantities;
- they may be recycled if the spent fuel is reprocessed in the preparation of new nuclear fuel (uranium and plutonium); or
- they may be placed in interim controlled storage and must eventually be disposed of as radioactive wastes.

After a period of reactor operation, spent fuel is removed and either stored or reprocessed. The spent fuel, if defined as waste, and the highly radioactive wastes produced in reprocessing plants are called high-level wastes. The volume of high-level waste is a fraction of the total radioactive waste generated in the operation of nuclear power plants and reprocessing facilities.

2.3 CHARACTERISTICS OF RADIOACTIVE WASTES

In general, there are three characteristics of radioactive waste that determine its potential hazard and thus the way it is managed and classified. The first characteristic is the activity level of the radioactive material which is typically measured in becquerels or disintegrations per second. For a given material, the higher the activity level the greater the potential hazard. The amount of heat generated by the material is the second characteristic of concern. High-level waste disposal systems are designed to account for the heat emitted by the waste. The third characteristic of concern is the half-life, or the time it takes for the material to lose half its radioactivity. More than a hundred different radionuclides are generated during reactor operation. Their half-lives vary from less than a second to millions of years. In general, if the half-life is greater than 30 years, the element is considered to be long-lived. Box 1 shows a common qualitative description scheme for categorising radioactive wastes.

Box 1. A common qualitative description scheme for categorising radioactive wastes.

- Low-Level Wastes (LLW) generally contain negligible amounts of long-lived radionuclides. They are produced by nuclear activities in industry, medicine, research, and in nuclear power operations. LLW include items like packaged gloves, rags, glass, small tools, paper and filters which have been contaminated by radioactive material. Uranium mill tailings are exceptional in containing several long-lived radionuclides.
- Intermediate-Level Wastes (ILW) contain lower levels of radioactivity and heat content than high-level wastes, but must still be shielded during handling and transport. Such wastes may include resins from reactor operation or solidified chemical sludge, as well as pieces of equipment or metal fragments.
- High-Level Wastes (HLW) are generated by the reprocessing of spent fuel from nuclear power reactors to recover uranium and plutonium. These wastes contain transuranic elements, and fission products that are highly radioactive, heat-generating, and long-lived. Before final disposal and isolation from the biosphere, they require treatment and solidification. Spent fuel that is not reprocessed is also considered a high-level waste.
- Alpha-Bearing Wastes (also called transuranic or plutonium- contaminated material) include wastes that are contaminated with long-lived, alpha-emitting nuclides. They arise principally from spent fuel reprocessing and mixed-oxide (plutonium) fuel fabrication.

2.4 EXAMPLES OF DISPOSAL SYSTEMS FOR RADIOACTIVE WASTE

Disposal system design is dependent, among other things, upon the waste characteristics. For example, low-level waste consisting primarily of short-lived nuclides that generate an insignificant amount of heat, may in many countries be disposed of near the Earth's surface. After a few hundred years the radioactivity in the waste will have decayed to levels that no longer present a hazard to humans. It has been judged reasonable to assume that monitoring and access restrictions, or institutional control of these disposal sites, can be maintained for that amount of time. An example of a low-level waste disposal facility is shown in Figure 2.

High-level wastes present a different problem because initially they may generate a large amount of radiation and heat. Although the radioactivity of the waste declines over time, as depicted in Figure 3, a higher degree of isolation is necessary. To provide this isolation from the human environment, these wastes can be disposed of deep, i.e. several hundred metres, within the earth in geological formations. A concept for such a system is shown in Figure 4. In this case, emphasis is placed on stable, remote, and passive disposal systems. These systems will ensure the long-term integrity and safety of the wastes, and can be designed to be independent

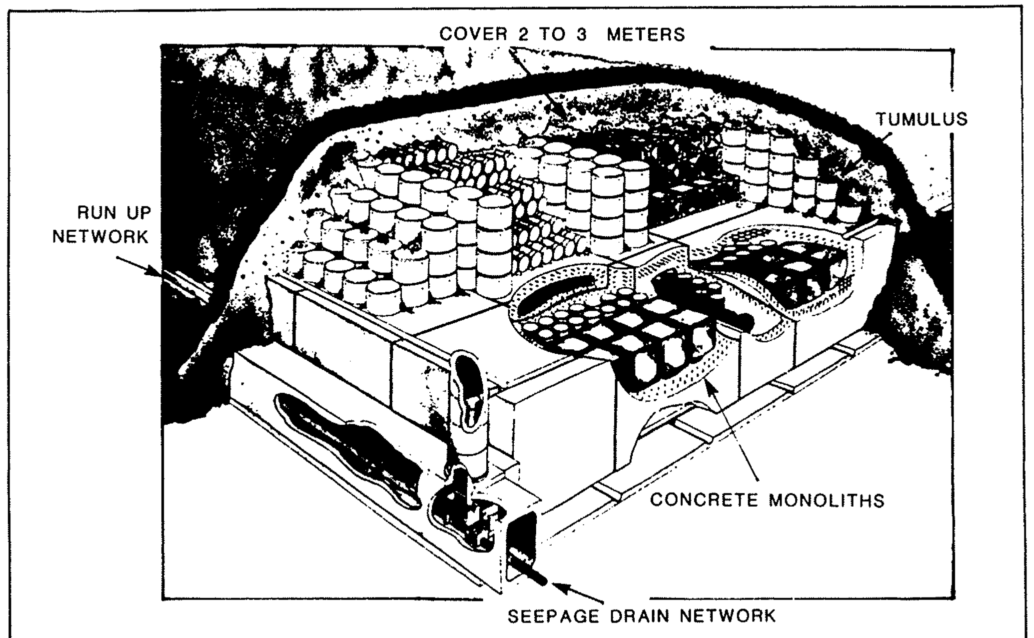

Figure 2: France's first surface repository for low-level waste, the "Centre de la Manche", has been in operation since 1969 in a 12 hectare area located at the western tip of the Cotentin Peninsula, close to the La Hague reprocessing plant. The total capacity of this centre is about 500 000 m3 of waste and up to now, it has received about 400 000 m3 of waste. The French plan to start operations at a new disposal facility, Centre de l'Aube in north-eastern France, by early 1991. The disposal capacity will be 1 million m3 of waste.

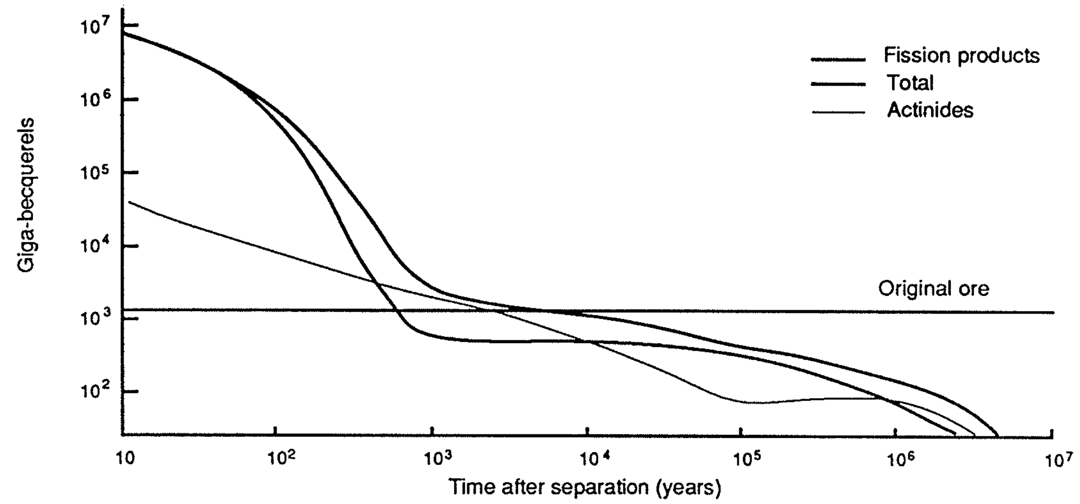

Figure 3: The radioactivity of high-level waste declines steadily over time, most dramatically over the first few hundred years. Eventually, the radioactivity level will be lower than that of the natural uranium ore from which the spent fuel originally came. The graph shows the levels of radioactivity in waste products per one tonne of fuel.

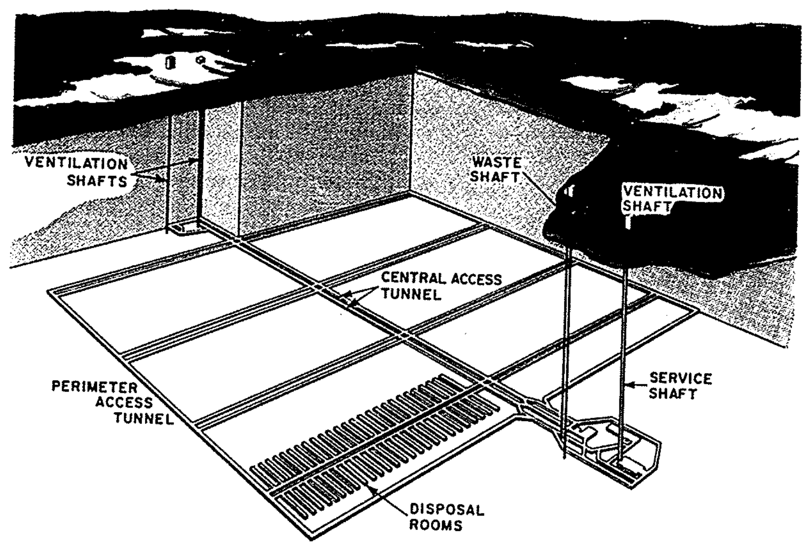

Figure 4: The Canadian concept for permanent nuclear fuel waste disposal is to bury the suitably packaged waste 500 to 1000 metres deep in stable rock in the Canadian Shield. A network of underground tunnels and disposal rooms about two kilometers square would hold 190,000 tonnes of used natural uranium fuel.

Box 2. Tentative Schedules for some HLW Repository Programmes

Country	Geological Formation	Planned Start of Disposal Operations	Remarks
BELGIUM	CLAY	~2025	Underground research laboratory in operation since 1983 at ~200m depth in the boom clay underlying the Mol Centre.
CANADA	CRYSTALLINE ROCK	>2010	Underground research laboratory in operation since 1985 at 240-400m depth in crystalline rock at Lac du Bonnet, Winnipeg.
FINLAND	CRYSTALLINE ROCK	~2020	Preliminary site investigations including deep drilling performed at several sites
FRANCE	SEVERAL OPTIONS	~2010	Geological investigations at four different sites (clay, salt, crystalline rock, shale) 1987-1989. Deep drilling operations pending outcome of independent review of radioactive waste programme.
GERMANY	SALT	~2008	Site investigations underway since 1979 at the Gorleben Site. Two shafts are now being sunk into the salt dome formation. The final results of the underground investigations are expected by the end of the 1990s.
SWEDEN	CRYSTALLINE ROCK	~2020	Geological investigations (including deep drilling) at several sites during the 1980s. Underground research at the Stripa mine since 1977. A new deep hard rock laboratory at Oskarshamn is now under construction.
SWITZERLAND	CRYSTALLINE ROCK OR SEDIMENTS	~2020	Geological investigations in northern Switzerland including seven deep (~1000m) drill-holes into the crystalline basement. Underground research since 1984 at the Grimsel Test Site in the Swiss Alps
UNITED STATES	TUFF	~2010	Geological investigations previously performed in several types of formations. Site investigations are now to focus on investigations at Yucca Mountain, Nevada. Site access is expected in 1991. A ten year site characterization phase is planned prior to license submittal.

of institutional controls after final closure. Some of the geological repositories currently under consideration are listed in Box 2.

It is possible to use deep geological disposal for all types of radioactive wastes, including low- and intermediate-level waste. Deep disposal of low-level waste would remove the need for institutional control measures to ensure disposal system safety.

Although the use of institutional control for deep geological disposal has not been excluded, it is thought that such control should not be relied upon to provide safety into the far future.

2.5 THE DESIGN OF MULTI-BARRIER CONTAINMENT SYSTEMS

All land disposal concepts in use or under serious consideration rely on containment systems. These systems are designed to operate long enough to ensure that any subsequent release to the human environment will be compatible with accepted radiation protection criteria. Containment systems consist of a number of interrelated, often redundant barriers between the waste and the human environment. This disposal concept is referred to as a multi-barrier system and an example for high-level waste is shown in Figure 5.

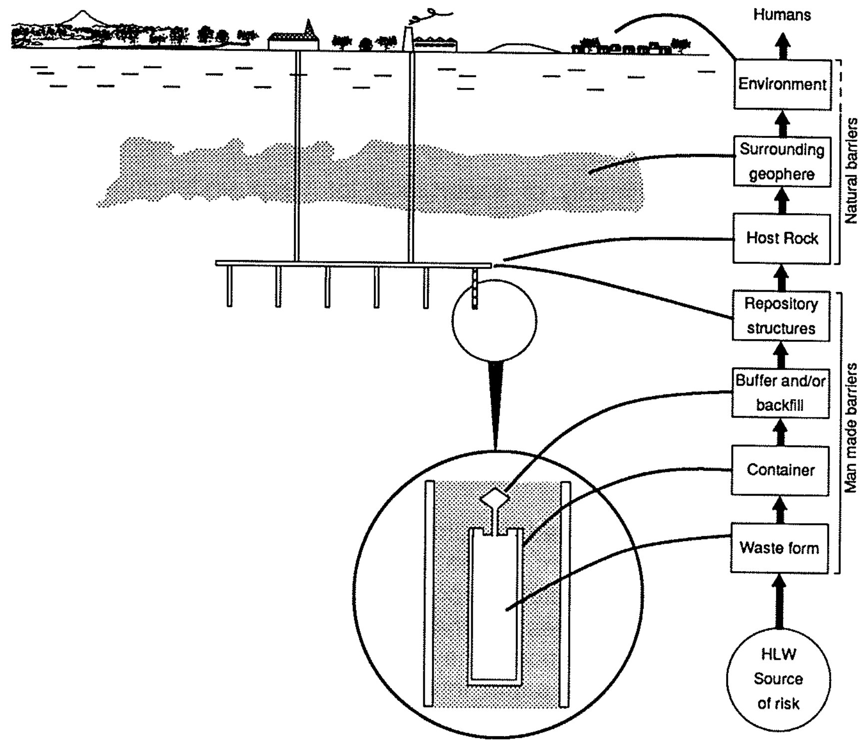

Figure 5: In the case of high-level waste, the waste form acts as the first barrier to radionuclide migration. This is important during the period immediately after disposal when the radioactivity and heat generation is still high. If the container fails, the waste matrix may undergo a leaching process which initiates the radionuclide migration toward the subsequent barriers: the backfilling and/or structural materials of the repository, the host rock and the surrounding geosphere where most radionuclides are strongly retained or delayed until their almost complete decay. The radionuclides which succeed in reaching the biosphere may be dispersed or diluted before coming in contact with humans. Due to this sequence of barriers, it is expected that exposure to humans can be kept below acceptable levels.

In multi-barrier design the details of the individual barriers may differ from one disposal system to another, but the purposes of the individual barriers remain basically the same. The multi-barrier system is described below.

- The first barrier is the waste package, consisting of the waste form in a container. The waste form can be designed to be resistant to leaching by groundwater, the primary agent for transport of radionuclides from the waste to the human environment. For example, in the case of high-level wastes, the waste form could be a special glass matrix containing immobilised radionuclides. The container in which the wastes are placed can also act as a barrier if it is constructed of materials resistant to the chemical and physical environment expected in the waste repository.

- The repository's engineered barrier consists of backfill material (e.g. clay) placed around the waste containers. It can also consist of materials used for backfilling of drillholes, access shafts, and tunnels in the repository. The backfill inhibits the movement of water within the repository and may provide a chemical environment that reduces the solubilities of many radionuclides thus serving to retard their transport.

- The final barrier, primarily of importance for deep underground disposal of high-level wastes, is the geological structure of the repository site. The geological barrier isolates the waste from the human environment and provides a chemically and mechanically stable environment for the repository. It prevents or restricts the access of circulating groundwater. Finally it serves to retard the transport to the biosphere of any releases of radionuclides.

2.6 PLACING RADIOACTIVE WASTE IN PERSPECTIVE

The potential hazard presented to humans by radioactive waste arises from the radionuclides contained in them. The emission of ionising radiation from the radionuclides is potentially harmful. Exposure to ionising radiation may occur as a result of the intake of radionuclides by inhalation, if they are in the form of a gas or an airborne particulate, or by ingestion if they are present in food or drinking water. In these respects, they have the same intake and exposure routes as many other hazardous substances. Only the additional route, that of direct exposure of the body to external radiation is unique to radionuclides. The potential consequences of exposure to radioactive materials can also be compared to those from other hazardous materials. For many of these substances and for radioactive materials, the most important potential effect is the induction of cancer in humans.

Radioactive waste disposal systems are designed for operation long into the future. As a result, the regulatory, social, and political dimensions of this challenge have been widely debated. In many cases, the conclusions reached and the technical and

methodological advances achieved can influence the handling of a much broader challenge currently facing society. That challenge is the safe and final disposal of highly toxic hazardous wastes. The result of one survey to determine the relative volumes of radioactive and hazardous waste is shown in Figure 6.

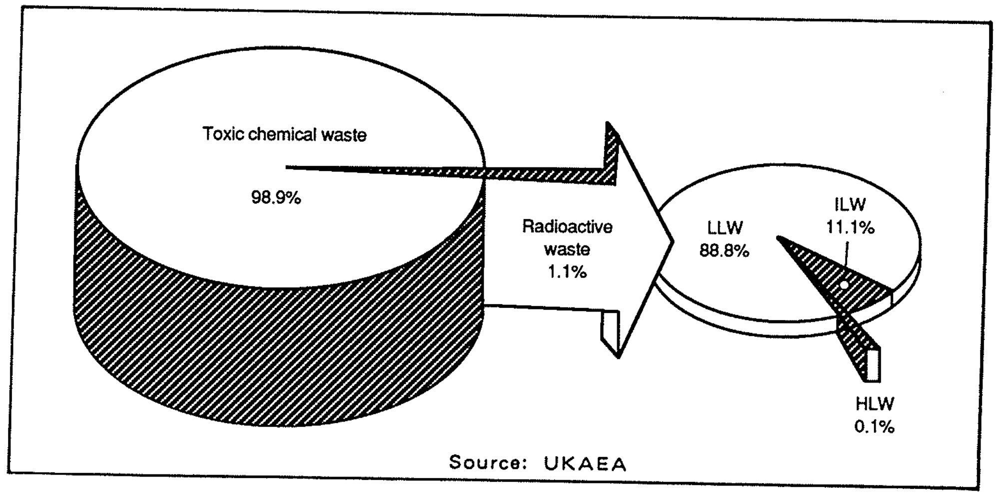

Figure 6: In the United Kingdom each year, more than 4 million cubic metres of toxic waste are produced. 1.1 % of this amount is radioactive waste. Of this fraction, most of the waste contains low levels of radioactivity.

3. THE FUNDAMENTALS OF PERFORMANCE ASSESSMENT

This Chapter contains background information on the approach and roles of performance and safety assessment methods. It will provide an understanding of the general considerations affecting performance assessments and their use in the development of repository programmes.

3.1 THE APPROACH TO PERFORMANCE ASSESSMENT

Some radioactive waste will present a potential hazard to humans and the environment for a long period of time. To help assess this hazard, predictive models that can describe the future behaviour or performance of disposal systems are needed. In the case of short-lived, low-level waste, assessments need to extend for several hundred years. For high-level and other long-lived wastes, the potentially hazardous lifetime can be tens of thousands of years or more. Assessments that cover this length of time require models and information that can adequately describe the disposal system and its possible evolution. Much of this needed information can be obtained from field investigations at potential repository sites and from laboratory testing.

In general, there is wide consensus regarding the overall approach to safety assessment. This approach includes broad procedures for developing and using models, as well as for performing and reviewing safety assessments. The general approach to safety assessment includes the interrelated steps listed below.

- The wastes that require disposal need to be identified and characterised. This step is necessary to help determine the general system design and requirements, and to provide data needed for safety assessments. As previously discussed, the activity level, heat generation, and the half-lives of the elements in the waste will influence the system requirements.

- The potential repository site must be identified and characterised. Site characterisation is done in stages using different techniques (e.g. testing and sampling from boreholes) for investigation of geology, groundwater flow, and water chemistry.

- The engineering design for the repository must be specified. This process will consider the characteristics of the waste, the engineered barrier, and the repository site.

- The main processes determining the release and migration of radionuclides from the waste to the human environment have to be identified. This includes the interactive processes between the waste, the barrier materials, the natural geological medium, the biosphere, and humans, for the range of external circumstances that can reasonably occur.

- The behaviour and evolution of the disposal system must be studied. This can be done through the identification of scenarios and the use of mathematical models that simulate repository behaviour in response to future events.

- The disposal system's overall behaviour has to be evaluated. This step ties all the various aspects of the previous steps together and documents the safety of the repository in terms of the potential radiological consequences and, as far as possible, their likelihood of occurence.

- The assessment result has to be compared with the design goals and the regulatory criteria. The acceptability of the waste disposal system can be determined only after considering the uncertainties associated with the performance assessment results.

Although wide international consensus exists on this general approach, the purpose of the assessment and the safety criteria required determine the specific techniques used. In addition, the models and data used for safety assessment differ depending upon waste-specific, concept-specific, and site-specific conditions.

3.2 MODELS AND DATA ARE CRITICAL TO PERFORMANCE ASSESSMENT

Calculational models are the primary tool of the performance assessor. They are derived from an understanding of how disposal systems might function and evolve. This understanding can be translated, normally after some simplification, into a system of mathematical models. The mathematical models can then be embedded into computer codes to provide numerical values of possible system performance.

These models are based on fundamental physical, chemical, and mathematical principles. It can, however, be difficult to apply these principles to sites and disposal systems, which are highly heterogeneous. Here, the performance assessor must rely on specific data contributed from a range of disciplines. Confidence in the models and calculational tools used to describe a particular disposal system can then be built through testing and refinement.

The availability of directly measured data is an indispensible basis for any calculation of system performance. In this respect, the quality and breadth of the database used to test and validate models for the evaluation of disposal system performance or safety are important. Performance assessments used in support of license applications require a substantial amount of data to be collected at the proposed repository site. These site characterisations require a massive investment in earth science investigations and multi-disciplinary cooperation between scientists. Several projects to develop site investigation methods, such as the Stripa Project shown in Figure 7, are currently underway.

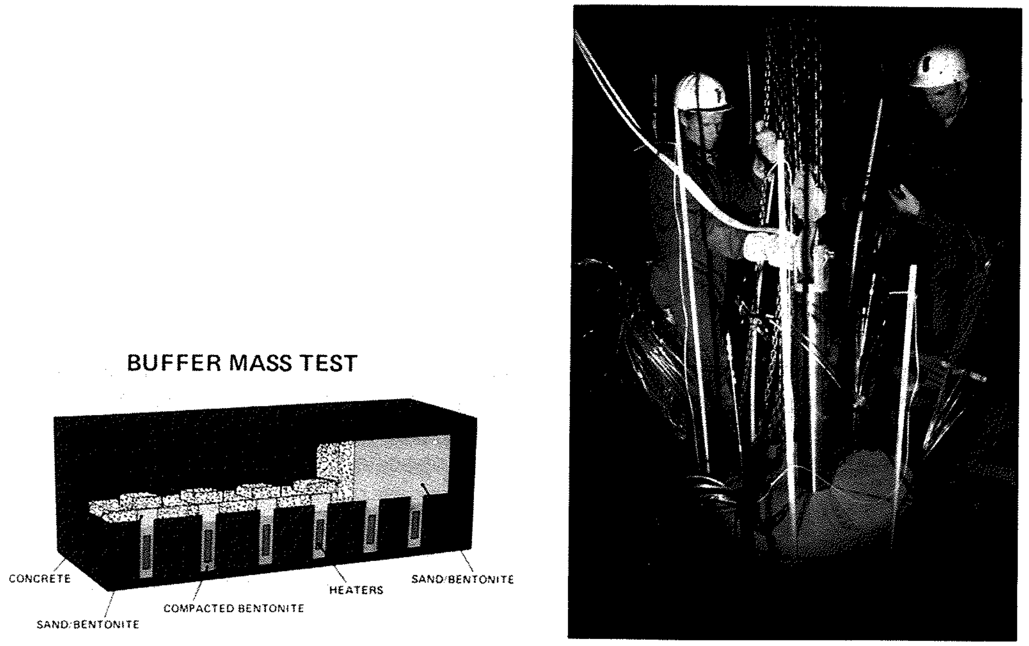

Figure 7: The Stripa Project is an in situ research project jointly undertaken by seven OECD Member countries under the auspices of NEA at an abandoned iron ore mine. SKB, the Swedish Nuclear Fuel and Waste Management Company, is the coordinating organisation for this deep hard rock laboratory. Tests at Stripa, which is not a potential repository location, were focused on geochemistry, nuclide migration, and hydrogeological characterisation. Tests included the use of bentonite clay as a buffer material as pictured above.

3.3 PERFORMANCE ASSESSMENT IS MULTI-DISCIPLINARY AND ITERATIVE IN APPROACH

The performance assessment team must interact with a wide range of scientists and understand the basics of repository design, data collection, and the development and testing of the various models of subsystem behaviour. An analysis of the waste products and their relationship to the containment system must be conducted;

information on the radionuclides, including the physical characteristics of the waste form and waste container are necessary before determining the type of engineered barriers to use and before the repository layouts are designed. Data on the geological response to excavation, heat, and radiation are collected. The processes and mechanisms of the transport of radionuclides through the geosphere to humans require investigation and understanding. The components and behaviour of systems to seal underground openings made during repository characterisation and development require study. It is therefore obvious that a large and multi-disciplinary team is needed to collect and analyse the data needed for performance assessment.

The performance assessment team must integrate all of the subsystem elements into an overall understanding of how the disposal system will behave and evolve. Such integrated modelling is the foundation of all long-term safety assessments. Integrated assessments are made using an interative process during project development. This iterative process is of particular value to the performance assessment team and those involved in the repository design and disposal system characterisation prior to licensing.

3.4 DETERMINING THE VALIDITY OF THE PERFORMANCE ASSESSMENT

Estimates of long-term system or subsystem performance are meant to be used as indicators of system performance or safety. These indicators can then be compared to the regulatory criteria established by the appropriate national and international authorities. The demonstration that possible sources of uncertainty have been systematically identified and evaluated is as important as the calculation of an indicator of system or subsystem performance. This must be done in the appropriate context, either quantitatively or, if not feasible, qualitatively.

It must be recognised that the ultimate validity of these assessments cannot, in the strict sense of the word, be proven. That is, one cannot compare the predicted and observed behaviour of the actual disposal system over the long period for which system performance has to be predicted. However, a variety of techniques are available to build confidence in the validity and conservatism of performance assessments. Such techniques are necessary to allow disposal sites to be licensed using these assessments and other tools. Measures to build confidence in performance assessment are discussed in detail in Chapter 5.

3.5 THE USE OF GENERIC AND SITE-SPECIFIC ASSESSMENTS

Performance assessment plays an important role throughout the development of repository programmes. Performance assessments are often used at an early stage to determine the feasibility of major disposal concepts. They are also used to limit the number of disposal systems studied to a reasonable set of options. The wide range

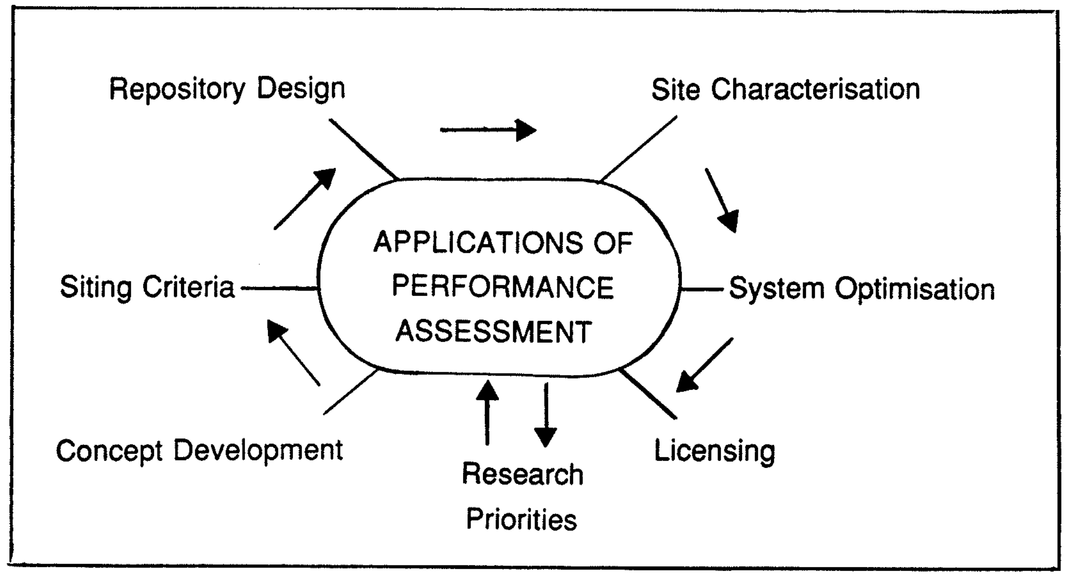

***Figure 8:** Performance assessment plays an important role throughout the development of repository programmes.*

of performance assessment applications is shown in Figure 8. This section will discuss the use of two types of assessments: generic and site-specific.

Generic system assessments are assessments that are independent of the data at a particular site. Generic assessments are able to help focus site investigations and research programmes on the most relevant issues and assist in decision-making between different disposal concepts. They are also used to demonstrate the feasibility of a particular disposal concept, and may gain acceptance for developing the concept further. Finally, generic assessments can be performed to demonstrate the use of performance assessment methods and techniques that may later be used for site selection or licensing purposes.

Generic assessments for the disposal of high-level waste have been conducted both nationally and internationally. These generic studies have shown that safe disposal of high-level waste is feasible and, on this basis, several countries are now developing disposal concepts in detail. Some of these countries have already started procedures for site-selection and investigation in preparation for the construction of deep geological repositories.

At a later stage, generic assessments are replaced by site-specific assessments. These form an integral part of the decision-making process during the siting, characterisation, design, construction, operation, and final sealing of radioactive waste disposal systems. For a particular site, an updated system assessment is often

performed at suitable intervals in order to provide input for further decisions. Such assessments are needed prior to the licensing of a particular site, to determine if further information is required for licensing purposes. The assessment will help determine what types of information should be collected. Performance assessments form an important part of the licensing documentation for disposal systems.

Site-specific assessments for licensing purposes have already been completed for several low-level waste repositories in operation or under development. In France, the United Kingdom (Drigg), and the United States there have been near-surface disposal sites in operation for several decades. In Sweden, SFR, the Final Repository for Low and Intermediate-Level Wastes built in the bedrock under the Baltic Sea, has received an operating permit. In Finland, a rock cavern repository is under construction at the Olkiluoto power plant. The regulatory review process for the Konrad mine, a deep disposal facility in the Federal Republic of Germany, is in process. In France, a new engineered surface facility for low-level wastes is being implemented at the Centre de l'Aube. In the United States, a deep repository is under development in a salt formation in New Mexico. This latter facility, the Waste Isolation Pilot Plant, is intended for alpha-bearing wastes from the U.S. defence programme.

Although many countries have initiated site-specific performance assessment programmes, there are no high-level waste disposal systems either under regulatory review or in operation. The Federal Republic of Germany and the United States have each selected a single repository site for more detailed investigation and assessment. In other countries, preliminary investigations and assessments have been undertaken at several sites. As an interim step in the process of selecting a potential disposal site for detailed evaluation. In this context, performance assessments are being used to identify critical issues requiring further study as part of the site investigation and research programmes.

Ultimately, a complete site-specific performance assessment for the licensing of a high-level waste repository will be achieved. It is thus clear that the most crucial and important application of performance assessment work still lies ahead, and that there will be further advancement and refinement of the methods over the coming years.

3.6 THE REGULATORY ASPECTS OF PERFORMANCE ASSESSMENT

During final licensing, the results of performance assessment programmes will be evaluated in terms of regulatory standards and criteria. The existing international criteria for the radiological protection of individuals and populations form the basis for the development of national long-term safety criteria for radioactive waste repositories in practically all countries. It is not obvious, however, how compliance with basic radiological protection criteria should be demonstrated for the long-term safety of repositories. The potential impact of a repository may happen far in the future and be dependent upon events that are not certain to occur. The probability in many of these cases is difficult, if not impossible, to estimate with precision.

Some countries currently have detailed regulations in place for radioactive waste disposal. Others have only general regulations. However, basic radiological criteria for waste disposal in terms of dose and risk targets do exist internationally. Work is currently underway both at national and international levels to further develop the criteria needed for the licensing of high-level waste repositories. Safety assessments for licensing a repository will be closely scrutinised by regulatory authorities, the scientific community, public interest groups, and, for certain aspects, the public.

3.7 OTHER ASPECTS OF PERFORMANCE ASSESSMENT

This report is largely concerned with the scientific task of long-term performance assessment. However, inherent limitations in predicting the future lead to the need to recognise non-technical aspects of the performance assessment challenge. Not only will qualitative judgements by experts in relevant areas of natural science and engineering need to be factored into judgements of future repository performance, but socio-economic and socio-political factors are also important determinants of the acceptability of a given disposal concept.

Continuing dialogue between specialists and generalists is essential to ensure that policy decisions are made that are both politically and socially acceptable, yet consistent with the existing state of technical knowledge. Although the assessment of the long-term performance of radioactive waste disposal systems is highly technical, the assessments and their conclusions must be clearly expressed in order to make a contribution. Improvements in the communication of risk information are required to narrow the existing gap between public, political, and scientific perception of these issues. Greater understanding will benefit both the public and the involved technical community.

4. PERFORMANCE ASSESSMENT TOOLS

This chapter discusses the analytical and methodological tools used to conduct safety assessments. These tools are used to understand disposal system behaviour and to assess the effects and processes that might affect the system during its service life. Although it is not necessary, or possible, to predict future behaviour in every detail, there is a need to understand enough to be assured that the risk of harmful releases of radionuclides to the environment is acceptably low. This understanding and its communication to regulatory authorities and the public is one of the major objectives in a nuclear waste disposal programme.

4.1 PERFORMANCE ASSESSMENT - STRUCTURE AND REQUIREMENTS

Performance assessments need to be structured and well organised. This requires the use and integration of data and mathematical models, a consideration of the effect of possible future external events, and a quality assurance process to ensure the comprehensiveness and traceability of the whole procedure.

4.1.1 Data and Mathematical Models Provide the Basis for Conducting Safety Assessments

A large amount of information is necessary for the design and assessment of a disposal system. Data must be gathered on the repository layout, the waste composition, the materials used to construct the engineered barriers, and the site characteristics. The proper collection and analysis of this information is important to both the design and assessment of a safe system.

Data is collected and interpreted according to appropriate scientific and engineering procedures and principles. These data sets and interpretations are then used to create mathematical models, which identify and describe the processes affecting the repository. Mathematical models are useful because they can help the safety assessor quantify change over the lifetime of a repository system. For example, they can be used to predict the gradual degradation or corrosion of a waste container. This information can then be used to estimate the time it takes for the container to fail and allow the waste form to interact with its immediate environment.

The safety analysis of a repository requires a scientific understanding of each part of the system. This includes a variety of aspects:

- the physical and chemical properties of the waste materials and containers (the source);

- the chemical and physical interactions and transport phenomena within the repository (the near-field);
- the chemical interactions and transport phenomena in the geological formation surrounding the repository (the far-field); and
- the effects of dispersion and/or reconcentration of any releases to the biosphere.

4.1.2 Mathematical Models of Subsystems are Integrated in the Performance Assessment Process

The performance of a waste disposal system is determined by the integrated behaviour of many interdependent subsystems. Each of these subsystems can, to some extent, be analysed separately as discrete parts of the total system. However, the ultimate goal is an integrated analysis that can quantify the performance of a repository in terms of radiological safety. A flow chart of the parts of this integrated analysis is shown in Figure 9.

Mathematical models can be used to understand and predict the relationships that exist between barrier systems. For example, groundwater from the geosphere will interact with the engineered barriers, and the heat produced by waste may influence groundwater flow, chemistry, and the mechanical properties of the geosphere. Knowledge of these and other interactions are important for an adequate understanding of the repository system. Although these relationships provide a challenge to the safety assessor, information can be gained through research, data collection, and the use of mathematical models. See Figure 10.

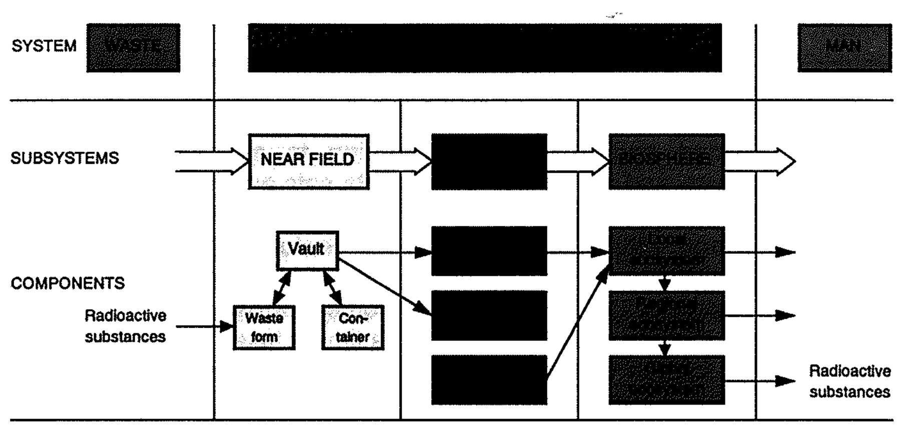

Figure 9: To understand the long-term safety of a waste isolation system, a detailed assessment of its component parts is necessary. The engineered near-field and the geosphere provide isolation of the radioactive substances. Any releases to the biosphere may be dispersed or diluted in the ecosystem before possibly reaching humans.

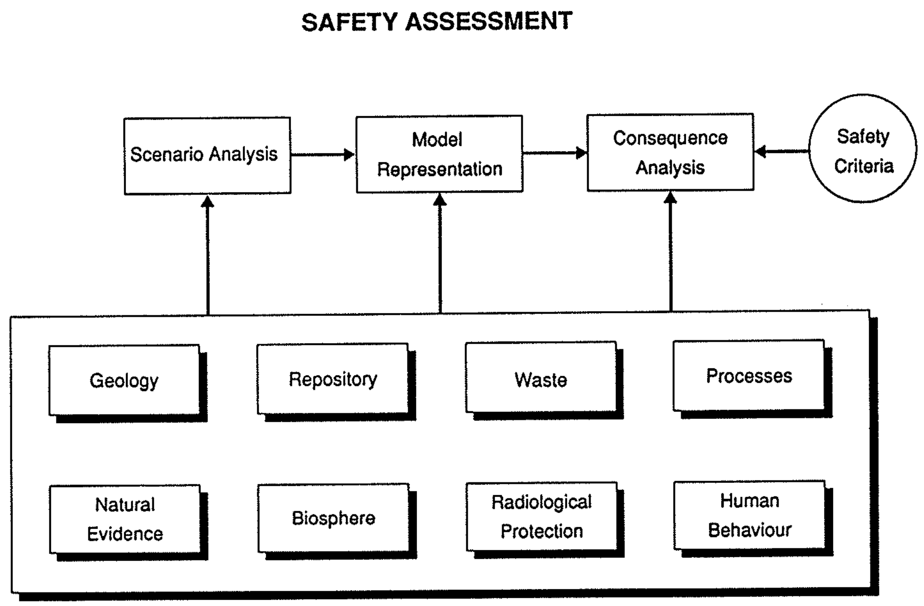

Figure 10: Integrated safety assessments of a disposal system are based upon extensive and systematic use of information from many scientific and technical areas.

4.1.3 The Effect of External Factors is Considered in the Performance Assessment Process

A performance assessment must also consider external factors that can affect the future of the repository environment. Climate changes, geological events, and human intrusion all have the potential for site impact. The different combinations of these possible future events are referred to as scenarios and their influence on disposal system performance is considered in an integrated performance assessment.

4.1.4 Quality is Vital to Performance Assessment Results and Acceptance

The quality of a performance assessment is critical to both the results and their acceptance. An assessment that is of high quality will generate confidence in technical reviewers and can expect a more favourable reception from the public. The quality of a total system performance assessment can be ensured by meeting the following conditions:

- all factors that could initiate the release of radionuclides from the waste, cause their transport through the geosphere and biosphere to humans, or influence release and transport rates, are identified;

- scenarios covering the critical combinations of the important features, events, and processes have been systematically selected for detailed assessment in characterising disposal system performance;

- the conceptual models, mathematical models, and corresponding computer codes give a correct description of the processes and their interactions at the level of detail needed for the particular safety assessment;

- the input data used adequately represent the range of actual site conditions and the repository design;

- the calculation of the consequences of each scenario and the estimate (if required) of the probability of occurrence are made sufficiently accurately; and

- the interpretation of the results, including estimates and integration of the uncertainties in scenario identification, models, and data, are defensibly made in accordance with appropriate scientific principles.

The emphasis on each of the elements varies according to the purpose of the assessment and the level of understanding required. For preliminary assessments designed to screen sites and analyse engineering options, it may be sufficient and appropriate to consider only the most likely radionuclide release and transport scenarios. In this case the probabilities and uncertainties would be considered primarily qualitatively. A full system assessment designed to provide input for final decisions on disposal sites and repository design would generally require as comprehensive and quantitative a treatment as possible.

Before accepting the calculated repository safety, the safety assessor must evaluate the uncertainties in the available data and their effect on assessment results. Reviewers must be able to assess and compare repository safety to specific goals or acceptance criteria. For the public to have confidence in the acceptance criteria, it must be evident that the criteria address factors that are relevant measures of potential detriment due to the repository.

4.2 SCENARIO DEVELOPMENT - EXAMINING THE FUTURE

Environmental changes will occur during the expected lifetime of radioactive waste disposal systems. These changes will result from natural processes and possibly through human action. Since what will happen in the future cannot be guaranteed, there is a need to account for the uncertainties. Scenario develoment, the identification and description of alternative futures that have to be assessed, is the most commonly used technique for this purpose.

4.2.1 Scenario Development is the First Step in Performance Assessment

Scenario development is a procedure to identify the features, events, and processes that require treatment by modelling and consequence calculations. Human imagination and scientific judgement, coupled with knowledge of natural systems and engineered barriers, form the basis of scenario development. Over the last few years, scenario development methods have been substantially improved by using clear and systematic approaches. Approaches to scenario development have been discussed within an NEA Working Group and some general considerations are listed in Box 3.

Box 3. Extract from the NEA Working Group report on the Identification and Selection of Scenarios for Performance Assessment of Nuclear Waste Disposal.

In summary, the group considers that a scenario development procedure should:

1) take a broad perspective;

2) provide a logical and consistent framework which can encompass alternative methodologies, models, and regulations;

3) document the reasons for analysing some scenarios in detail and rejecting others, in an understandable and traceable way;

4) allow the judgement and reasoning power of experts and generalists to be integrated with more quantitative considerations;

5) involve people with a wide variety of expertise;

6) provide a systematic way of compiling a comprehensive list of potentially important events, features, and processes;

7) result in a manageable number of representative scenarios through a well-defined screening procedure;

8) be a practical tool rather than just an intellectual framework;

9) be applicable to any type of waste repository or site;

10) provide feedback to model development, research, repository design, and site investigation;

11) be of use to regulators and developers, and be communicable to decison makers and the public.

Extensive lists of the phenomena to be considered in safety assessments have been developed. These lists, generated through a number of safety studies, provide an excellent foundation that can be modified as new phenomena of potential importance are identified. An extract from such a list is given in Box 4. Methods for constructing scenarios and system models will develop further with experience.

Scenario development is central to safety assessment for several reasons. First, scenarios provide the context in which safety analyses are performed. That is, the long-term safety of a repository cannot be analysed without considering future site conditions. Second, scenarios influence model development and data collection efforts. Finally, scenarios provide an important area of communication between repository developers, regulators, and others with an interest in repository safety.

4.2.2 Methods for Approaching Scenario Development

The scenario development methods that have been applied in safety assessments can be discussed under four main classes: (1) judgemental, (2) fault/event-tree analysis, (3) simulation, and (4) systematic.

In the judgemental method, the analyst supported by a group of experts examines the phenomena that could potentially lead to the initiation of a release and defines the conditions of possible release situations using informed judgement. The judgemental method has been used in the majority of the safety assessments reported to date.

The fault/event-tree method is a technique of traditional risk analysis and is used in reactor accident risk assessments. This method describes system behaviour as an event or series of events leading to system failure. Application of the technique yields a number of combinations of basic events whose occurrence causes system failure. These combinations of events are then evaluated by various screening techniques to determine the high risk scenarios. Although it has been used as an aid in analyses finally reported under a judgemental format, or as an integral part of a scenario development procedure, the application of the fault/event-tree analysis method to the geological isolation problem has not often been reported in literature.

The simulation approach is an attempt to set up an overall system model that can simulate the behaviour of the isolation system including the evolving environment with time. This would, in principle, cover all the individual scenarios of the scenario approach, and would incorporate everything needed for subsequent modelling and consequence calculations. However, the simulation approach must start with a systematic procedure for selection and combination of those phenomena that should be considered. A full assessment application of this method has not yet been done, but attempts at developing the method started several years ago in the United States. The most recent developments have been made in the United Kingdom.

Box 4. This is a partial list of the factors that are considered in scenario development. Many of these, after initial screening, will not be included in scenario construction. However, the remaining factors will be analysed further and eventually combined to form the set of scenarios to be assessed in detail.

1. NATURAL PHENOMENA
1.1 EXTRA-TERRESTRIAL
1.1.1 Meteorite impact
1.1.2 Solar insolation

1.2 GEOLOGICAL
1.2.1 Plate Tectonics
1.2.2 Changes in the Earth's magnetic field
1.2.3 Magmatic activity
1.2.4 Metamorphic activity
1.2.5 Diagenesis
1.2.6 Uplift and subsidence
1.2.7 Diapirism
1.2.8 Seismicity
1.2.9 Fault activation

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1.5 HYDROLOGICAL
1.5.1 River flow/lake level changes

1.5.2 Site flooding
1.5.3 Recharge to groundwater
1.5.4 Groundwater discharge
1.5.5 Groundwater flow
1.5.6 Groundwater conditions
1.5.7 Saline or freshwater intrusion
1.5.8 Effects at saline/fresh water interface
1.5.9 Natural thermal effects

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1.6 TRANSPORT/GEOCHEMICAL

1.6.1 Advection and dispersion
1.6.2 Diffusion

1.6.3 Matrix diffusion
1.6.4 Gas mediated transport
1.6.5 Multiphase flow and gas driven flow
1.6.6 Solubility limit

1.6.7 Sorption
1.6.8 Dissolution, precipitation and crystalisation

2. HUMAN ACTIVITIES
2.1 DESIGN AND CONSTRUCTION
2.1.1 Undetected past intrusions
2.1.2 Investigation borehole seal failure/degradation
2.1.3 Shaft or access tunnel seal failure/degredation
2.1.4 Stress field changes, settling, subsidence or caving
2.1.5 Dewatering of host rock
2.1.6 Material defects, e.g., early canister failures
2.1.7 Common cause failures
2.1.8 Poor quality construction
2.1.9 Design modification

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2.3 POST-CLOSURE SUB-SURFACE ACTIVITIES (INTRUSION)
2.3.1 Recovery of repository materials
2.3.2 Malicious intrusion,e.g. sabotage, act of war
2.3.3 Exploratory drilling
2.3.4 Exploitation drilling
2.3.5 Geothermal energy production
2.3.6 Resource mining
2.3.7 Tunnelling
2.3.8 Underground construction
2.3.9 Archaeological investigation
2.3.10 Injection of liquid wastes
2.3.11 Groundwater abstraction
2.3.12 Underground nuclear testing

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3. WASTE AND REPOSITORY EFFECTS
3.1 THERMAL (nuclear and chemical)
3.1.1 Differential elastic response
3.1.2 Non-elastic response
3.1.3 Host rock fracture aperature changes

The term systematic approach is used here to denote approaches based upon work at Sandia National Laboratories in the early 1980s and later applied and developed not only in the United States, but in recent studies in Canada, France, Sweden, and the United Kingdom. Its main characteristics are a comprehensive initial phase of identification of factors that could influence repository safety, directly or indirectly, and a structured and well-documented procedure for selecting and combining these factors into scenarios for detailed modelling.

All these methods, when applied, have a lot in common and may be seen as different ways to organise and present the same available information about nuclear waste isolation systems.

4.2.3 Scenario Development Needs to be Comprehensive, Systematic and Well-Documented

Recently there have been significant advances in making scenario development as clear and systematic as possible. This has been due, in large part, to intense international co-operation and technical exchange. The practical approach to scenario development most commonly adopted uses the following interactive steps:

- identification and classification of the factors that could be considered important for disposal system safety (this is done by several possible schemes to ensure completeness);

- preliminary screening of this list of factors according to explicit screening criteria, such as physical reasonableness, probability of occurrence, or potential for affecting the repository or the environment;

- combination of the remaining factors into a set of scenarios (usually most remaining factors will form part of a single base-case scenario that includes all factors that are reasonably likely to occur); and

- screening of this set of scenarios according to explicit criteria and establishment of a final set of representative scenarios for detailed modelling and consequence analysis.

4.2.4 The Modelling of Environmental Change is an Area Under Development

In a simplified manner, scenario development might be described as a systematic progressive focusing of the assessment work on a set of significant scenarios. If the scenario development is comprehensive, the assessment will cover all the important aspects of the disposal system with respect to its long-term safety. An increasing effort is being made in some national programmes to develop a basis and a capacity for modelling of environmental effects due to climate change over time. The applications of environmental simulation to date have tended to be limited to climate

driven processes, rather than including phenomena caused by the repository or by humans. However, in principle the technique is more widely applicable and this approach is being developed within some assessment programmes.

4.2.5 Scenario Development Needs to be Flexible and Iterative

Since scenario development is an iterative process, different approaches can be integrated to provide an adequate set of scenarios for detailed consequence calculations. A flow chart for scenario development is shown in Figure 11.

Normally, at the end of the iterative procedure, a base-case scenario will remain, along with several disturbed-case scenarios. The disturbed-case scenarios incorporate most of the factors of the base-case, plus one or more perturbing effects. Where required, the probability of each of these scenarios can be estimated. This estimate can be based on the probabilities of occurrence of the components, or by using some other technique such as subjective probability assignment.

SCENARIO DEVELOPMENT

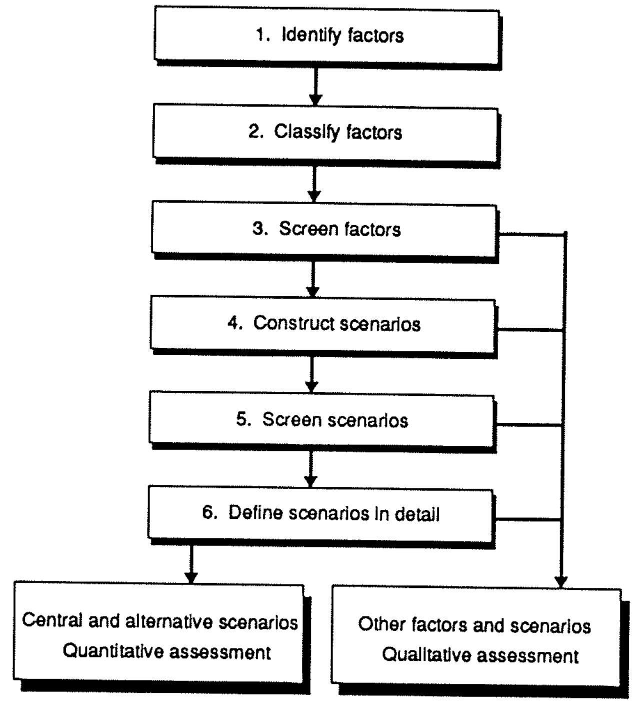

Figure 11: This figure shows a typical flow chart for scenario development. Scenario development is an iterative process with multiple feedback loops. Scenario screening, for example, is influenced by the modelling and consequence calculations that follow.

Since there is no absolutely rigorous and objective procedure to assure scenario completeness, strong reliance must be placed on human judgement. To estimate the likelihood of a particular scenario, the technical community accepts that analyses can be based upon lists of credible scenarios and that a degree of human judgement will always be needed.

4.2.6 Human Intrusion - A Special Consideration

Human activities that may interfere with the barrier system of a repository form a special category of scenarios. In fact, in some cases, potential human actions are the dominating risk factor to consider when predicting system safety. Although this may be especially true for the shallow disposal of radioactive waste, the safety assessor must also consider the intrusive actions of humans in the vicinity of deep geological repositories. Some basic questions regarding human intrusion are provided in Box 5.

Box 5. Questions about man and society in the future that need to be discussed when making assessments of human intrusion risks.

- How efficiently and for how long can institutional control be maintained?
- What will be the ability to keep and understand information about the repository and the waste?
- How do we look upon intrusion deliberately decided upon by future societies? Or by future individuals? i.e., for recovery of resources, negligence or even sabotage?
- If we assume that the intruders are unaware of the waste, what do we assume about their abilities to understand and to make remedial actions once they have intruded into the repository and detected the waste?
- What can we assume about the relation between level of technology and social organisation in future society and the related likelihood and consequences of intrusion?
- Should we try to build in retrievability/repairability to our disposal systems in addition to isolation of the waste? If so, does a balance between these objectives need to be sought?

Questions like these have no scientific answers. Assessors should present their own judgements on these matters so that they can be openly discussed.

The development of society cannot be scientifically predicted. It is not possible to predict what human activities might affect the Earth's subsurface environment thousands of years from now. Therefore assumptions must be made about the behaviour of future society. These assumptions will form the basis for the selection of scenarios, and the models and data used for consequence and risk calculations. This requires prediction of future technologies, social organisations, and society's ability to retain and understand information. As these cannot be accurately predicted, the problem of human intrusion must be approached with moderation and balance; the limitations must be clearly recognised.

4.3 MODELLING - SIMULATING REPOSITORY BEHAVIOUR

Modelling is used extensively in safety assessment for a variety of purposes. Models varying in both level of detail and complexity are used to describe and understand individual processes, subsystems, and overall system performance. The field of modelling, as it is applied to safety assessment, is so wide that it is not possible to cover all the facets in this document. However, a large number of international workshops and meetings have been held to discuss the most important aspects of performance assessment modelling.

4.3.1 Modelling Plays an Important Role in Safety Assessment

Predictive modelling is an essential part of the safety assessment process. The general procedures used to develop models are well accepted and predictive models have already been developed in key areas. During the last few years, models have been substantially improved in terms of both realism and detail.

There are a variety of models available to treat the key processes that determine the performance of radioactive waste disposal systems. However, further development is still needed in some areas to help clarify or reduce uncertainties associated with assessment results. These improvements will in turn contribute to the ability to optimize disposal system design. Special attention has been given during the last few years to the interdependence between model development and the corresponding effort to gather data. A current area of development is the coupling of models for specific processes into larger integrated models and their simplification to make them practical tools for safety assessments.

4.3.2 How the Modelling Process Works

The first step in modelling is to develop a conceptual model. A conceptual model represents an understanding of the features and processes of interest. It is an abstraction which only includes those relationships necessary to describe the system for the particular application. Ideally, the relationships are stated in terms of testable hypotheses. Conceptual models are based on accepted laws, existing knowledge of the behaviour of the system under consideration, and expert judgement. An illustration of a conceptual model for radionuclide migration in groundwater is shown in Figure 12.

The conceptual model is then expressed quantitatively through mathematical equations in a calculational model. The calculational model may be as simple as an algebraic equation, e.g., Darcy's law, or so complex that only a computer solution is possible. In the modelling of real world situations, simplifications are almost always introduced in the transition from conceptual models, to mathematical models, and finally to implementation using computer codes. A simplified example of a calculational model is shown in Box 6 below.

Performance assessment modelling must ultimately be carried out on an integrated, total system level. This requires proper linkage between the models needed to describe the overall behaviour of the system. Integrated assessments are discussed in the following sections. A flow chart showing the iterative nature of the modelling process is provided in Figure 13.

Box 6. A simplified example of the mathematical formulation of a model for radionuclide transport in the geosphere.

a b c d1 d2 e f

$$\frac{\partial C_i}{\partial t} = -V\frac{\partial C_i}{\partial t} + D_L\frac{\partial^2 C_i}{\partial x^2} - \lambda_i C_i + \lambda_{i-1} C_{i-1} + D_e a\frac{\partial C_i}{\partial z}\Big|_{z=0} - F_i$$

$$\frac{\partial S_i}{\partial t} = -\lambda_i S_i + \lambda_{i-1} S_{i-1} + F_i$$

a) The rate of change of the concentration of radionuclide i in the flowing liquid phase is dependent on the following processes:

b) Advection, which is governed by the average water velocity V; x is the distance from the near-field-geosphere interface.

c) Dispersion-Diffusion, is governed by the dispersion coefficient D_L which is dependent on the interstitial water velocity. If the water velocity is 0, only diffusion of the radionuclides occurs.

d1,d2) Radioactive decay chains take into account the radioactive decay of the nuclide i, and the formation of nuclide i from radioactive decay constants λ_i and λ_{i-1}.

e) Matrix diffusion, is governed by the effective diffusivity, D_e, in the stagnant water in microfissures and pores in therock matrix; a is the area of the surface of the rock matrix in contact with the flowing water per volume of flowing water and z is the distance from that surface.

f) Interaction with solid phase. This term takes into account sorption and desorption phenomena on the surface of the rock in contact with the flosing water. S_i represents quantity of radionuclide i sorbed to solid phases per unit volume of flowing water.

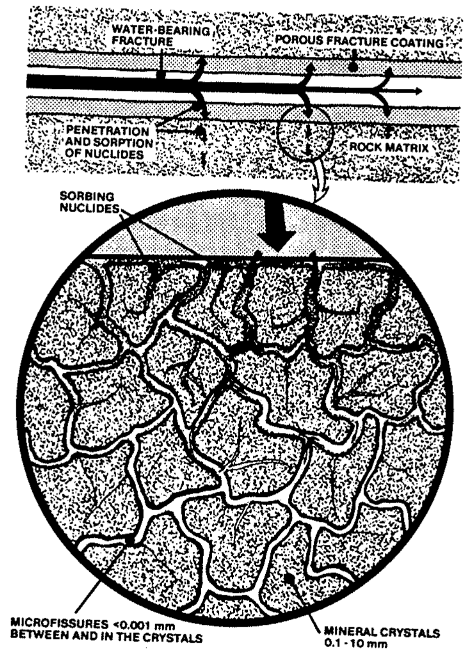

Figure 12: This is an illustration of a conceptual model for radionuclide migration in groundwater. Here the migration is delayed in fractures of crystalline rock, due to diffusion into the rock and sorption on to mineral crystals. This phenomena is called "matrix diffusion".

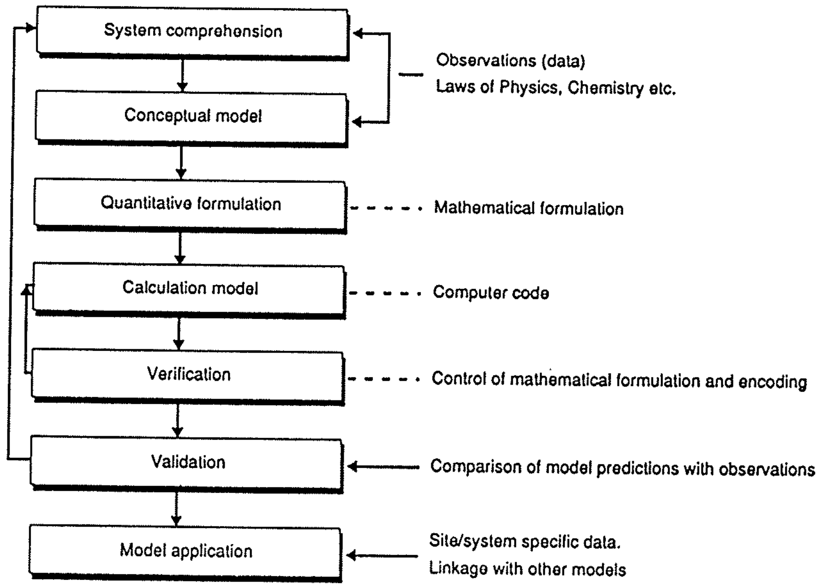

Figure 13: The different stages of the modelling process. The process is highly iterative, leading to a gradual refinement and optimisation for the particular application. The issues of verification and validation are further discussed in Chapter 5.

4.3.3 Improving the Modelling Process

Several modelling areas are still under active development. This is either due to gaps in capabilities or because an improved model can help optimise an overall disposal system. It is important to distinguish between these two reasons.

If the primary aim is to ensure that a required level of safety is achieved, then simplified models can be used and certain processes can be neglected. However, there must be sufficient system understanding to show that the resulting analyses yield conservative predictions of repository performance. If the system is to be optimised, then the closeness of the models to physical reality is much more important. The relative importance of the various models could vary greatly for different disposal concepts. The priorities given for further development and improvement of models are therefore site-specific and concept-specific.

4.3.4 Several Issues in Radioactive Waste Disposal Modelling

One area where there is significant development is the modelling of groundwater flow and nuclide transport in heterogeneous geological media. For example, fractured hard rock may have a very complex and variable structure through which water may flow and allow nuclides to migrate. It is not feasible to characterise every detail of large geological formations and to model the corresponding aspects of radionuclide transport. However, advanced concepts and modelling techniques are being developed to obtain a more realistic picture of the transport process. This will make it possible for safety assessments to use models that adequately simulate the barrier function of the geosphere.

In systems where groundwater transport is an important process, the possible effects of various influences on transport rates and capacities have to be considered. An important example is the influence of micro-organisms and colloids as potential carriers of radionuclides. The questions here are to what extent such entities are present in groundwater, how they interact with the host rock, and how they interact with dissolved radionuclides. Whether they can significantly affect repository performance and whether the net effect is positive or negative is not yet clear.

Gas production and release are also recognised as important factors, especially in assessing the performance of low and intermediate-level waste disposal systems. Gases can be formed due to the corrosion of metals or degradation of organic waste materials in a repository. Gases may also be released when the integrity of the spent fuel cladding is lost. Gases might dissolve in the groundwater, or they could migrate toward the biosphere. The consideration of gaseous releases has led to some new developments in modelling. For example, modelling of microbial processes generating gas or modelling of simultaneous flow of water and gas has improved the understanding of overall system behaviour.

Other modelling issues under discussion concern the time dependence of processes. As performance assessment for specific concepts becomes more

advanced, the importance of understanding transient behaviour grows. How quickly and uniformly does a bentonite buffer resaturate? Are the times needed for seals to become fully operative, or for excavations to close, appropriate for the expected rates of gas generation, container corrosion, and nuclide release? How valid are the assumptions of equilibrium thermodynamics which are used in place of treating kinetic effects throughout many analyses?

Conservative models for the maximum release and transport of radionuclides from repositories are generally available. However, improved modelling may help to design an optimum system; current models often underestimate the tendency for radionuclides to be retained in the repository system. For example, radionuclides migrating from degraded waste forms, with failed waste containers, still experience sorption by the materials in the near-field. The radionuclides will have long transport times through a well-designed near-field, and will encounter resistance to transport in the geological formation surrounding the repository.

The development work currently underway in modelling does not mean that there is insufficient modelling capability to conduct performance assessments. Immense progress has been made over the last ten years and the encouragement to improve some of the models further stems from the conviction that performance assessment plays a strong role in system optimisation. Models continue to provide essential information to repository developers and allow them to design and site repositories while accounting for aspects of safety, technology, and economics.

4.4 DATA REQUIREMENTS FOR REPOSITORY DEVELOPMENT

Data acquisition is one of the most extensive and expensive activities in repository development. This is especially true for the central and sometimes politically sensitive task of obtaining the data needed for potential repository sites. Therefore, a well-planned and well-managed site-investigation programme with appropriate and effective control over data requirements is important to a successful repository programme.

4.4.1 Trends in the Use of Data in Performance Assessment

During the last decade, major improvements have been made to the data bases used in the safety assessment of radioactive waste disposal systems. Data quality has improved due to increased understanding of processes and advanced measurement techniques and instruments. In addition, more and more site-specific data are available. There is a concern, however, that data are recorded because they are measurable and not because they are needed for the prediction of repository behaviour. Therefore, there is a need to further strengthen the link between performance assessment and data collection. Unfortunately, it is still difficult, in many areas of the world, to gain access to potentially suitable sites for investigation and evaluation. Assessments can provide direct guidance on the need for data measurement and management.

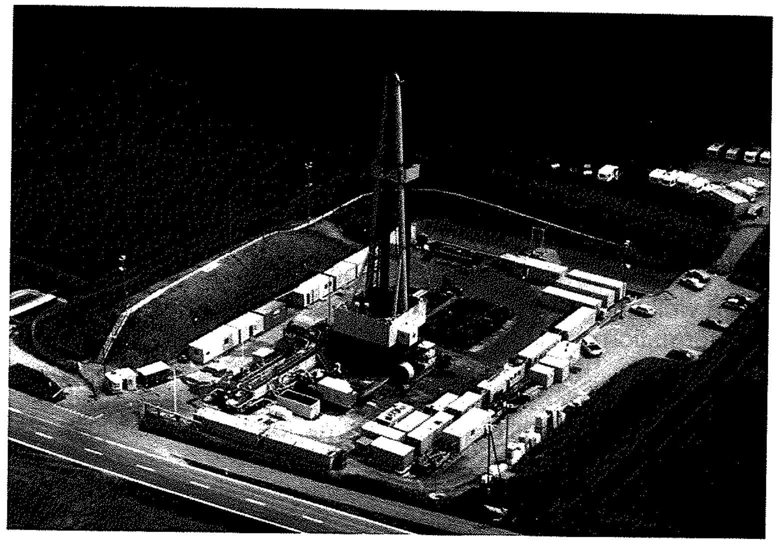

Figure 14: Geological, hydrological, and chemical data are obtained by measurements in deep boreholes during site investigations. This picture shows a deep drilling site at Weiach in Switzerland. The depth of the borehole at this site is about 2500 metres.

4.4.2 The Data Used for Modelling are Acquired from a Variety of Sources

Data are obtained from observations and measurements in both the laboratory and the field as shown in Figure 14, and allow hypotheses to be formulated. Models can then be used to identify additional measurements that can improve understanding of the actual process. Thus, data provide the foundation for both model development and application.

The sources and accuracy of data needed at various stages of the modelling process differ. At an early stage, it might be sufficient to estimate the order of magnitude or an upper limit for a particular parameter. In this way the assessor would be able to obtain useful information for screening important versus unimportant processes. In a complete system assessment, including an extensive uncertainty analysis, the assessor must know more. Ideally the assessor would know the span of possible values and the associated probabilities for each parameter.

Some data must be obtained from measurements made under the conditions that will prevail in the repository area while others can be obtained from existing scientific databases. For example, radionuclide half-lives are independent of repository conditions. Therefore the existing values measured at nuclear physics laboratories can

be used. On the other hand, laboratory experiments that measure radionuclide leach rates from vitrified high-level waste may not directly reflect repository conditions. Such experiments do, however, help scientists to understand release mechanisms. In addition, leaching experiments that closely simulate the expected conditions in a deposition hole have become more frequent.

Laboratory experiments that closely resemble actual site conditions can be valuable. One experiment uses radionuclides, dissolved in water, in contact with pieces of rock taken from a site. The fraction of radionuclides that are sorbed on the rock is measured and provides information on the potential retention capacity of the host rock during radionuclide migration. However, where feasible this information should be complemented with data from experiments at the site. In this case, radionuclide tracers could be injected into the groundwater and the subsequent migration measured in situ.

The examples discussed above demonstrate the variety of sources from which data can be acquired. In some cases data are taken from existing physical/chemical databases or from measurements in well-prepared laboratory experiments. In other cases they are most reliably obtained through measurements at the site.

4.4.3 The Importance of Data Quality

Growing importance is now attached to the quality and traceability of data. In many countries the repository development programme is approaching the licensing stage. Regulatory authorities and others involved in the decision-making process must be able to clearly determine where the data were generated and how they were measured and evaluated. This knowledge is necessary to determine that the data used in the assessment are correct. The overall question of confidence and quality is further discussed in Chapter 5.

4.5 CONSEQUENCE CALCULATIONS

The capability to perform consequence calculations has increased rapidly due to improved modelling techniques and the growing capacity of computers and database systems. The computers and associated systems provide the tools for very advanced and complex methods. It is important that the effort to provide oversight and maintain transparency keeps pace with the development of these technical methods.

4.5.1 Two Observations on Consequence Calculations

Safety assessments normally provide an estimate of consequences in terms of radiation dose or risk to humans. For long-lived radioactive waste the disposal objective is extended to passive isolation of the waste from the environment. Caution is required in the interpretation of the estimated radiological consequences of waste disposal activities. For example, the calculation of a dose that results from a release at an operating nuclear plant represents an estimate of the dose that will actually be received by an existing population. Dose calculations for potential waste repository releases are calculations for hypothetical individuals and two observations should be made.

- Doses to future generations from waste repositories are postulated to occur from the gradual degradation and possible severe disruption of the system's safety barriers. Therefore, in order to assess the actual risk, both the severity and the probability of the event must be considered.

- Owing to the speculative nature of extrapolating conditions into the far future, dose calculations based on a release from the disposal system several thousand years in the future are normally based on current living habits. The calculations should therefore be viewed as an illustration of what the dose would be if the release occurred today, rather than as a prediction of the actual dose to humans living in the far future.

4.5.2 Consequence Calculations and Safety Criteria

Several quantitative criteria have been discussed and proposed for safety assessments. Most of them relate in some way to the concept of dose (e.g. individual dose, collective dose, dose and dose rate to biota, annual dose or risk to a critical group, etc.). This can then be compared with dose-limits, normally set by using recommendations from the International Commission of Radiological Protection as a basis. Other criteria may specify limits on the amount and distribution of radionuclides released from the geosphere into the biosphere. In the latter case, one does not enter into detailed biosphere or dose modelling.

Safety criteria determine the requirements with which an assessment must comply. Some countries have already defined criteria for radioactive waste disposal in detail. Other countries use general radiological protection criteria as a basis for their judgements. Whatever the detailed criteria might be, the assessment work that has to be done remains to a large extent the same. All relevant safety factors must be evaluated by the safety assessor, and reviewed by the regulator, in a clear and comprehensive manner. Although the numerical outcome of the assessment is important, it is meaningless without the understanding of the disposal system provided by the assessment. The basic aim of assessments is to provide a thorough understanding of the various roles of the barriers in a repository system and the

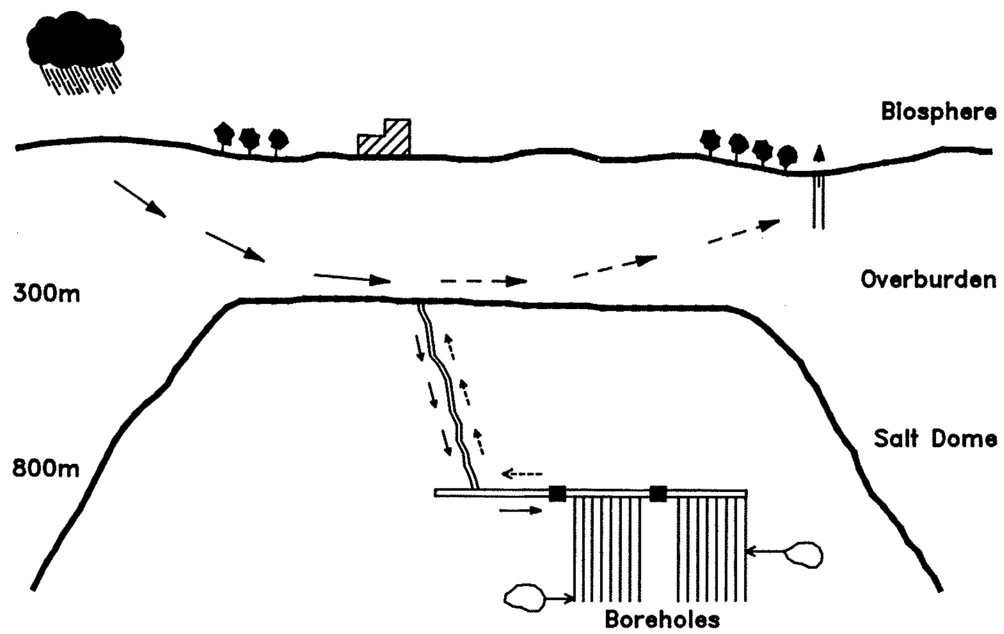

Figure 15. The absence of groundwater in salt formations is one of the reasons they are being considered as potential sites for geological repositories. If a waste container were to lose its integrity, groundwater would not be available to dissolve and transport radionuclides from the waste to the environment. However, safety assessments are still used for salt formations to assess the possible mobilisation and transport of radionuclides due to salt water (brine) inclusions in the salt rock or external brine intrusion. A schematic of this concept is illustrated above.

processes of interaction within that system, so that an evaluation of the safety of the disposal system can be made. Figure 15 depicts a possible migration path at a salt repository.

4.5.3 Consequence Calculations with Respect to Time

Some national authorities have considered it appropriate to introduce a time limit (e.g., 10,000 years) for detailed quantitative performance assessment of a disposal system. Therefore, the demonstration of compliance with the dose or risk limit through predictive quantitative modelling may not be required after a certain amount of time. There are two basic facts behind the interest in discussing a time limit for safety assessments. One is that uncertainties associated with assessment results will increase with time. The second reason is that the radioactivity of the waste decreases with time. These two general trends taken together will cause the meaning and need for quantified assessment results to reduce as time increases. In some countries (e.g., the United States, Canada, and the Federal Republic of Germany), these general considerations have led the regulatory authorities to specify or consider limits for the time-frame (e.g., 10,000-100,000 years) of formal quantitative safety assessments.

Box 7. Approximate time frames for major social, industrial, ecological, biological, geological and astronomical events.

Years	Events
1 billion	High probability of "near-by" supernova explosions and impact on earth of very large astronomical objects. Increase in the solar intensity sufficient to erase biological life on earth.
100 million	Large-scale geological changes such as movements of some continents by thousands of kilometres.
10 million	Significant biological changes, for instance the appearance of entirely new families of species. The evolutionary branching between hominids and the apes took place some 10 million years ago.
1 million	A few million years ago, hominides were starting to be replaced by homo sapiens. One million years is a period over which stable geological formations remain relatively unchanged.
100,000	Time between the onsets of major glaciations. 50,000 years ago humans appeared who could use a variety of tools and lived in rock-shelters.
10,000	10,000 years ago humans began to farm and the last ice cover left northern Europe.
1,000	Large ecological changes, e.g. deforestation - reforestation occur. Mineral and energy sources may be exhausted.
100	Most of the world's industrial production has taken place in the last 100 years. Beyond 100 years from now, we can hardly foresee the developments in ecology, medicine, technology, economy and social structure.
10	Political and economic planning rarely have horizons much beyond 10 years.

The time frames for changes in the geosphere and the biosphere are very different. While the geosphere in most respects is stable over periods of millions of years, the biosphere and living habits of humans may change drastically in less than a few hundred years. This observation has led some regulatory authorities to consider replacing the commonly used dose calculations with some other measure of safety for longer periods. One measure proposed is to compare the radionuclide release from the geosphere to the biosphere with the naturally occuring amounts or flow of radionuclides in the environment.

Examples of the inherent uncertainties with time are illustrated in Box 7. The level of detail and sophistication of safety assessments and the presentation of the results should be adopted accordingly.

4.5.4 Consequence Calculations and Regulatory Requirements

The system of dose limitation for practices involving radiation risks applies to situations where the exposure is certain to occur (probability equal to one). Two complications arise when applying such dose limits to the disposal of radioactive waste. In most cases of waste disposal, radiation exposure scenarios are not certain to occur (probability less than one). The other complication results from the extended period in which the radiological impact could arise. This situation was recognised early by international organisations, such as ICRP, IAEA, and OECD/NEA. In the 1980s, these organisations started work aimed at the clarification of the radiation protection and safety principles as applied to waste disposal. As a result of this work there is now an international consensus on the general radiological protection principles for disposal of radioactive waste. These principles are summarised below.

- The individual risk for members of the public should be limited within a level corresponding to the risk associated with the current ICRP individual dose limit (1 mSv per year). This corresponds to a risk on the order of 1 in 100,000 of experiencing fatal cancer, when the probability of the events giving rise to exposure and the potential health consequences of the exposure are considered. For single repositories a risk target of 1 in 1,000,000 has been adopted by some national authorities.

- The ALARA principle (i.e., to keep the doses as low as reasonably achievable) should be taken into account as far as possible in the overall optimisation of the disposal system.

The implication of the first principle is that the risk of health effects from scenarios that are highly improbable will be small compared to the risk limit, and detailed analysis of such scenarios need not be included in a safety assessment. Some countries prefer to formulate a criterion for maximal individual radiation dose together with a qualitative statement about the probability of various release scenarios. In this case the scenarios considered in formal safety analyses are limited to those judged to be realistic or reasonable and comparisons are made with an annual dose limit.

4.5.5 The Process to Determine Consequences Quantitatively

Quantitative consequence calculations require scenarios, models, data for model parameters, and boundary conditions. The analysis of radiological consequences is based on calculations of the release, dispersion, and transport of radionuclides. The calculations start with the waste form, proceed through the engineered barriers, the repository, the geosphere, and the biosphere, and end with the radiation dose to man. The interactions between the parts of the repository system cause modelling requirements to be interdependent. For example the use of deep groundwater as a source of fresh water will result in pathways in both the biosphere and geosphere models. Consistent assumptions must apply through all models and for all data used.

The types, number of components and models, and the variety of input data to be included in a particular consequence calculation depend on the purpose of the calculation and the scenario under study. Calculations using complex models of parts of the system are often used to provide a basis for a simpler representation of that part of the system in the overall consequence calculation. For instance, the hydrological characterisation of a site might involve extensive three-dimensional modelling of groundwater movements. The results are then analysed to extract the most essential characteristics of the system and to set up a simpler hydrological model that can be used in conjunction with geochemical models for the simulation of radionuclide migration in the geosphere.

There are two reasons for simplifying the detailed models used in system assessments. First, it might not be feasible to include the detailed model in the chain of coupled models because calculations would be too complex or take too long. Second, by simplifying and focusing on the essential characteristics of each component, the overall assessment will be easier to understand.

A potential drawback to the simplification of detailed models is the possible removal of an important piece of information. If something important is overlooked and not included in the simpler model, the results of the assessment will not fully reflect the real performance of the system. That is why model simplifications are often done in a conservative way, and the simpler model underestimates the actual capabilities of the barrier or system it describes.

4.5.6 Use of Deterministic Calculations

Deterministic analysis methods are the classical methods used in predictive mathematical modelling of system behavior. Parameter values are considered as exactly known in such analyses and the effect of uncertainties in these values may be demonstrated either by conducting bounding analyses or by using statistical methods. These analyses may provide best estimate or extreme estimates of system performance. For complex models it is not always clear which combination of input parameters will lead to bounding estimates of system performance. The methods for deterministic evaluation have gradually been refined and developed. In particular,

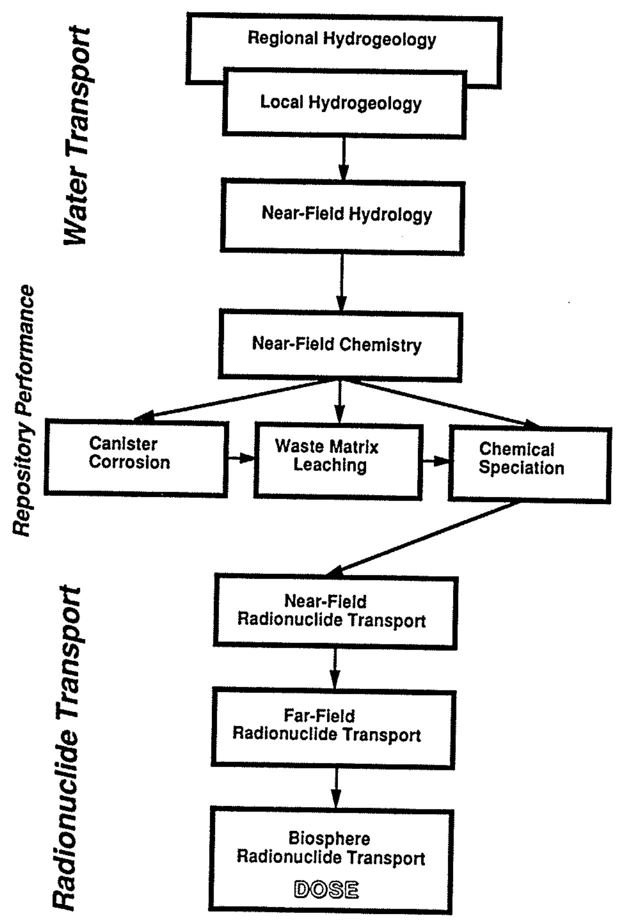

Figure 16: Example of a model chain for safety assessment of a radioactive waste repository.

progress has been made in the coupling of the various submodels into an overall system assessment model. An example of a model chain is shown in Figure 16.

4.5.7 Use of Probabilistic Calculations

Stochastic analysis methods are used in the probabilistic system assessment (PSA) approach. PSA codes couple a set of subsystem models into an overall system model. In the PSA approach, it is assumed that the underlying uncertainties are adequately described using probability distribution functions for the model parameters. That is, a parameter is not assigned a single best estimate or worst credible value. Instead it has a range of possible values with their relative likelihood of occurrence expressed through the probability weights assigned. For one simulation, the PSA codes select parameter values from the distributions, using a sampling strategy such as random sampling. Parameter values are then passed to the system model, and used to calculate the performance of the disposal system. The simulation process is repeated, using different sets of parameter values, until there is some measure of statistical convergence. PSA codes therefore yield a distribution of estimates of performance, and the distribution reflects the uncertainties in the parameters of the model of the chosen system and its representation of variability.

The NEA has established and manages the activities of a Probabilistic System Assessment Group (PSAG), reflecting the increasing interest in the PSA approach to safety assessment. This Group has discussed and documented many of the difficult tasks associated with the successful development and application of PSA codes, such as developing valid system models, deriving suitable probability density functions, choosing efficacious sampling strategies, and proving that a consistent set of results has been obtained. Progress in the probabilistic modelling of performance has been considerable and most countries now have the possibility to conduct both deterministic and probabilistic consequence calculations. Figure 17 shows one example of a probabilistic system assessment approach to modelling system behaviour.

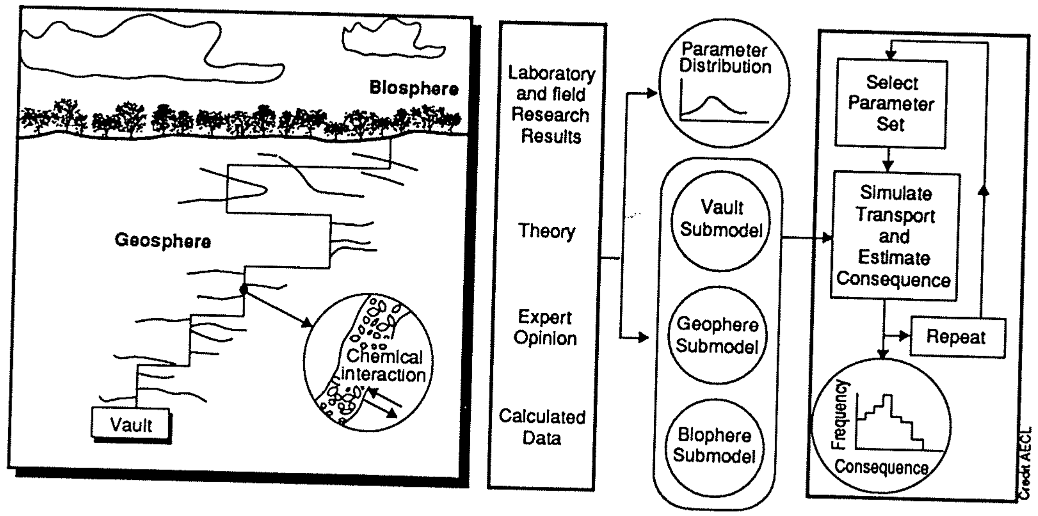

Figure 17: Schematic of the conceptual representation of a deep disposal system and illustration of a probabilistic system assessment approach to modelling system behaviour. For each parameter set, modelling will result in a calculated consequence. By repeating the calculations hundreds or thousands of times, using different selected parameter sets from the given distributions, a diagram of potential consequences and their frequencies can be generated.

4.6 UNCERTAINTY ANALYSIS

Uncertainties are an inherent part of assessment results. Although they can be reduced through improved data collection and modelling, they can never be completely eliminated. This is because uncertainties reflect a genuine variability in natural systems and in some cases a limited understanding of current or future controlling processes. However, by using both quantitative methods and expert judgement, the amount of uncertainty can be evaluated and a basis for decisions can be provided.

How much uncertainty is acceptable is a central question for decisions regarding the implementation of disposal systems. Integrated performance assessments can help locate areas where uncertainties most need to be reduced. This guidance is specific to disposal site and concept and can be used to direct resources for research and development to the areas where they are needed most.

4.6.1 Several Types of Uncertainties must be Considered in the Performance Assessment Process

Uncertainties are always present in performance assessments of complex systems. Although the methods to evaluate and quantify uncertainties may vary, there is a general agreement on the types of uncertainties that have to be considered. These uncertainties, discussed on the next page in Box 8, are related to the items listed below.

- Scenarios. This uncertainty is caused by the possible omission of important events or processes, by faulty interpretation of the geology, or by failing to realistically estimate the probabilities of occurrence.

- Models. This uncertainty is caused by the possible use of an inadequate conceptual model, an overly simplified mathematical representation, or code errors.

- Data for the repository site or the engineered barriers. This uncertainty results from either measurement uncertainty or insufficient data to describe natural variability. Examples include the dimensions and location of waterbearing fractures, and the density and diffusion properties of backfill material used in tunnels and shafts.

To a significant degree, uncertainty can be treated by obtaining more accurate data, by performing model verification and validation, and by using formalised approaches for scenario selection. But uncertainty in performance assessments can never be eliminated. Accordingly, a consensus has developed that uncertainty analyses must be done in conjunction with performance assessments and that uncertainties should be quantified to the extent possible.

Uncertainties in the evolution of the repository and the environment can be reduced using scenario techniques. To assure that all important possibilities are assessed a systematic approach to the identification of alternative futures is necessary. In a strict sense, one can never guarantee the completeness of scenarios. However, it is accepted by the technical community that analyses can be based upon a list of credible scenarios and that a degree of subjective judgement will always be needed.

Box 8: There are several sources of uncertainty in the observations, assumptions, models, and data underlying safety assessments.

Scenarios	Completeness in identifying initiating factors (FEPs). Interaction and combination of factors. Future system states and their consequences.
Models and computation	Conceptual Models Mathematical models Numerical approximations Coding errors Accuracy Computational limits
Parameters and Data	Scarcity or lack of data Measurement error Spatial and temporal variability

Uncertainty analysis is a systematic study of the overall uncertainties due to scenarios, models, and data. Quantitative uncertainty analysis is most easily done for parameter and data uncertainties and advanced techniques are available within the framework of probabilistic system assessments.

The term sensitivity analysis generally refers to a means of quantitatively estimating the amount of variation in model output due to the variation in input parameters. That is, it is a means of identifying so-called key or important parameters. The information obtained can be used to direct research towards understanding the behaviour and influence of those parameters.

Model uncertainties can be difficult to quantify, although uncertainties due to approximations introduced in mathematical formulation and encoding of a model can normally be estimated. If there is more than one model to describe a process, the effect of conceptual uncertainty can be determined by making calculations with both

models and comparing the results. Still, more understanding should be sought in this situation to resolve the conceptual uncertainty. Verification and validation exercises are now extensively performed in order to reduce and to clarify model uncertainties. For further discussion see Chapter 5.

In general, parameter uncertainties can be more readily quantified than scenario and model uncertainties. Therefore considerable progress has been made in developing methods to analyse the effects of parameter uncertainties on overall assessment results. The use of probabilistic techniques is a particularly systematic and efficient method for this purpose.

4.6.2 The Importance of Perspective on Uncertainty

The issue of uncertainties is a matter of some confusion in discussions on radioactive waste disposal safety. It is difficult for experts to put uncertainties in their specific fields in perspective. Therefore those performing integrated performance assessments have an important role to play in keeping a perspective on uncertainties in assessment results. For instance, large uncertainties in the modelling of a particular process may have little influence on the overall assessment results because other processes and barrier functions dominate. A process or phenomenon might be completely unimportant in the expected evolution scenario, and still be crucial to the results for an assessment of some more unlikely scenario. Therefore, discussions of uncertainties should not take place in isolation. By identifying and quantifying uncertainties and by understanding how they affect the results of consequence calculations, it will be possible to make evaluations of the safety of a disposal system. Uncertainty information should also be provided to the repository designers since it can help them improve the design and the siting of the repository.

4.6.3 Probability of the Occurrence of Events

The calculated long-term consequences of a repository should be considered with respect to their probability of occurrence. To do this the probabilities associated with different scenarios must be determined. There are statistical techniques available to characterise events and features. For example, the probability of occurence of a meteorite impact at a repository site has been estimated based on data from observations of past meteoritic impacts. The probability has been shown to be so low that the meteorite impact scenario need not be considered in detail.

However, in most cases of probability estimation, human judgement has to be used in conjunction with incomplete or only partially relevant data and observations. For example, the probability that in the future humans will drill into a waste container deposited in a deep repository can be estimated from existing data on deep geological drilling. The results, however, cannot be taken literally because too little is known about future human activities in this respect. Therefore, the data used for probability estimation is only partially relevant. As a result, human judgement will constitute a key element in evaluating the risks associated with such an intrusion scenario.

In fact, most probability estimates include a substantial amount of judgement and cannot be considered as mathematical predictions. However, a systematic and quantitative approach will help identify the important factors in a safety assessment and ensure the most appropriate use of available data and evidence. (See Box 9)

Box 9. Extracts from Publication no. 46 by the International Commission on Radiation Protection (ICRP)

The use of subjective probability is acceptable as long as the quantitative value assigned through "best estimates" or "engineered judgements" is consistent with the quantitative value of the relative frequency in situations where more information is available. Thus, the probabilities assigned for various events will be consistent and continuous, and low probability events can be integrated with higher probability events into a complete analysis of the options under consideration.

A distinction should be made between the probability of occurence of an event at a waste repository, the probability that the event will have a consequence for the integrity of the repository, and the probability that an exposure will be received by an individual as a result of the event. The outcomes of these three probabilities are conceptually distinct, and care should be exercised in combining them.

4.7 PRODUCING AN INTEGRATED ASSESSMENT - THE ULTIMATE GOAL

An integrated assessment describes the characteristics of the disposal system and quantifies the performance of the overall system in terms of radiological safety. An integrated assessment is the ultimate goal of scenario development, modelling, and consequence calculations and is indispensable for the licensing of a repository. Experience has also shown that integrated assessments are of considerable value and should be carried out in an iterative way throughout the repository development process. Box 10 lists some of the major integrated safety studies conducted for high-level waste and spent fuel disposal.

Central to the presentation of the safety case for a repository are the results of the integrated consequence calculations. These calculations link the relevant models and cover the full range of selected scenarios. In addition, simplified calculations may be used to shed additional light on the safety characteristics of the system or on the

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Box 10. Some major integrated safety studies of HLW and spent fuel disposal.

Study	Characteristics	Results
KBS-3, Sweden	Disposal of spent fuel encapsulated in copper canisters at 500 m depth in crystalline rock. Deterministic, conservative assessment.	Based on KBS-3 results and after one year of extensive national and international review, the Swedish government judged the KBS concept as feasible and safe.
Gewahr, Switzerland	Disposal of vitrified HLW encapsulated in massive steel canisters at 1,200 m depth in crystalline rocks overlain by sediments. Deterministic conservative assessment.	After several years of review, the Swiss authorities agreed that safety assessment methodologies demonstrated that the required level of safety could be achieved but asked for further verification that the field data used are sufficiently representative and that some specific processes do not result in unacceptable perturbations to the disposal system.
AECL, Canada	Disposal of spent fuel in crystalline rock. Concept evaluation. Extensive use of probabilistic system assessment techniques.	Preliminary results indicate that with suitable constraints on facility design, the risk-target 10^{-6} can be met. A comprehensive public review process is underway.
PAGIS, CEC	Deep geological disposal of HLW in clay (Belgium), granite (France) and salt (Germany). Subseabed was also included. Both deterministic and probabilistic methods were used.	The overall conclusion was: "... there are no reasonable doubts about the possibility of achieving safe disposal of vitrified HLW in any of the formations examined provided that appropriate sites are selected and repositories are designed and built according to sound engineering practice".

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potential for releases or consequences. One example would be a calculation where all the radioactivity present is immediately released to the geosphere. This is a completely unrealistic scenario but it might help to understand the importance of the engineered barriers. In a similar way the effect of other barriers might be illustrated.

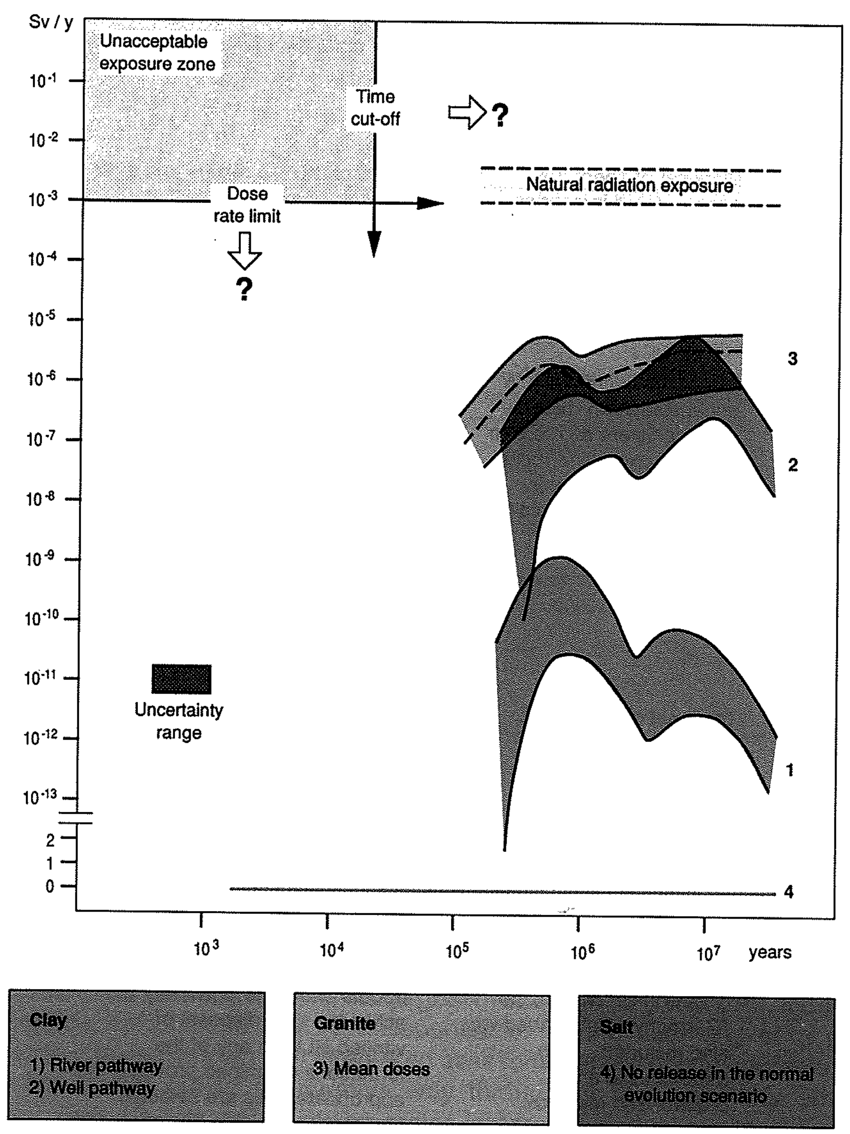

Figure 18: Summary of some of the results from the PAGIS Study (see Box 8). This figure illustrates that for normal evolution scenarios the calculated dose is zero over many thousands of years. Peak doses are calculated to be reached only after some millions of years. The dose rate levels, including consideration of uncertainties, are still minor fractions of those due to natural background radiation.

There are two different approaches to conducting integrated assessments. The first is aimed at licensing and is characterised by an intention to have a robust bounding analysis of the system. When using a robust bounding analysis, the goal is to demonstrate with high confidence that predicted consequences lie below specific values. In this approach, scenarios, models, and parameter values are chosen conservatively (that is, pessimistically). Thereby, the assessments are simplified and discussion of some uncertainties not crucial to system safety become less important in the licensing procedure. The second approach is aimed at research and development guidance. These assessments use detailed research models and their results are needed to evaluate design and engineering options. They are also used to provide a defensible basis for excluding processes not important to safety in the more robust and simplified modelling. A summary of some of the results of the PAGIS study are shown in Figure 18.

5. BUILDING CONFIDENCE IN PERFORMANCE ASSESSMENTS

One major objective of safety assessments is to provide a basis for well-founded decisions about radioactive waste disposal. To this end it is necessary that scientists, safety assessors, regulators and those involved in the decision-making process have confidence in the information, insight, and results provided by safety assessments. This raises the question of the relevance and the quality of safety assessment methods, as well as the procedures used to perform, quality assure, and review assessments.

This Chapter will discuss what can be done to assure that safety assessments address relevant issues and provide results that can be used as a basis for decisions. Efforts are directed in four areas: (1) verification and validation of models, (2) quality assurance, (3) critical review, and (4) international cooperation. There are, however, no sharp borderlines between these procedures for confidence building and in one way or another they all have the same objective. The procedures are designed to assure that the safety assessment tools adequately represent reality, and that they are correctly applied by those using them to assess the safety of repositories. This Chapter does not deal with the difficult and important question of how to present and explain the results of safety assessments in a clear and comprehensive way to decision-makers and the public.

5.1 VERIFICATION AND VALIDATION OF MODELS

Conceptual models, mathematical models, and the corresponding computer codes have to simulate the performance of the part of the system they describe. This must be done at the level of detail needed for the purpose of the assessment. There are two key questions which can be posed. First, does the model accurately simulate the process or system for which it has been developed? The procedure of validation seeks to answer this question. Second, does the computer code which embodies the model accurately solve the mathematical equations that constitute the model? The process of verification seeks to answer this question. Definitions of validation and verification are provided in Box 11 on the next page.

5.1.1 Verification

Verification of a computer program is achieved primarily through the execution of a set of verification test problems designed to show that the stated equations are

satisfactorily solved. An example of this is shown in Figure 19. Feedback from diversified use of the program becomes part of the verification process by building confidence in proper ranges of application of the program and by documenting limitations and errors detected and corrected. Thus, the means to determine the answer to the second question appear to be reasonably well in hand.

5.1.2 Validation

Validation is concerned with the genuine understanding of nature, that is, of the reality behind the models. Two types of models for performance assessment can be distinguished. Models are needed to synthesize the structural characteristics of the system from a limited number of measurements and observations. The location and characteristics of faults, layering in the geosphere, and heterogeneities in a backfilled shaft are examples of structural characteristics of the system that need to be defined. Process models predict how the system will evolve with time due to the physical and chemical processes occurring and interacting within the system. Examples of these include: groundwater flow, colloidal transport, dissolution, and precipitation.

Box 11. Definitions of Validation and Verification in the IAEA-TECDOC-447 Radioactive Waste Management Glossary. Second edition, Vienna, 1988.

Validation is a process carried out by comparison of model predictions with independent field observations and experimental measurements. A model cannot be considered validated until sufficient testing has been performed to ensure an acceptable level of predictive accuracy (note that the acceptable level of accuracy is judgmental and will vary depending on the specific problem or question to be addressed by the model).

A mathematical model, or the corresponding computer code, is verified when it is shown that the code behaves as intended, i.e., that it is a proper mathematical representation of the conceptual model and that the equations are correctly encoded and solved.

Validation of Structural Models

Structural models assign characteristics to the host rock on the basis of a limited amount of primary data. They can also be used to assign a representative quantity to an engineered barrier on the basis of sampling and a few large-scale tests. Confidence in the structural description is based on the quality of the primary data, and the validity of the extrapolation models used.

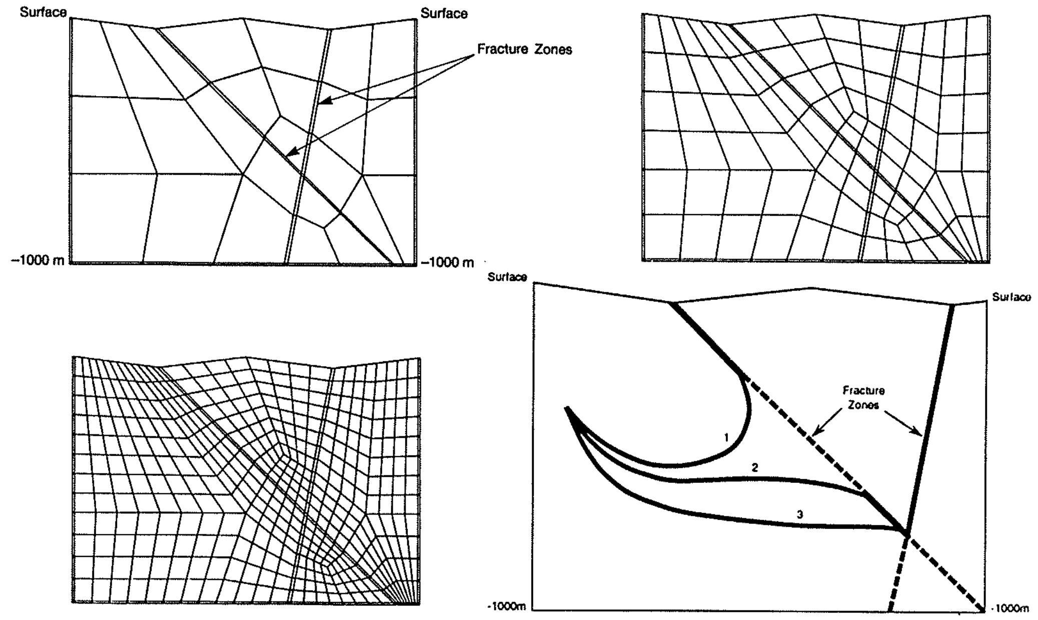

Figure 19: The International HYDROCOIN (Hydrologic Code Intercomparison) Project was concerned with the modelling of groundwater flow. Hydrocoin Level 1 dealt specifically with the verification of groundwater flow codes. This figure depicts a set of finite elements networks at three different levels of detail. Network 3 provides the most accurate description of the path that a water particle would take, but also requires the most computer time.

The validity of these structural models has a different meaning than the validity of process models. If confidence in the structural description is too low, one can always, in principle, make more measurements. The balance to be found, e.g., in site investigations, is between the value of many measurement points and the uncertainties caused by disturbing the natural host rock. In practice, there may be absolute limits to the density of data collection (e.g., for fracture distributions in hard rock). Also, the structure of a host rock might change with time, for example if fractures were to become filled or closed.

Validation of Process Models

Process models are in most cases more generic than structural models. Some are only slightly influenced by structural data. Some have been developed and tested for purposes other than performance assessment of radioactive waste disposal. Sometimes, they are already validated to a level beyond what is required; sometimes, however, they have to be applied to simulate performance of a process or a system under conditions for which they can only partly be tested. In this case, the long time spans involved in radioactive waste management often represent the new feature to be taken into account. Slow processes which can be neglected in normal time frames might be important in the very long term.

The validity of models involving as many parameters as those used, for example to predict radionuclide transport in the geosphere, cannot be established by one or by even a few experiments. The establishment of validity will require a sequence of laboratory measurements, field testing at various scales, in situ testing, and investigation of natural analogues. Some of the work to validate such models is being done through the INTRAVAL Project. See the discussion in Box 12.

Another important issue for validation concerns the difference between the mathematical models used in research and those used in assessing the total repository performance. While there is often an effort in a research model to rigorously treat the individual phenomena involved, complex research models often require simplifications when used in an assessment. The process of transferring the validity of research models to assessment models must be done carefully and clearly. The same problem is even more pronounced for some of the highly simplified models used in probabilistic assessments.

5.1.3 Natural Analogues

Natural analogues are occurrences of materials or processes that can be found in nature and which are analogous to expected materials or processes in a waste repository. The uranium deposit at Cigar Lake, shown in Figure 20, is one example of a natural analogue. Natural analogues can provide information on processes which,

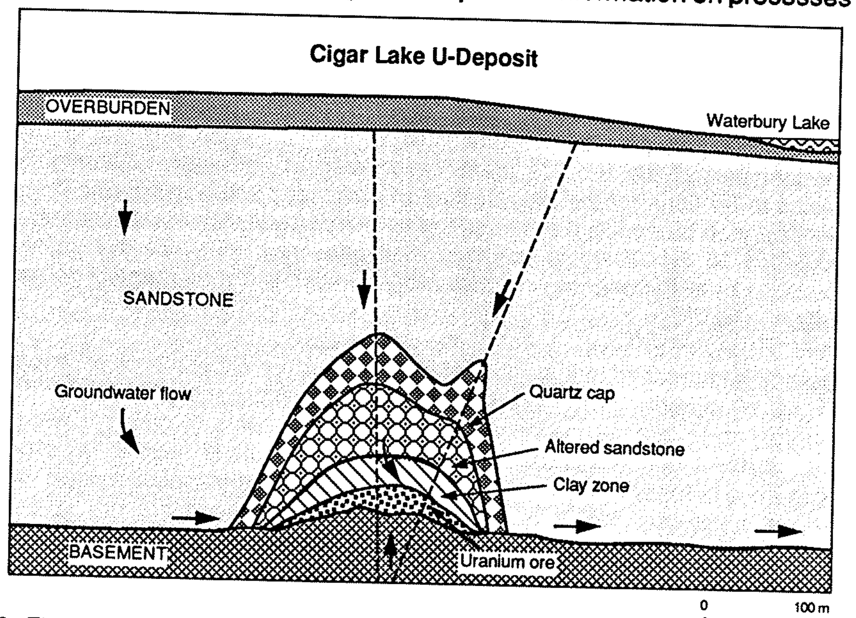

Figure 20: The uranium deposit at Cigar Lake in Canada has many features that are similar to a repository for spent fuel. The high grade uranium ore, mostly uraninite (UO2), has persisted for approximately one billion years without indication at the surface that the ore deposit exists, despite groundwater flow through the deposit. Thus, the combination of natural barriers has been effective in isolating the uranium ore from the surface environment for more than one billion years.

Box 12. The International INTRAVAL project was started in 1988. Phase I will be finished in 1991 and a second phase (1991-1994) is being planned.

INTRAVAL is an international project concerned with the use of mathematical models to predict the transport of radioactive substances in the geosphere. The purpose of the INTRAVAL project is to increase the understanding of how various geophysical, geohydrological, and geochemical phenomena of importance for the radionuclide transport from a repository to the biosphere can be described by mathematical models developed for this purpose. This is being done by systematically using information from laboratory and field experiments as well as from natural analogue studies as input to mathematical models in an attempt to validate the underlying conceptual models and to study the model validation process.

Seventeen test cases have so far been included in the study. The test cases are based on experimental programmes performed within different national and international projects. Several of the cases are based on international experimental programmes, such as the Stripa Project, the Alligator Rivers Project, and the Pocos de Caldas Project. A Pilot Group has been appointed for each of the test cases. The responsibility of the Pilot Group is to compile data and propose formulations of the test cases in such a way that it is possible to simulate the experiments with model calculations.

Most of the progress in Phase I of INTRAVAL has been made in the area of process identification. It has been demonstrated that experiments at different scales, flow rates, tracer concentration, etc., are needed in order to unambiguously distinguish between the effects of different dispersion phenomena and matrix diffusion. It has also been demonstrated that statistical analysis forms an important part of the process identification step of validation. Although work remains to be done for the identification of processes active in specific systems, there are good prospects that Phase I of INTRAVAL will significantly increase the confidence in the ability to mathematically describe many of the processes believed to be of importance in radionuclide transport in a wide range of geological media.

The work has resulted in a number of ideas for further experiments or improved designs of already performed experiments. A suggestion for many of the laboratory experiments has been to run the experiments at different waterflow rates, different concentrations, and over different sample lengths, in order to discriminate between different processes considered in the applied models. It can thus be concluded that it is a great advantage if modellers are given the opportunity to interact with experimentalists in order to ensure that the data required by the models will be determined satisfactorily. The modeller can give views on the data needed, e.g., for distinguishing between different phenomena and can analyse different suggested experimental setups.

because of the large distances and/or the long times involved, cannot be studied solely in laboratory or field experiments. Natural analogues can be used in the modelling and assessment process in the ways listed below.

- As natural experiments which duplicate processes that are being considered in a model. This can be a quantitative application, and can aid in the extrapolation of laboratory experiments to longer times or larger geometric scales.

- For determining bounds on parameter values. This application provides a modeller with limiting values on a parameter.

- As qualitative indicators of which phenomena and processes can occur in the disposal system.

- In an empirical sense to integrate the results of many processes at a potential repository site, over long periods. An example might be to determine whether there is any surface radiological manifestation of a deeply buried ore body.

The study of natural analogues has increased over the last few years. The ability to extract unambiguous information or detailed quantitative data from each single analogue study may be limited, because the variations in the long-term environmental conditions are often difficult to determine. Taken together, however, results of natural analogue studies can contribute to confidence building in models and data being used for safety assessments, and in communicating the results of safety assessments.

5.2 QUALITY ASSURANCE AND PERFORMANCE ASSESSMENT

Quality assurance is a planned and systematic set of procedures to provide adequate confidence that a product will perform satisfactorily in service. Quality assurance is a central concept in modern technology. Formalised quality assurance and quality control procedures are being developed for the construction, operation, and sealing of repositories. However, the need to generate confidence in repository performance assessments requires that a quality assurance policy be applied to all relevant aspects of the assessment, including data collection, modelling, computer code calculations, and integrated assessments. A suitable policy must provide a framework of procedures under which assessment activities are performed and records that confirm that the procedures have been followed. In this way it can be ensured that reliable and traceable sources of information are being used. As a result, the clarity and traceability of the assessment procedure, as well as the scientific basis for it, will be enhanced.

Limited attention was given to quality assurance in the early days of safety assessments when the main aim was to study the feasibility of different options. However, as the time for licensing and implementation approaches, quality assurance procedures are being introduced into the assessment methods. As a large number of quality assurance techniques exist, and are well developed, the task is mainly to adopt and to apply systematically these techniques in a balanced manner.

5.3 CRITICAL REVIEW OF THE PERFORMANCE ASSESSMENT

In every scientific discipline, critical review forms an integral part of the development of a well-founded theory and valid results. Scientific work and results are published in open literature and are thereby available for detailed scrutiny by experts active within the same discipline as well as by anyone interested and knowledgeable in the subject. This well-established practice is, of course, also followed for scientific work used as a basis for safety assessments of radioactive waste repositories. In key areas supporting safety assessments (e.g., waste form characterization, chemical speciation, hydrology of deep formations, mathematical modelling of migration), there is a large number of scientists active at universities and specialised research institutes. The results are being openly published and critically discussed at seminars, workshops, and symposia at national and international levels.

In addition to the critical review provided by the normal mechanisms of the scientific community, other forms of review and scrutiny are included within national repository development programmes. Licensing authorities are, in most countries, closely following the work done within repository development programmes. An active approach by the authorities to obtain independent competence, well in advance of any formal licensing will help to assure that they will be able to handle a licence application with the insight needed to focus regulatory review on the important issues. Usually the authorities actively participate during the long process of choosing the disposal concept, developing repository design, and selecting and investigating potential sites. They ask questions, provide comments or even formally review R&D plans, site-characterisation plans, or interim safety assessments. Such regulatory reviews can be useful in assuring that all relevant safety aspects are being addressed in the repository development programme.

In several countries, integrated safety assessments have been performed as part of the disposal concept development. In several cases the authorities or the government have organised critical review by independent bodies nationally and, in some cases, internationally. Thus, a broad variety of national and international organisations as well as independent individual scientists with relevant competence have been asked to critically review and comment on the assessment. Such a review can be very helpful to identify weak points in the data and models, and in the conclusions drawn from the assessment. In some countries there are also permanent groups of independent scientists charged by the government or its authorities to continuously follow the repository development programme and to provide comments at regular intervals.

Box 13. List of some major international activities and projects with relevance to the long-term safety assessment of radioactive waste disposal.

Project	Scope and Objective	Participants
PAAG, Performance Assessment Advisory Group	Provide guidance on the safety assessment programme of the OECD/NEA. Promote quality and coherence of assessment methods.	OECD/NEA Member countries.
PSAG, Probabilistic System Assessment Group	Information exchange on PSA methods. Intercomparison (verification) exercises.	11 NEA Member countries. NEA provides Secretariat.
TDB, Thermochemical Data Base	Critical review of thermodynamic data for selected elements.	NEA Member countries. Managed by NEA Data Bank.
HYDROCOIN	Verification and validation of codes and models for calculation of ground water movements. Intercomparison exercise. 1987	10 NEA Member countries. Project managed by Swedish Nuclear Power Inspectorate (SKI).
INTRAVAL	Validation of models for radionuclide migration in the geosphere.	10 NEA Member countries. Project managed by SKI.
BIOMOVS	Biospheric model validation study for testing models used to determine ecological transfer and bioaccumulation of radionuclides and other trace substances.	13 countries. Project managed by Swedish National Institute of Radiation Protection (SSI).
PAGIS/PACOMA	Performance assessment of geological isolation systems for radioactive waste. Multinational safety assessment for repositories in salt, clay, crystalline rock and seabed. 1987	EC Member countries with coordination and support of the CEC.
CHEMVAL	Verification of computer programs for chemical speciation calculations.	EC Member countries coordinated and supported by CEC with non-EC country participation.
MIRAGE	Development of data and methods for assessing migration of radionuclides.	EC Member countries coordinated and supported by CEC with non-EC participation.
NAWG, Natural Analogue Working Group	Forum for discussion about natural analogue programmes and applicability.	Worldwide participation, established and sponsored by CEC.
NSARS	Verification and validation of models for the safety assessment of low-level, near-surface waste repositories.	IAEA Member Countries.

5.4 INTERNATIONAL CO-OPERATION IN PERFORMANCE ASSESSMENT

International co-operation is an important feature of science, technology, and environmental protection in society today. However, in few areas has it become so substantial and integrated with national activities as the assessment of the safety of radioactive waste disposal. It is an area of high priority for the three international organisations with substantial programmes in this field (CEC, IAEA, and NEA), and there is active and substantive co-operation between Member countries. Thus, the co-operation is not limited only to the arrangement of symposia, workshops and experts' meetings, but includes a large set of co-operative projects dealing with different aspects of safety assessments and their scientific basis. Practically every important aspect of assessing the safety of different national concepts for radioactive waste disposal is being discussed and reviewed, not only within the national programmes and in this broad international framework, but also through bilateral projects between nations with similar disposal concepts and safety assessment needs. This process will help to ensure that the important safety aspects are being considered and assessed with state-of-the-art methods. In this way international co-operation contributes substantially to confidence building in safety assessments. Some of the major international efforts are listed in Box 13.

6. IMPROVING PERFORMANCE ASSESSMENT

This chapter discusses the expected development of performance assessment methods, and outlines research needed to further improve assessments. The general trends and observations noted in this chapter are expected to be valid for most repository development programmes. The priorities and specific content of further research and development will be strongly linked to the disposal concepts and sites under consideration. To learn more about the specific content of current research programmes, the reader is referred to the specialised literature in the respective subject areas.

6.1 PERFORMANCE ASSESSMENT USE WILL VARY WITH FUTURE NEEDS

Interrelated needs that will influence the development of performance assessments during the next few years include:

- the need to apply performance assessment methods and use the results in repository development programmes;
- the need to improve the available basis for assessments in terms of underlying scientific knowledge and relevant data; and
- the need for validation.

As repository programmes develop and approach the licensing stage, the use of performance assessment is expected to increase. The disposal concept, repository design, site selection, and detailed repository layout will, at least in part, be based on arguments supported by performance assessment. However, it is important to note that performance assessment is not the only, or even the primary, decision-making tool. From a safety standpoint, performance assessments can rarely provide a clear choice between disposal systems and sites; social and political factors will also need to be included in the decision process.

The most important applications of performance assessment in the next decade will be site-specific. Performance assessments will be used to help define the site investigation programmes and to help answer a range of questions. What types of surface investigation are needed? What is the proper balance between deep drill-holes and investigation from shafts and tunnels? What is the best procedure for sinking shafts without disturbing the site characteristics? What is important to measure and at what stage of site development should it be done?

Site investigations are expected to be conducted under a single programme and coordinated by a single organisation. However, performance assessments can and will be done by independent groups. Regulatory authorities regard performance assessment as one of their main tools. Thus, regulators will continue to develop their own competence and capacities in performance assessment methods.

6.2 IMPROVEMENTS IN THE SCIENTIFIC BASIS FOR PERFORMANCE ASSESSMENT

The scientific basis for performance assessment has developed substantially during the last ten years. Major progress has been made in the areas of waste form characterisation, and in understanding of geochemical speciation, deep groundwater movements, and radionuclide migration. Although performance assessment will never be perfected, the expected focus in the coming years will be to test, and either change or confirm the existing concepts and models. Emphasis will be on the validation and application of assessment methods, rather than on completely new research. The site-specific application of scientific studies will be an important part of the overall performance assessment effort.

The understanding and modelling of the essential disposal system processes has in most cases reached a mature and well-advanced stage. However, the detailed understanding and modelling of external perturbations, due to long term environmental changes like glaciation, is still relatively young. Significant improvement is expected in these areas and there are already signs of progress. It is possible that in the next decade modelling of such effects will develop to a stage where it can be consistently integrated in overall assessments rather than be treated on an ad hoc basis. However, even if such modelling capabilities were developed, the need to use them and the level of detail required would depend on safety criteria and on the characteristics of the disposal concepts and sites.

6.3 MODEL VALIDATION AND CONFIDENCE IN PERFORMANCE ASSESSMENT RESULTS

Validation efforts are a necessary part of the process to achieve confidence in predictive capabilities, and it is necessary to develop a strategy for establishing priorities with respect to validation. The need for such a strategy can be illustrated by the selection of backfill material used in a repository. By introducing materials with high sorption capacity, the barrier function of the backfill may be enhanced. On the other hand, the chemical modelling of the near field might then become more complex and thus more difficult to validate. Therefore, it is important that those selecting the

barriers and those studying the possibility of validating the models work together. It might well be that a repository built so that its performance can be assessed with high confidence is more acceptable than a repository aimed at maximum safety.

The need for model validation and the fact that the process can never be perfect is recognised. However, there has been substantial progress with regard to the definition of procedures and methods as well as efforts to establish an accepted terminology. A number of international validation efforts are now underway that will further develop validation procedures and advance the interaction between model construction and experimentation/field observations. Model validation is expected to continue to draw attention in the future. Concept and site-specific assessments are expected to further focus validation efforts and provide guidance on reasonable validation requirements.

6.4 ASSESSMENT METHODS - THE NEXT GENERATION

Further development of performance assessment methods are expected. Improvements will make performance assessments more coherent and more systematic in approach. The results will be presented with greater clarity. Computer capacity and speed will continue to increase and thus improve the capability to perform complex modelling through the integration of more detailed submodels and larger amounts of data.

The expected advances in performance assessment will require a balance between the increased capacity to conduct detailed and complex assessments and the capability of the assessor to maintain perspective. In fact, the power of performance assessment tools can also be used to identify the most important safety characteristics of radioactive waste disposal systems. Used in this way safety assessment will help correctly assess the safety of the system and provide an understanding of what is needed to assure safety for both present and future radioactive waste disposal systems.

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ANNEX 1

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